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Preface

The semiarid tropics (SAT) cover large areas of sub-Saharan Africa, parts of Asia and northern Australia, and large portions of several Latin American countries. The largest area of the SAT in Asia is located in India where it covers nearly 75% of the nation's cultivated land. It contributes 40% to the total food production of the country and supports almost one-third of the population.

Historically, lack of moisture has been considered the greatest limit to production in the SAT. In the recent past, however, it has been increasingly recognized that these soils have significant requirements for fertilizer nutrients including nitrogen, phosphorus, and zinc. Ample evidence exists that fertilization increases yields of SAT crops with favorable economics. However, sharp contrasts in rainfall patterns across the years and seasons preclude uniform and firm recommendations on the use of fertilizers, their sources, and methods of application. The great diversity in the characteristics of soils occurring in the SAT adds further to this complexity. Optimizing fertilization strategies, given the uncertainties of climate and variability in soils, is a challenge that confronts agricultural scientists working in this region.

This colloquium, held at the International Crops Research Institute for the Semi-Arid Tropics (ICRISAT) Center, October 10-11, 1988, was organized to bring together scientists having firsthand knowledge and understanding of the problems related to soil fertility in the Indian SAT. It provided a forum in which agricultural scientists could share knowledge, explore possibilities for increasing fertilizer use efficiency in India, and establish research priorities.

These proceedings contain the papers presented during the colloquium as well as the summaries of the discussion sessions. Although the contents of the papers are those of the individual authors, the papers have been edited for publication. The cooperation of the authors in this process is gratefully acknowledged. By approaching the problems of sustainable agriculture from a variety of perspectives, the proceedings should become an important bibliographic resource for future research work in India.

Acknowledgment

The staff and management of IFDC are grateful for the support and efforts of our cosponsor, ICRISAT, in helping to organize and conduct this timely colloquium. Special thanks go to Drs. J. L. Monteith, S. M. Virmani, J. R. Burford, K. L. Sahrawat, T. J. Rego, and S. P. Wani of ICRISAT and Dr. J. C. Katyal of the Indian Agricultural Research Institute (IARI), formerly with IFDC. We also wish to thank the United Nations Development Programme (UNDP) for providing financial support of the meeting.

We are especially grateful to the speakers for the time and effort spent in preparing their very informative papers.

Finally, the workshop could not have been the success that it was without the contributions of the many delegates who participated in the discussions that followed the presentation of each paper.

Donald L. McCune
Managing Director
International Fertilizer
Development Center

November 1989

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World Fertilizer Market Review and Outlook

J. H. Allgood, Market Analyst, and L. L. Hammond, Director, Agro-Economic Division, International Fertilizer Development Center

Abstract

The world fertilizer market has changed dramatically during the past two decades. The 1970s will be remembered as a growth era in terms of fertilizer production, consumption, and trade. In contrast, the 1980s has been a decade of instability, with total fertilizer consumption per year declining three times during the 1980-87 period. Since the mid-1970s, there has been a basic restructuring of the market with the centrally planned economies and developing market economies accounting for an increasing share of world fertilizer production, trade, and consumption. The outlook for the world fertilizer market over the next few years is varied. Nitrogen fertilizer supply and demand are expected to be in close balance by 1990.[1] The potential for a surplus in phosphate and potash supply is expected to persist through 1992.

Introduction

The world fertilizer market of the 1980s offers a striking contrast to that of the 1970s. The 1970s will likely be remembered as the decade of growth in terms of fertilizer consumption, production, trade, and investment in new manufacturing facilities. Globally, fertilizer use increased every year during the 1970s (with the exception of 1975) and fertilizer production increased every year. For nitrogen, phosphate, and potash, production capacity increased by 90%, 84%, and 24%, respectively, during the 1970s, and much of the new capacity was located in the Developing Market Economies (DgME) and Centrally Planned Economies (CPE). In contrast, thus far the 1980s has been a decade of instability. World fertilizer consumption per year declined three times during the period from 1970 to 1987. Such fluctuations in world demand and the resultant unfavorable economic conditions for the world fertilizer industry contributed to a decline in fertilizer production in 2 of these years. In today's market environment, investment in new manufacturing facilities is down sharply from the 1970s. It is expected that during this decade nitrogen, phosphate, and potash capacity will increase by only 22%, 33%, and 17%, respectively; most of this new capacity is already in place. As occurred during the latter part of the 1970s, the bulk of the new capacity during the 1980s will be located in the DgME and CPE. In view of the relatively low level of investment in new capacity, the world fertilizer supply-demand outlook ranges from adequate supplies of phosphate and potash to a likely deficit for nitrogen by 1991.

It is apparent that the world fertilizer market has changed dramatically during the past two decades. Three very significant market trends have become well established during this time. One is the reduced rate of growth in world fertilizer demand and the resulting more conservative plant investment plans. A second is the increasing role of government-controlled industries in world fertilizer production and trade. Third is the declining share of fertilizer consumption, production, and trade accounted for by the Developed Market Economies (DME). The CPE and DgME are primarily responsible for the recent growth in the world fertilizer market. Further, these two regions will be the main areas of future market expansion. The purpose of this paper is threefold: (1) to provide a brief review of the fertilizer market developments that occurred during the past two decades, (2) to provide an overview of the current market situation, and (3) to provide an indication of the near-term market outlook.

A Review of the 1970s

The world fertilizer market experienced a major expansion during the 1970s. World fertilizer consumption increased from 62.3 million tonnes of plant nutrients in 1970 to 111 million tonnes in 1980, thus yielding a compound growth rate of 6% per annum (Table 1). On a yearly basis, fertilizer use increased fairly consistently throughout the decade, except in 1975 when a number of

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[1] Authors' note: During the past 12 months, the political uprising in China and the weaker than expected demand for fertilizers in North America have contributed to a substantial inventory buildup in key market areas, thereby shifting the projected tight supply situation for nitrogen fertilizers to 1991 or possibly 1992.

Table 1. World Fertilizer Consumption Trends

Region/Year	1970	1980	1987	Compound Growth Rate 1970-80	Compound Growth Rate 1980-87
	(million tonnes nutrient)			------(%)----	
Developed					
North America	15.3	22.7	19.6	4	(2.1)
Western Europe	16.1	21.7	21.4	3	(0.2)
Other	4.4	5.2	4.4	1.7	(2.4)
Total Developed	35.8	49.6	45.4	3.3	(1.3)
Developing					
Latin America	2.5	6.6	8.5	10.2	3.7
Africa	0.6	1.1	1.8	6.2	7.3
Near East	1.1	2.8	4.6	9.8	7.3
Far East	3.1	9.4	16.8	11.7	8.6
Other	a	a	a		
Total Developing	7.3	19.9	31.7	10.5	6.8
Centrally Planned Economies (CPE)					
Eastern Europe & U.S.S.R.	15.1	27.4	36.2	6.1	4.1
C.P. Asia	4.1	14.0	18.9	13.0	4.4
Total CPE	19.2	41.4	55.1	8.0	4.2
World Total	62.3[b]	111.1[b]	132.3[b]	6.0	2.5

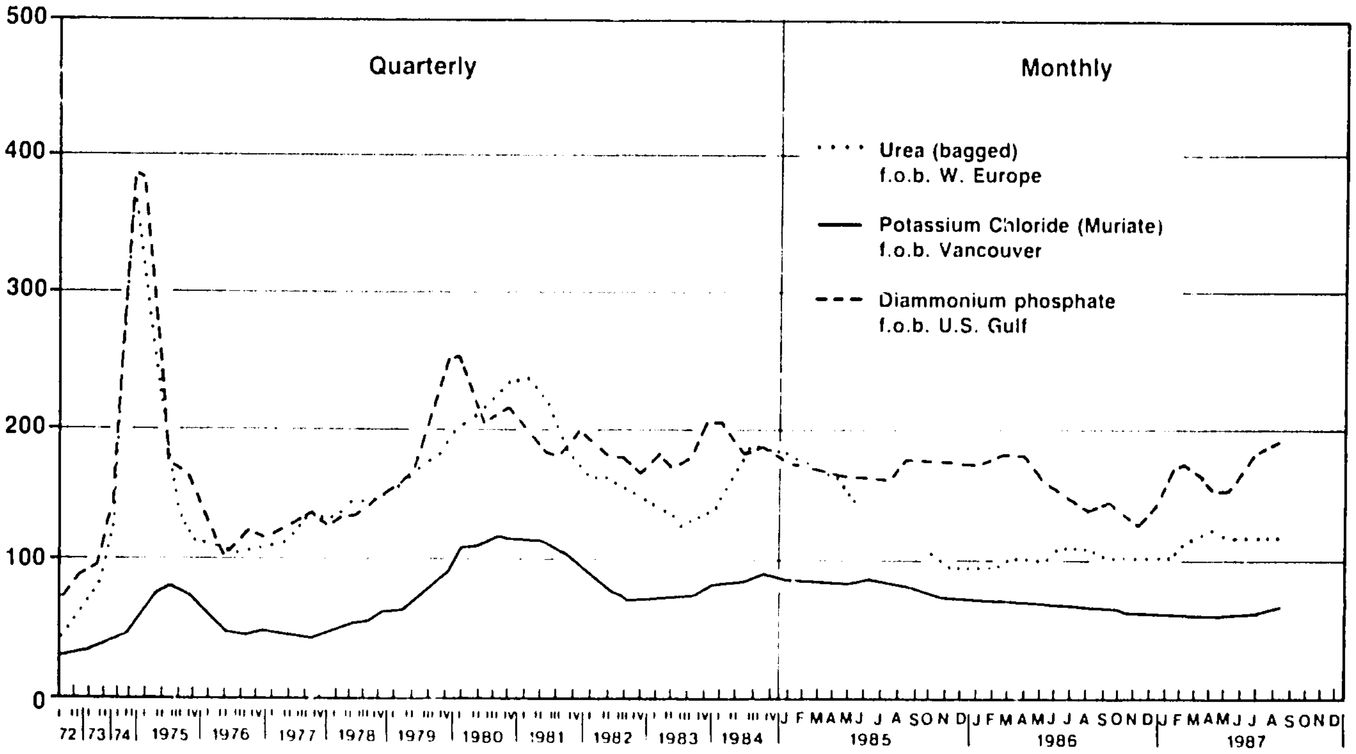
a. Consumption < 100,000 tonnes.
b. Totals may not add due to rounding.

factors (the 1973/74 oil crisis, panic stockpiling by some countries in the early 1970s to ensure adequate fertilizer supplies, insufficient market intelligence, etc.) contributed to a record increase in fertilizer prices (Figure 1).

Primarily as a result of the price escalation, fertilizer use declined by 3.3% in 1975. However, the period of high prices and their impact on demand was short-lived. During the following year, fertilizer demand rebounded to the precrisis growth trend.

On a regional basis, the CPE accounted for almost one-half of the growth in world fertilizer consumption during the 1970s, and use increased at a compound rate of 8% per annum (Table 1). China and the U.S.S.R. are the major fertilizer users in the CPE, and as a result of aggressive agriculture and fertilizer market development programs during the 1970s, use increased by 14.2% per annum and 7.5% per annum, respectively, in the two countries.

The DME and DgME each accounted for slightly over 25% of the increase in world fertilizer use during the 1970s. However, in terms of market growth, fertilizer use in the DgME increased at an impressive rate of 10.8% per



Source: World Bank, 1965 to October 1975. November 1975 to August 1987 based on information obtained from various sources.

Figure 1. Export Price Trends for Some Major Fertilizer Materials (U.S. Dollars Per Tonne of Product).

year and reached almost 20 million tonnes of nutrients in 1980. Fertilizer use in the DME increased by 14 million tonnes of nutrients during the 1970s, yielding a compound growth rate of 3.3% per year.

On a nutrient basis, nitrogen dominates the world market. In 1970, the worldwide N:P_2O_5:K_2O ratio was 1:0.67:0.54. Owing to the rapid growth in fertilizer use in the CPE and DgME (particularly in Asia), by 1980 the nutrient ratio shifted in favor of nitrogen to 1:0.52:0.42.

The rapid and apparently sustained increase in fertilizer demand contributed to a massive investment in new fertilizer production capacity and a basic restructuring of the industry during the 1970s. Such investment decisions were based upon a number of criteria, the most notable of which were the desire to (1) expand a potentially profitable business activity, (2) ensure stability of supply for critical agricultural inputs, (3) develop a natural resource base and thereby reduce foreign exchange requirements for importing fertilizers, and (4) diversify foreign exchange earnings capability. Globally, ammonia capacity increased from 50.7 million tonnes of N per year in 1970 to over 96.2 million tonnes of N per year in 1980 (Table 2). During the same timeframe, phosphoric acid capacity

Table 2. World Ammonia Capacity

Region/Year	1970[a]	1973	1980	1985	1986	1987	1988	1989	1990	1992[b]
	('000 tonnes of N)									
Developed										
North America	13,814	13,982	17,652	16,318	16,268	15,907	15,891	15,891	15,891	16,150
Western Europe	11,932	14,020	15,053	14,321	14,000	13,906	13,567	13,892	13,892	15,230
Other[c]	3,431	4,889	3,995	3,548	3,004	3,004	3,082	3,082	3,082	3,450
Total Developed	29,177	32,891	36,700	34,187	33,272	32,817	32,540	32,865	32,865	34,850
Developing										
Latin America	1,324	1,745	3,975	5,830	5,830	5,830	5,830	6,200	6,200	7,360
Africa	25	347	75	404	429	404	948	1,266	1,266	1,290
Near East	658	1,397	3,451	4,281	4,553	4,879	5,279	5,279	5,822	6,210
Far East	2,639	3,545	8,002	10,681	12,568	12,731	13,117	14,728	14,972	16,170
Other	-									
Total Developing	4,646	7,034	15,503	21,196	23,380	23,844	25,174	27,473	28,260	31,030
Centrally Planned Economics (CPE)										
Eastern Europe	5,383	6,419	9,762	10,787	11,304	11,512	11,512	11,512	11,512	35,520
U.S.S.R.	7,530	9,406	17,890	23,366	24,516	24,886	24,886	24,886	24,886	
C. P. Asia	3,925	4,907	16,302	17,320	17,864	18,164	19,348	19,348	19,513	19,870
Total CPE	16,838	20,732	43,954	51,473	53,684	54,562	55,746	55,746	55,911	55,380
World Total	50,661	60,657	96,157	106,856	110,336	111,223	113,460	116,084	117,036	121,250

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a. Data for 1970-90 are from the National Fertilizer Development Center of the Tennessee Valley Authority.

b. FAO/UNIDO/World Bank Working Group on Fertilizers. June 1987. The capacity estimates for 1992 include plants that are currently idle and may resume operation.

c. Oceania, Israel, Japan, and South Africa.

increased from 14.4 million tonnes of P_2O_5 per year to 26.4 million tonnes of P_2O_5 per year (Table 3). The growth in potash production potential was less dramatic but still more than adequate to satisfy demand. During the 1970s, world potash capacity increased from 26.1 million tonnes of K_2O per year to 32.5 million tonnes (Table 4).

The investment in production capacity was not uniform worldwide. In fact, the 1970s was a period of industry restructuring; many former export-oriented industries (Western Europe, United States, and Japan) gave way to producers blessed with indigenous, low-cost raw material supplies (U.S.S.R., North Africa, and the Middle East). For example, the Japanese nitrogen industry, which is largely based upon imported naphtha, reduced capacity by almost one-third to 2.8 million tonnes of N during the 1970s. Meanwhile, the U.S.S.R. developed a major nitrogen export potential by increasing capacity from 7.5 million tonnes of N in 1970 to nearly 18 million tonnes of N in 1980. The U.S.S.R. accounted for 23% of all ammonia capacity commissioned during the 1970s.

As a result of the rapid increase in production capacity, along with improved operating rates in existing plants, world fertilizer production exceeded demand every year during the 1970s. As indicated in Table 5, world fertilizer production increased from 66 million tonnes of nutrients in 1970 to 118 million tonnes in 1980. Contrary to the rumored shortages of 1974, world fertilizer production exceeded use by a comfortable margin of 5% (N by 5%, P_2O_5 by 3.4%, and K_2O by 7%).

Table 3. World Phosphoric Acid Capacity

Region/Year	1970[a]	1973	1980	1985	1986	1987	1988	1989	1990	1992[b]
	('000 tonnes of P_2O_5)									
Developed										
North America	6,667	7,139	10,273	11,744	11,221	10,431	10,318	10,318	10,318	11,930
Western Europe	3,500	3,685	4,548	4,286	4,197	4,024	4,029	4,029	4,029	4,880
Other[c]	1,347	1,570	1,914	2,194	2,170	2,136	2,136	2,136	2,136	2,130
Total Developed	11,514	12,394	16,735	18,224	17,588	16,591	16,483	16,483	16,483	18,940
Developing										
Latin America	521	595	796	1,233	1,233	1,486	1,734	1,734	1,734	1,970
Africa	374	574	1,774	2,979	3,309	3,899	4,229	4,559	4,559	4,740
Near East	99	356	712	1,594	1,594	1,594	1,634	1,634	1,634	1,950
Far East	410	501	1,274	1,793	1,793	1,674	1,854	2,112	2,112	1,970
Other										
Total Developing	1,404	2,026	4,556	7,599	7,929	8,653	9,451	10,039	10,039	10,620
Centrally Planned Economies (CPE)										
Eastern Europe	547	948	1,850	2,045	2,045	2,045	2,045	2,283	2,283	7,710
U.S.S.R.	882	1,529	3,244	5,379	5,845	6,265	6,265	6,265	6,265	
C. P. Asia	40	40	40	76	76	76	76	76	136	300
Total CPE	1,469	2,517	5,134	7,500	7,966	8,386	8,386	8,624	8,684	8,010
World Total	14,387	16,937	26,425	33,323	33,483	33,630	34,320	35,146	35,206	37,580

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a. Data for 1970-90 are from the National Fertilizer Development Center of the Tennessee Valley Authority.

b. FAO/UNIDO/World Bank Working Group on Fertilizers. June 1987. The capacity estimates for 1992 include plants that are currently idle and may resume operation.

c. Oceania, Israel, Japan, and South Africa.

Table 4. World Potash Capacity

Region/Year	1970[a]	1973	1980	1985	1986	1987	1988	1989	1990	1992[b]
	('000 tonnes of K_2O)									
Developed										
North America	10,833	10,679	10,593	11,390	13,480	13,480	13,085	13,085	13,085	13,810
Western Europe	6,340	7,240	6,550	6,000	6,250	6,300	6,000	6,000	6,050	6,050
Other[c]	600	600	780	1,260	1,260	1,260	1,260	1,260	1,260	1,800
Total Developed	17,773	18,519	17,923	18,650	20,990	21,040	20,345	20,345	20,395	21,660
Developing										
Latin America	30	30	-	-	-	-	300	300	300	300
Africa	500	500	-	-	-	-	-	-	-	-
Near East	-	-	-	720	720	720	840	840	840	840
Far East	-	-	-	-	-	-	-	-	-	-
Other	-	-	-	-	-	-	-	-	-	-
Total Developing	530	530	-	720	720	720	1,140	1,140	1,140	1,140
Centrally Planned Economies (CPE)										
Eastern Europe	1,920	2,620	3,450	3,475	3,475	3,475	3,475	3,475	3,475	16,230
U.S.S.R.	5,860	6,070	11,040	12,590	12,590	11,130	11,130	11,880	12,730	
C. P. Asia	50	50	50	50	50	50	50	120	120	120
Total CPE	7,830	8,740	14,540	16,115	16,115	14,655	14,655	15,475	16,325	16,350
World Total	26,133	27,789	32,463	35,485	37,825	36,415	36,140	36,960	37,860	39,150

a. Data for 1970-90 are from the National Fertilizer Development Center of the Tennessee Valley Authority.

b. FAO/UNIDO/World Bank Working Group on Fertilizer June 1987. The capacity estimates for 1992 include plants that are currently idle and may resume operation.

c. Oceania, Israel, Japan, and South Africa.

Table 5. World Fertilizer Production Trends

Region/Year	1970	1980	1987	Compound Growth Rate 1970-80	Compound Growth Rate 1980-87
	(million tonnes nutrient)			(%)	
Developed					
North America	19.5	32.0	28.9	5.1	(1.4)
Western Europe	18.5	23.4	20.6	2.4	(1.8)
Other	5.2	5.5	4.9	0.6	(1.6)
Total Developed	43.2	60.9	54.4	3.5	(1.6)
Developing					
Latin America	1.0	3.0	4.8	11.6	6.9
Africa	.5	.7	1.7	3.4	13.5
Near East	.4	2.3	5.1	19.1	12.0
Far East	1.8	6.0	12.9	12.8	11.6
Other	-	-	-		
Total Developing	3.7	12.0	24.5	12.5	10.7
Centrally Planned Economies (CPE)					
Eastern Europe and U.S.S.R.	17.0	33.2	46.0	6.9	4.8
C. P. Asia	2.4	11.7	15.4	17.2	4.0
Total CPE	19.4	44.9	61.4	8.8	4.6
World Total	66.3	117.8	140.3	5.9	2.5

During the 1970s, the bulk of the world's fertilizer production occurred in the DME. The DME accounted for 65% of world fertilizer production in 1970 (Figure 2). However, during the decade a definite trend was established toward a more balanced distribution of production. As a result of the rapid industry development programs in the CPE and DgME, by 1980 the DME's share of world fertilizer production declined to 52%. The CPE's share of world production increased from 29% in 1970 to 38% in 1980 and the DgME's share from 6% to 10% during the decade.

The 1980s

The rapid pace and encouraging consistency in market development that characterized the world fertilizer market during the 1970s have been replaced by a more volatile environment. As a result of a number of factors including unfavorable crop:fertilizer price relationships, acreage reduction programs in the United States, unfavorable weather conditions, etc., world fertilizer consumption declined three times during the 1980-87 period, including consecutive declines in 1982 and 1983. Fertilizer use also declined in 1986 before staging a recovery in 1987. As a

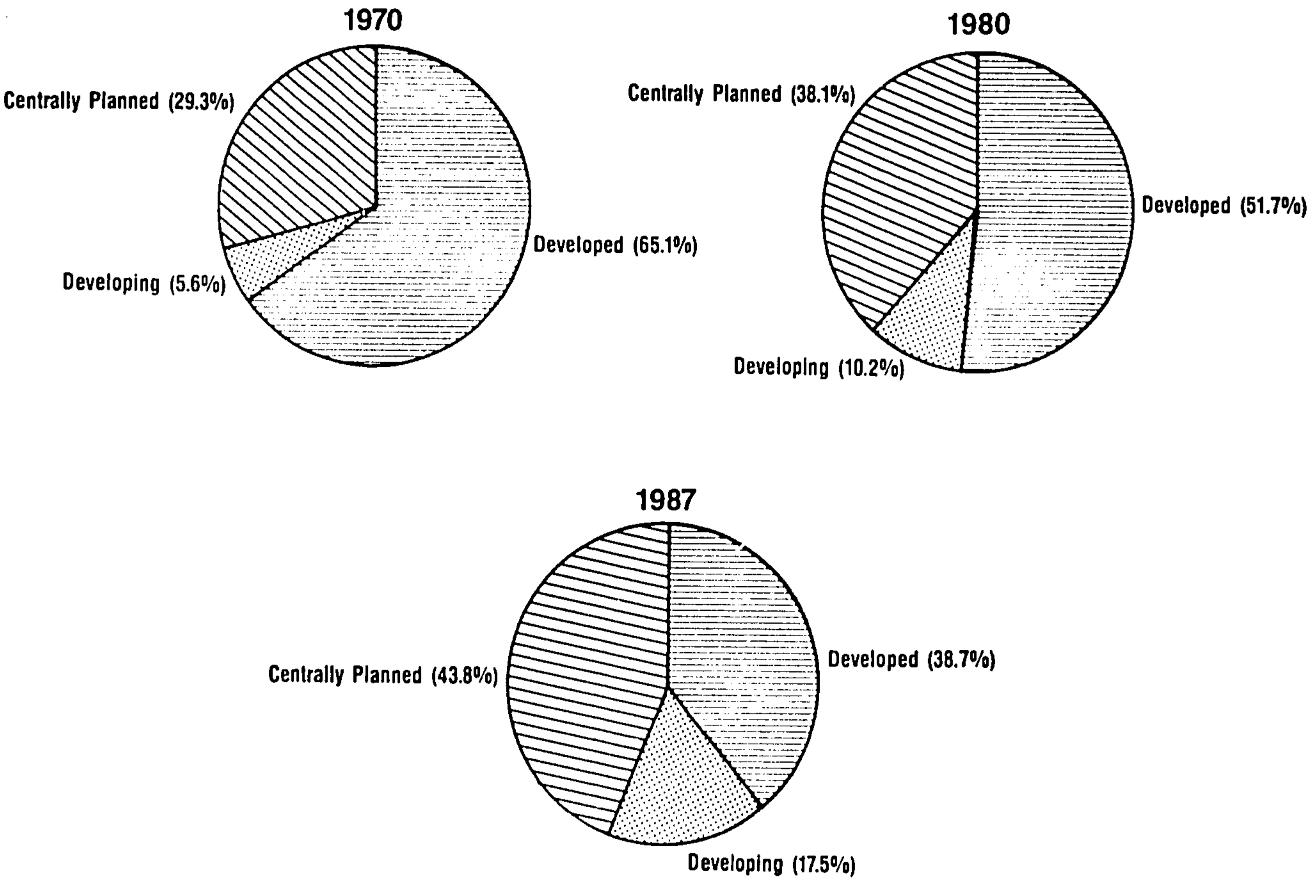


Figure 2. Share of World Fertilizer Production by Region.

result of the market instability, the compound growth rate in fertilizer consumption for the period 1980-87 was only 2.5% per annum.

On a regional basis, the fertilizer use pattern is quite varied. The DME countries are clearly mature fertilizer markets. In such markets, fertilizer marketing systems perform relatively efficiently, farmer knowledge of fertilizer products and the potential benefits from their use is widespread, and fertilizer market information is readily available. In the DME, fertilizer demand is primarily a function of the anticipated profitability of fertilizer use and government policy decisions. Developments in the U.S. agricultural sector during the 1980s offer an excellent example of the influence of government policy on fertilizer use. In 1983 the U.S. Government's Payment In Kind (PIK) program resulted in almost one-third of the planted acreage in the United States being taken out of production. Therefore, even though per hectare application rates on such major crops as corn and wheat actually increased, the net result in 1983 was that U.S. fertilizer use declined by almost 16%. Various other acreage reduction programs since that time, although less severe, have continued to encourage farmers to idle a portion of their cropland and have thereby restricted fertilizer use. A similar but less severe situation exists in Japan. As a result of government policy, rice acreage declined by an estimated 5% and 26% in 1986 and 1987, respectively. The total area planted to rice in Japan is now about 2.17 million ha.

Between 1980 and 1987, total fertilizer consumption in the DME declined in 5 of the 7 years. In 1987 fertilizer use totaled 45.5 million tonnes of plant nutrients as compared with the use record of 49.7 million tonnes of plant nutrients achieved in 1980. Thus, fertilizer use declined by about 1.3% per year during this period. Further, and more importantly, the gradual decline/stagnation in fertilizer use in the DME is characteristic of each of the four individual regions that constitute the DME (in North America, Western Europe, Oceania, and other developed countries).

On a nutrient basis, the DME's nitrogen market has demonstrated more demand stability than either phosphate or potash markets. Nitrogen use increased from 22.7 million tonnes in 1980 to 23 million tonnes in 1987 or a compound growth rate of 0.2% per year. Conversely, both phosphate and potash use are down dramatically; phosphate and potash consumption declined by 21% and 13%, respectively, between 1980 and 1987.

Fertilizer use in the DgME and CPE has continued to increase during the 1980s, albeit at a slower pace than that of the 1970s.

Fertilizer use in the DgME increased from about 20 million tonnes of plant nutrients in 1980 to 31.7 million tonnes in 1987, a compound growth rate of 6.8% per year. The Far East region, which includes such major fertilizer-using countries as India, Indonesia, and Pakistan (consumption totaled 9.6 million, 2.1 million, and 1.7 million tonnes of plant nutrients, respectively), accounts for over one-half of the fertilizers used in the DgME; with a compound growth rate of nearly 9% during this decade, it is also the world's fastest growing fertilizer market. At the other end of the spectrum is Africa where in 1987 farmers used only 1.8 million tonnes of plant nutrients or about 6% of the total fertilizers consumed by the DgME. However, the fertilizer markets in most African countries are in an early stage of market development and offer an excellent opportunity for long-term growth. Africa is the only region in which the fertilizer consumption compound growth rate of the 1980s (7.3% per annum) exceeds that of the 1970s (6.2% per annum).

In the CPE, fertilizer use increased by an average of 4.2% per year between 1980 and 1987, and consumption exceeded 55 million tonnes in 1987. In the U.S.S.R. and China, by far the major CPE fertilizer users, consumption totaled 26.5 million tonnes and 17.2 million tonnes of plant nutrients, respectively, in 1987.

The net effect of the market growth led by the DgME and CPE is that, in 1987, the CPE accounted for 42% of world fertilizer consumption, the DME for 34%, and the DgME for 24% (Figure 3). The nutrient use ratio has also

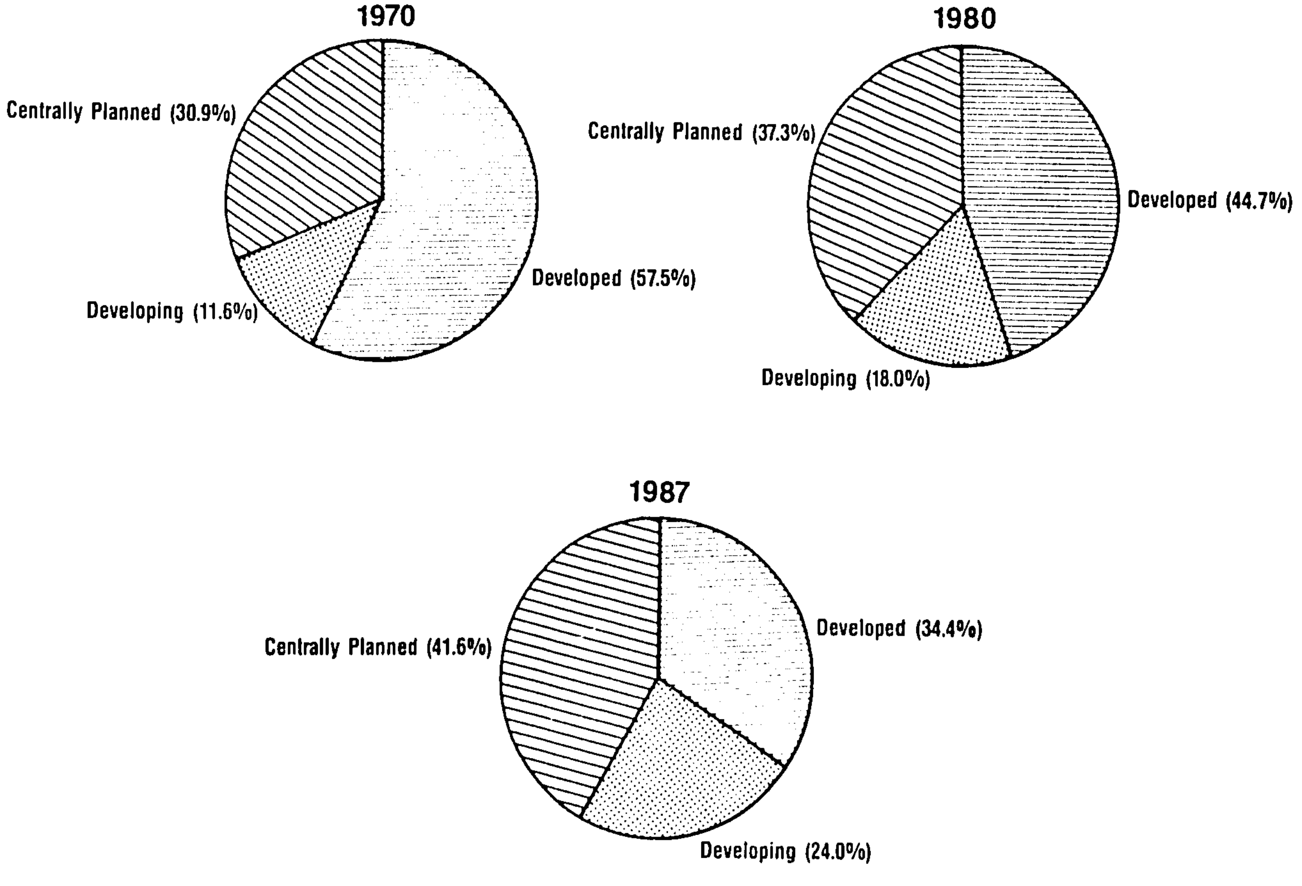


Figure 3. Share of World Fertilizer Consumption by Region.

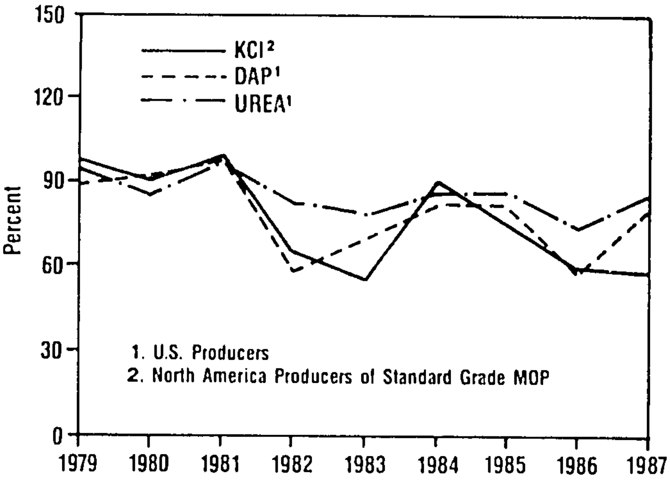
continued to change in favor of nitrogen (1:0.46:0.36) as the rice-dominated agriculture sectors of China, India, Indonesia, etc., maintain very favorable growth trends for nitrogen fertilizers.

The relatively slower growth in fertilizer demand thus far during the 1980s has precipitated a much more conservative approach to investment in new production capacity. During the period 1980-87, global capacities to produce ammonia, phosphoric acid, and potash increased by 16%, 27%, and 12%, respectively. The new capacity thus is being developed at a much slower pace than that of a decade ago; moreover, the location of the new plants, particularly in the case of nitrogen, is altering the market structure. In 1980, the profit-oriented DME accounted for 38% of the world's ammonia capacity. However, because of unfavorable market conditions (i.e., stagnant or declining demand in domestic markets, low prices, and intense price competition in export markets), their nameplate ammonia capacity has declined by over 4 million tonnes of N (11%). Conversely, ammonia capacity in the DgME and CPE has increased by 8.3 million tonnes and 10.6 million tonnes of N, respectively. Almost 50% of the world's ammonia capacity is now situated in the CPE; the DME and DgME account for 30% and 21%, respectively, of world ammonia capacity.

The commercially suitable phosphate rock and potash deposits are not nearly as widely dispersed geographically as the nitrogen feedstocks. Therefore the trend in the regional distribution of phosphate production capacity has not been as severe as that for nitrogen capacity. The DME, DgME, and CPE accounted for 63%, 17%, and 20%, respectively, of world phosphoric acid capacity in 1980. As a result of major capacity developments in such countries as the U.S.S.R., Morocco, Jordan, Tunisia, and Iraq, by 1987 the DME's share of world phosphoric acid capacity had declined to 49%, and the DgME and CPE each accounted for about 25% of world capacity.

In 1980, only 11 countries operated potash production facilities; an additional producer emerged in 1983 with the commissioning of Jordan's production facility. The DME accounted for 55% of world potash capacity in 1980, and their share increased to 57% in 1987. The bulk of the remaining potash capacity is located in the CPEs; Brazil and Jordan are the only producers of potassium chloride in the DgMEs.

Given the reduced growth rate in fertilizer consumption and the more conservative approach to investment in capacity, it is not surprising that world fertilizer production increased at a compound rate of only 1.8% per annum during the 1980-87 period. On a regional basis, the trend in production has been very similar to that of consumption. Fertilizer production in the DME declined from nearly 61 million tonnes of nutrient in 1980 to about 54 million tonnes in 1987. The drop in production was due to permanent plant closures as well as reduced operating rates. For example, in the profit-driven industry of North America, reduced domestic demand and intense price competition in export markets resulted in U.S. urea and diammonium phosphate (DAP) plants being operated at only 78% and 70% of capacity, respectively, in 1983 (Figure 4). Similarly, potash producers in the United States and Canada operated their facilities at only 55% of capacity. Conversely, in non-market-driven economies, production increased significantly during the 1980s. Production in the DgME more than doubled, reaching 24.5 million tonnes of nutrient in 1987, and production in the CPE was up by 37% to 61.4 million tonnes. Thus, the CPE and DgME accounted for 44% and 17%, respectively, of world fertilizer production, and the DME's share declined to 39%.



Source: The Fertilizer Institute (TFI), Based Upon Industry Average for TFI Members.

Figure 4. Fertilizer Plant Operating Rates, 1979-87.

World fertilizer trade has continued to expand during the 1980s because a number of countries, including such major consumers as China, India, and the United States, are required to rely on imports to meet farmer demand. At the same time, such countries as Kuwait, Morocco, Jordan, Qatar, Saudi Arabia, and Tunisia have developed indigenous low-cost fertilizer raw materials with export markets in mind. The United States offers a good example of a country that is heavily involved in both the importation and export of fertilizers in accordance with the seasonal requirements of farmers and international prices.

World fertilizer exports have increased at a compound growth rate of 3.7% per year during this decade, reaching 44.2 million tonnes of nutrient in 1987. This means that one-third of all fertilizers produced worldwide find their way to international markets. As with fertilizer production and consumption, the recent trend has been toward a more balanced regional distribution of shares in world exports: for the DME, about 60% of all exports, and for the CPE and DgME, about 26% and 14%, respectively. On a nutrient basis, potash and nitrogen each account for about 39% of world trade.

On the other side of the trade ledger, fertilizer imports in 1987 were estimated at about 42 million tonnes of nutrient. The DME imported 21 million tonnes of plant nutrients in 1987 or about one-half of the world total. The DgME and CPE accounted for 31% and 19%, respectively, of total imports. On a nutrient basis, again nitrogen and potash fertilizers account for the largest share of total imports, which in 1987 was about 41% each of the world total.

Market Outlook

The world fertilizer market outlook for the 1987-92 period offers signs of guarded but encouraging optimism. World fertilizer consumption registered a solid 3.5% increase in 1987, and early indications suggest that use will be up again in 1988. Buoyed by improved global demand, international prices have increased to more reasonable levels. For example, in early 1987, the international price of DAP was about $135/tonne (bulk, f.o.b. vessel), about 10% below the estimated production cost for U.S. producers. In 1988, DAP rose to about $180/tonne on the international market. The past instability in the world marketplace has shocked decisionmakers into realizing that fertilizer demand cannot continue at the high growth rates achieved during the 1970s. This realization, coupled with improved availability of world fertilizer market information, has contributed to a much more conservative approach by industry toward investment in new manufacturing facilities. However, with the possible exception of nitrogen, which is an area of growing concern, existing plants plus those under construction and/or firmly scheduled should be adequate to satisfy fertilizer demand at least through 1992.

Based upon 1987 estimates by the FAO/ UNIDO/ World Bank Working Group on Fertilizers, which have been updated to reflect more current market information, world fertilizer consumption is forecast to increase at an average compound growth rate of 2.86% per annum during the next few years. It is expected that world fertilizer consumption will total 152 million tonnes of nutrients in 1992. The $N:P_2O_5:K_2O$ use ratio is expected to be 1:0.46:0.35 in 1992 or essentially the same as that of 1987.

The CPE, which emerged during the 1980s as the major fertilizer use region, will maintain this status. By 1992, it is expected that 42% of all fertilizers will be used in the CPE. The DME will continue to be the second largest fertilizer-using area, accounting for 31% of the world total. However, this is only because of the heavy use of potash in the DME. The use of nitrogen and phosphate in the DgME will be approximately equal to that in the DME.

Although the commissioning of new capacity during 1987-92 will be low in relation to previous years, total fertilizer production potential is expected to increase at a compound growth rate of 2.14% per year during this period. World fertilizer production potential should reach 156 million tonnes of plant nutrients in 1992. The CPE and DME will account for about 41% and 39%, respectively, of all fertilizers produced.

Although, on the whole, the world fertilizer supply-demand estimate offers little reason for concern, the specific outlooks for nitrogen, phosphate, and potash are quite varied. In fact, the nitrogen market is an area of major concern. World nitrogen fertilizer consumption is expected to increase at a compound growth rate of 2.95% per annum during the next few years and to reach 84.2 million tonnes of N in 1992. During this same period, only about 10 million tonnes of new nitrogen capacity will be commissioned; hence, the compound growth rate will be only 1.7% per annum (Table 2). As a result, the world nitrogen market will likely approach a supply-demand balance by 1990, and thereafter a deficit is likely to occur. The world nitrogen production potential in 1992 is estimated to be only 81.3 million tonnes of N; thus, a nitrogen deficit of 2.9 million tonnes is projected (Table 6).

On a regional basis, the CPE will be the only economic region where nitrogen production potential will exceed demand, and even this will decline substantially in the years ahead. During the period 1987-92, nitrogen demand in Centrally Planned Asia and Eastern Europe (including the U.S.S.R.) is expected to increase at compound growth rates of 3.1% and 2.7%, respectively. Meanwhile nitrogen capacity in the CPE will increase by less than 1.9 million tonnes of N. As a result, the CPE's potential nitrogen surplus will decline from a projected record high of 4.78 million tonnes of N in 1988 to only 2.0 million tonnes in 1992. Within the CPE, Eastern Europe (including the U.S.S.R.) is expected to have a nitrogen fertilizer surplus of 5.4 million tonnes of N in 1992,

Table 6. Nitrogen Fertilizer Supply-Demand Situation and Outlook: 1986-92

Region/Year	1986[a]			1987[b]			1988[c]			1989		
	Supply	Demand	Balance	Supply	Demand	Balance	Supply	Demand	Balance	Supply	Demand	Balance
	(million tonnes N)											
Developed												
North America	12.28	10.68	1.60	12.02	10.54	1.48	10.92	10.60	0.32	11.08	10.70	0.38
Western Europe	11.23	10.70	0.53	11.04	11.00	0.04	10.35	11.10	-0.75	10.51	11.10	-0.59
Oceania	0.27	0.37	-0.10	0.27	0.38	-0.10	0.36	0.04	0.32	0.39	0.40	-0.01
Other	1.55	1.10	0.45	1.47	1.10	0.37	0.79	1.10	-0.31	0.77	1.10	-0.33
Total	25.33	22.85	2.48	24.80	23.02	1.79	22.42	22.84	-0.42	22.75	23.30	-0.55
Developing												
Africa	0.40	0.84	-0.44	0.43	0.88	-0.45	0.27	0.90	-0.63	0.48	1.00	-0.52
Latin America	2.81	3.42	-0.61	2.96	3.82	-0.86	4.04	4.10	-0.06	4.15	4.30	-0.15
Near East	3.21	2.72	0.49	3.25	2.89	0.36	3.48	3.00	0.48	3.66	3.20	0.46
Far East	8.40	9.92	-1.52	9.83	11.06	-1.23	8.88	11.70	-2.82	9.71	12.30	-2.59
Total	14.82	16.90	-2.08	16.47	18.65	-2.18	16.67	19.70	-3.03	18.00	20.80	-2.80
Centrally Planned												
Asia	12.29	14.55	-2.26	13.04	15.05	-2.01	13.54	15.60	-2.06	13.96	16.10	-2.14
Eastern Europe and U.S.S.R.	20.83	15.54	5.29	21.86	16.02	5.84	23.24	16.40	6.84	23.43	16.90	6.53
Total	33.12	30.09	3.03	34.90	31.07	3.83	36.78	32.00	4.78	37.39	33.00	4.39
World Total	73.27	69.84	3.45	76.17	72.74	3.44	75.87	74.54	1.33	78.14	77.10	1.04

Region/Year	1990			1991			1992		
	Supply	Demand	Balance	Supply	Demand	Balance	Supply	Demand	Balance
	(million tonnes N)								
Developed									
North America	11.09	10.90	0.19	11.08	11.00	0.08	11.05	11.10	-0.05
Western Europe	10.62	11.20	-0.58	10.66	11.20	-0.54	10.67	11.30	-0.63
Oceania	0.39	0.40	-0.01	0.39	0.40	-0.01	0.51	0.50	0.01
Other	0.75	1.10	-0.35	0.73	1.10	-0.37	0.71	1.10	-0.39
Total	22.85	23.60	-0.75	22.86	23.70	-0.84	22.94	24.00	-1.06
Developing									
Africa	0.57	1.00	-0.43	0.58	1.10	-0.52	0.58	1.10	-0.52
Latin America	4.28	4.60	-0.32	4.53	5.00	-0.47	4.89	5.30	-0.41
Near East	3.82	3.30	0.52	4.00	3.40	0.60	4.14	3.60	0.54
Far East	10.24	12.90	-2.66	10.46	13.60	-3.14	10.88	14.30	-3.42
Total	18.91	21.80	-2.89	19.57	23.10	-3.53	20.49	24.30	-3.81
Centrally Planned									
Asia	14.08	16.50	-2.42	14.18	17.10	-2.92	14.20	17.60	-3.40
Eastern Europe & U.S.S.R.	23.48	17.30	6.18	23.58	17.80	5.78	23.70	18.30	5.40
Total	37.56	33.80	3.76	37.76	34.90	2.86	37.90	35.90	2.00
World Total	79.32	79.20	0.12	80.19	81.70	-1.51	81.33	84.20	-2.87

a. 1986 data are actual FAO statistics.

b. 1987 data are preliminary FAO statistics.

c. 1988-92 figures are IFDC estimates of demand, based upon forecasts by the FAO/UNIDO/World Bank Working Group on Fertilizers; supply estimates are from the Working Group.

whereas Centrally Planned Asia will see its nitrogen deficit grow from 2.0 million tonnes of N in 1987 to 3.4 million tonnes in 1992.

In the DgME, the regions of Latin America, the Near East, and the Far East are well into the growth stage of market development, whereas most of the countries in Africa are still in an early stage of fertilizer market development. Collectively, nitrogen use in the DgME is projected to increase at a compound growth rate of 5.4% per year through 1992. To satisfy this growing demand (some of the DgME will seek to maintain an export potential), the DgME will bring an additional 7 million tonnes of N capacity on stream during the next few years. Nonetheless, the region's nitrogen deficit will increase by over 75% to 3.8 million tonnes of N by 1992.

Nitrogen fertilizer use in the DME is expected to increase by an average of 0.85% per year or a total of 1.0 million tonnes of N during 1987-92. Because of the generally unfavorable competitive position of most of the DME in the international market, very little new capacity is planned. However, the DME's total potentially operational nitrogen capacity, including that which is currently idle and may resume operation given suitable market conditions, is expected to total 3.49 million tonnes of N in 1992 or 6% above the current level. A significant portion of the DME's nitrogen capacity is directed to producing ammonia for nonfertilizer purposes; therefore, even if the idle capacity is returned to operation, the DME will likely have a nitrogen fertilizer deficit beginning in 1988. By 1992 the annual deficit in the DME is expected to total 1.0 million tonnes of N.

Although the market outlook for nitrogen fertilizers is ominous from a buyer's viewpoint, the outlook for phosphate and potash supplies is more favorable. World phosphate fertilizer supplies should be adequate to meet demand through 1992. During the next few years, world phosphate fertilizer use is expected to increase at a compound growth rate of 3.04% per year, reaching a total of 38.85 million tonnes of P_2O_5 in 1992. Phosphoric acid capacity (including existing plants that are idle and may return to operation given the proper financial incentive) is estimated at 37.6 million tonnes of P_2O_5 or about 4 million tonnes of P_2O_5 more than the capacity in operation in 1987. Therefore, potential phosphate fertilizer supply will continue to exceed demand. The potential phosphate fertilizer surplus will peak in 1989 at 3.8 million tonnes of P_2O_5. By 1992 the potential supply surplus is expected to total 2.15 million tonnes of P_2O_5 (Table 7).

On a regional basis, by 1992 the DME will be the only economic region with a potential phosphate fertilizer surplus. During the next few years, phosphate demand in the DME is expected to increase at a compound growth rate of only 1.14%. Therefore, even in the absence of any significant investment in new facilities, plants that are currently in operation and those that may resume production, given improved market conditions, will allow the DME to maintain a sizable potential supply surplus. Largely because of the vast phosphate rock reserves and competitive downstream industry in the United States, the DME's potential supply surplus is expected to be about 7 million tonnes of P_2O_5 in 1992. North America will account for about 85% of this surplus.

Phosphate consumption in the DgME is expected to increase at a compound growth rate of 5.29% per annum with consumption totaling 11.35 million tonnes of P_2O_5 in 1992. Phosphoric acid capacity in the DgMEs will increase by 23% to 10.6 million tonnes of P_2O_5 in 1992. Despite this substantial investment in new capacity, the current deficit of about 1.4 million tonnes of P_2O_5 will increase to 1.7 million tonnes by the end of the forecast period.

Phosphate fertilizer use in the CPE is expected to increase at a compound growth rate of 3.05% per year during the next few years to a total of 15.57 million tonnes of P_2O_5 in 1992. Meanwhile, no significant change in capacity is expected, and phosphate fertilizer production potential is estimated at 12.5 million tonnes of P_2O_5. Therefore, the CPE's phosphate fertilizer deficit will reach 3 million tonnes of P_2O_5 in 1992.

Within the CPE classification, the phosphate markets in the two regions differ significantly. The phosphate markets in the U.S.S.R. and Eastern Europe are approaching a mature level, and as might be expected in the short term, phosphate use in the region is expected to increase at only 1.36% per annum; this is comparable to the expected growth in use in the DME. However, the absence of any significant levels of new phosphate capacity means that, collectively, the U.S.S.R. and Eastern Europe are expected to experience a growing phosphate fertilizer deficit that will reach 1.9 million tonnes of P_2O_5 in 1992.

The CPE markets of Asia are expected to place increased emphasis on more balanced fertilization programs. As a result, during the next few years, phosphate use is forecast to increase at an average compound growth rate of 8.25% per annum. By 1992 farmers in the CPE of Asia will use over 4.4 million tonnes of P_2O_5. Most of the growth in demand will be met through imports because phosphoric acid capacity in Centrally Planned Asia is due to increase by only 0.16 million tonnes of P_2O_5. The net result of these market developments in Centrally Planned Asia is that the current phosphate fertilizer deficit will nearly double to 1.21 million tonnes of P_2O_5 by 1992.

Table 7. Phosphate Fertilizer Supply-Demand Situation and Outlook: 1986-92

Region/Year	1986[a]			1987[b]			1988[c]			1989		
	Supply	Demand	Balance	Supply	Demand	Balance	Supply	Demand	Balance	Supply	Demand	Balance
	(million tonnes P_2O_5)											
Developed												
North America	8.41	4.49	3.92	8.61	4.28	4.33	9.15	4.34	4.81	10.59	4.40	6.19
Western Europe	4.76	5.14	-0.38	4.65	4.95	-0.30	5.32	4.96	0.36	5.33	4.97	0.36
Oceania	0.82	0.99	-0.17	0.79	0.94	-0.15	1.39	0.97	0.42	1.39	1.00	0.39
Other	1.16	1.12	0.04	1.05	1.10	-0.05	1.60	1.13	0.47	1.59	1.16	0.43
Total	15.15	11.74	3.41	15.10	11.27	3.83	17.46	11.40	6.06	18.90	11.53	7.37
Developing												
Africa	1.19	0.65	0.54	1.31	0.63	0.68	3.37	0.66	2.71	3.57	0.68	2.89
Latin America	1.61	2.24	-0.63	1.85	2.71	-0.86	1.82	2.82	-1.00	1.98	2.94	-0.96
Near East	1.29	1.47	-0.18	1.16	1.54	-0.38	1.31	1.64	-0.33	1.29	1.76	-0.47
Far East	2.64	3.55	-0.91	3.06	3.90	-0.84	1.74	4.11	-2.37	1.87	4.34	-2.47
Total	6.73	7.91	-1.18	7.38	8.78	-1.40	8.24	9.23	-0.99	8.71	9.72	-1.01
Centrally Planned												
Asia	2.02	2.96	-0.94	2.32	2.97	-0.65	2.63	3.22	-0.59	2.72	3.48	-0.76
Eastern Europe and U.S.S.R.	9.79	9.69	0.10	10.43	10.43	0.00	8.7	10.57	-1.87	8.89	10.72	-1.83
Total	11.81	12.65	-0.84	12.75	13.40	-0.65	11.33	13.79	-2.46	11.61	14.20	-2.59
World Total	33.69	32.30	1.39	35.23	33.44	1.78	37.03	34.42	2.61	39.22	35.45	3.77

Region/Year	1990			1991			1992		
	Supply	Demand	Balance	Supply	Demand	Balance	Supply	Demand	Balance
	(million tonnes P_2O_5)								
Developed									
North America	10.59	4.45	6.14	10.59	4.51	6.08	10.58	4.57	6.01
Western Europe	5.34	4.98	0.36	5.33	5.00	0.33	5.33	5.41	0.32
Oceania	1.39	1.03	0.36	1.39	1.06	0.33	1.39	1.10	0.29
Other	1.59	1.19	0.40	1.59	1.22	0.37	1.59	1.25	0.34
Total	18.91	11.65	7.26	18.90	11.79	7.11	18.89	12.33	6.96
Developing									
Africa	3.89	0.71	3.18	3.94	0.75	3.19	3.95	0.78	3.17
Latin America	2.01	3.07	-1.06	2.08	3.20	-1.12	2.16	3.34	-1.18
Near East	1.3	1.88	-0.58	1.50	2.00	-0.50	1.50	2.14	-0.64
Far East	1.96	4.57	-2.61	2.00	4.83	-2.83	2.02	5.09	-3.07
Total	9.16	10.23	-1.07	9.52	10.78	-1.26	9.63	11.35	-1.72
Centrally Planned									
Asia	2.83	3.77	-0.94	2.97	4.08	-1.11	3.20	4.41	-1.21
Eastern Europe & U.S.S.R.	9.16	10.86	-1.70	9.22	11.01	-1.79	9.28	11.16	-1.88
Total	11.99	14.63	-2.64	12.19	15.09	-2.90	12.48	15.57	-3.09
World Total	40.06	36.51	3.55	40.61	37.66	2.95	41.00	39.25	2.15

a. 1986 data are actual FAO statistics.

b. 1987 data are preliminary FAO statistics.

c. 1988-92 figures are IFDC estimates of demand, based upon forecasts by the FAO/UNIDO/World Bank Working Group on Fertilizers; supply estimates are from the Working Group and have been modified to deduct estimated production of ground rock used for direct application.

The outlook for the world potash market is similar to that for phosphate; existing plus firmly scheduled production capacity should be adequate to meet demand throughout the 1987-92 period.

World potash fertilizer consumption is expected to increase from 26.13 million tonnes of K_2O in 1987 to 29.27 million tonnes in 1992, an average compound growth rate of 2.28% per year. During this same period, world potash production capacity is expected to increase by almost 2.7 million tonnes of K_2O. Assuming market conditions encourage producers to maximize production, the potash fertilizer supply potential is expected to total 32.72 million tonnes of K_2O in 1992. Therefore, supply potential will exceed demand by almost 12% as compared with an actual supply surplus of 10% in both 1986 and 1987 (Table 8).

On a regional basis, it is expected that the use of potash fertilizers in the CPE will increase at a compound growth rate of 2.57% per annum through 1992. If this growth rate materializes, the CPE will likely be the largest consumer of potash; use will reach 12 million tonnes of K_2O or 41% of the world total in 1992. Within the CPE classification, the U.S.S.R. and Eastern Europe account for most (90%) of the potash used. However, the importance of potassium in crop production has been recognized by agriculturalists in Centrally Planned Asia and particularly China; in the future, development of these potash markets will likely receive increased attention.

Potash fertilizer production occurs in only three CPE countries. In 1987 the U.S.S.R., East Germany, and China produced 10.2 million, 3.5 million, and 0.025 million tonnes of K_2O, respectively, or a total of 13.7 million tonnes of K_2O. These three countries are expected to increase capacity by 1.67 million tonnes of K_2O by 1992. However, because relatively low operating rates are expected during the initial operation of the new facilities, the region's potash fertilizer supply potential is forecast to total only 13.36 million tonnes of K_2O in 1992. As a result, the potential potash supply surplus in the CPE is forecast to be 1.34 million tonnes of K_2O. Specifically, Eastern Europe and the U.S.S.R. are expected to have a surplus potential of 2.57 million tonnes of K_2O, whereas the Centrally Planned Asian countries should have a deficit of about 1.2 million tonnes of K_2O.

Potash fertilizer consumption in the DME is expected to increase from 11.23 million tonnes of K_2O in 1987 to 11.82 million tonnes of K_2O in 1992, thereby implying a compound growth rate of 1.3% per year. Western Europe and North America will each account for about 45% of the potash used in the DME in 1992.

Eight of the world's potash producers are classified as DME countries. Largely as a result of unfavorable market conditions, they produced only 14.42 million tonnes of K_2O in 1987; however, this still exceeded potash demand in the DME by 28%. Based upon existing capacity plus that which is scheduled to begin operation, potential potash supply in the DME will total 18.47 million tonnes of K_2O by 1992. Hence, the potential surplus is 6.65 million tonnes of K_2O or 56% of use in the DME.

Farmers in the DgME used 4.31 million tonnes of K_2O as potash fertilizers in 1987 or 15% of the world total. Despite this relatively low base, use is expected to grow at a compound rate of only 4.73% per annum during the next few years and to reach 5.43 million tonnes of K_2O in 1992. Latin America and the Far East region each account for about 45% of the potash used in the DgME.

Jordan and Brazil are the only two DgME countries that produce potash. In 1987 their combined production totaled 0.67 million tonnes of K_2O. An additional production facility with a capacity of 0.12 million tonnes of K_2O is currently under construction in Jordan and should begin operation in 1992. As a result of this additional capacity and the improved operating efficiency that is likely to occur in the recently commissioned Brazilian facility, potash supply potential will increase to 0.89 million tonnes of K_2O. Therefore, the current potash deficit will increase to about 4.5 million tonnes of K_2O by 1992.[2]

On the basis of the most current information available, the fertilizer market outlook through 1992 ranges from what appears to be a comfortable supply-demand relationship for phosphate and potash to a sizable deficit for nitrogen. However, as we have seen in the past, the demand for fertilizer is largely influenced by the expected economic gain from fertilizer use and by government policy. A poor cropping season will likely lead to the expectation of higher crop prices and thus more intensive use of fertilizer during the subsequent year. Conversely, we saw in 1975 that a significant upturn in fertilizer prices will be met with reduced demand. Government policy has been and will continue to be one of the most significant influences on the farmers' cropping patterns and their use of fertilizers; this is true of CPE, DgME, and DME countries. Therefore, rather than overreact to this analysis, we should realize that any one of a number of factors may alter either side of the supply-demand equation. As analysts, we can only provide our best estimate of the future and hope that industry responds in a rational manner.

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[2] IFDC has received an unconfirmed report that the potash mine in Brazil has been closed due to flooding. If this report is accurate, Brazil would continue to rely on imports to meet domestic demand. The estimate of world potash production in 1992 would decline by less than 1%, thus having little impact on the world supply-demand situation.

Table 8. Potash Fertilizer Supply-Demand Situation and Outlook: 1986-92

Region/Year	1986[a]			1987[b]			1988[c]			1989		
	Supply	Demand	Balance	Supply	Demand	Balance	Supply	Demand	Balance	Supply	Demand	Balance
	(million tonnes K_2O)											
Developed												
North America	7.48	4.98	2.50	8.26	4.79	3.47	10.71	4.87	5.84	10.91	4.95	5.96
Western Europe	5.27	5.38	-0.11	4.90	5.50	-0.60	5.16	5.52	-0.36	5.16	5.54	-0.38
Oceania	0.00	0.23	-0.23	0.00	0.21	-0.21	0.00	0.22	-0.22	0.00	0.22	-0.22
Other	1.14	0.77	0.37	1.26	0.73	0.53	1.20	0.74	0.46	1.20	0.75	0.45
Total	13.89	11.36	2.53	14.42	11.23	3.19	17.07	11.35	5.72	17.27	11.46	5.81
Developing												
Africa	0.00	0.32	-0.32	0.00	0.29	-0.29	0.00	0.31	-0.31	0.00	0.32	-0.32
Latin America	0.00	1.68	-1.68	0.01	2.02	-2.01	0.04	2.13	-2.09	0.06	2.22	-2.16
Near East	0.54	0.13	0.41	0.66	0.15	0.51	0.73	0.16	0.58	0.80	0.17	0.63
Far East	0.00	1.73	-1.73	0.00	1.85	-1.85	0.00	1.94	-1.94	0.00	2.03	-2.03
Total	0.54	3.86	-3.32	0.67	4.31	-3.64	0.77	4.54	-3.76	0.86	4.74	-3.88
Centrally Planned												
Asia	0.02	0.55	-0.53	0.03	0.83	-0.80	0.03	0.91	-0.88	0.05	0.99	-0.94
Eastern Europe and U.S.S.R.	13.83	9.84	3.99	13.69	9.76	3.93	12.04	9.94	2.10	12.34	10.13	2.21
Total	13.85	10.39	3.46	13.72	10.59	3.13	12.07	10.85	1.22	12.39	11.12	1.27
World Total	28.28	25.61	2.67	28.81	26.13	2.68	29.91	26.74	3.18	30.52	27.32	3.20

Region/Year	1990			1991			1992		
	Supply	Demand	Balance	Supply	Demand	Balance	Supply	Demand	Balance
	(million tonnes K_2O)								
Developed									
North America	11.53	5.03	6.50	11.56	5.11	6.45	11.56	5.20	6.36
Western Europe	5.18	5.56	-0.38	5.20	5.58	-0.38	5.20	5.59	-0.39
Oceania	0.00	0.23	-0.23	0.00	0.24	-0.24	0.00	0.25	-0.25
Other	1.20	0.76	0.44	1.45	0.77	0.68	1.71	0.78	0.93
Total	17.91	11.58	6.33	18.21	11.70	6.51	18.47	11.82	6.65
Developing									
Africa	0.00	0.34	-0.34	0.00	0.36	-0.36	0.00	0.38	-0.38
Latin America	0.07	2.31	-2.24	0.08	2.41	-2.33	0.09	2.51	-2.42
Near East	0.80	0.17	0.63	0.80	0.18	0.62	0.80	0.19	0.61
Far East	0.00	2.13	-2.13	0.00	2.24	-2.24	0.00	2.35	-2.35
Total	0.87	4.95	-4.08	0.88	5.19	-4.31	0.89	5.43	-4.54
Centrally Planned									
Asia	0.07	1.09	-1.02	0.07	1.19	-1.12	0.07	1.30	-1.23
Eastern Europe & U.S.S.R.	12.96	10.32	2.64	13.29	10.52	2.77	13.29	10.72	2.57
Total	13.03	11.41	1.62	13.36	11.71	1.65	13.36	12.02	1.34
World Total	31.81	27.94	3.87	32.45	28.60	3.85	32.72	29.27	3.45

a. 1986 data are actual FAO statistics.

b. 1987 data are preliminary FAO statistics.

c. 1988-92 figures are IFDC estimates of demand, based upon forecasts by the FAO/UNIDO/World Bank Working Group on Fertilizers; supply estimates are from the Working Group.

Fertilizer Production and Consumption Trends – India

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Abstract

The fertilizer production and consumption trends in India are discussed with special emphasis on the semiarid tropics (SAT). India produces a wide range of fertilizers, and with the exception of K (which must all be imported) domestic production provides 90% of the finished fertilizer nutrients consumed in India. Most of the phosphoric acid used in phosphate fertilizer production is also imported. With the introduction of high-yielding varieties (HYV) in the late 1960s, the demand for fertilizer rose rapidly and resulted in the establishment of a number of new production facilities in the 1960s and 1970s. Urea is the most commonly produced N source, and diammonium phosphate (DAP) dominates the P market. The emphasis on balanced nutrition has stimulated the production of a variety of NP and NPK complex fertilizers. Capacity utilization is high, and India is now the fourth and fifth largest producer of N and P, respectively, in the world. Fertilizer consumption has risen rapidly since the introduction of HYVs; the major fraction of nutrients (80%), however, is applied to irrigated crops despite the fact that rainfed agriculture occupies a much larger percentage of total land area. If moisture conservation is practiced, fertilizer use can play a key role in improving food production in the SAT.

Introduction

In India, the fertilizer industry is as old as agricultural research. The fertilizer industry started in 1906 in Ranipet in Tamil Nadu with the establishment of a single superphosphate (SSP) unit by E.I.D.-Parry, and agricultural research started in 1905 in old Pusa (Bihar) with the establishment of the Imperial Agriculture Research Institute (IARI). Fertilizer use probably started at the close of the last century on tea and coffee plantations. Presently, about 9.0 million tonnes of fertilizer (NPK) is used against the total production of 7.0 million tonnes (N + P_2O_5). Per hectare consumption is only 51.3 kg. About 80% of the fertilizer is used in irrigated areas and only 20% in the rainfed areas, which represent 70% of the cropped area. Fertilizer use in rainfed areas, particularly in the region of the SAT, has to be increased. Production technology is available, but proper adoption of technology at the farmer level is lacking.

India produces a large number of fertilizers. Ammonium sulfate and SSP were the main sources of N and P initially; now urea accounts for 80% of the N, and 84% of the P_2O_5 is found in NP/NPK complexes. Muriate of potash (MOP) makes up 99% of the potash used by farmers. Fertilizer diammonium phosphate (DAP) is the single largest source of P for the Indian farms, supplying 52% of the P_2O_5. Direct use of ground rock P is becoming popular in southern and eastern India in plantation and acid soil conditions.

Fertilizer Production

A whole range of N, P, and NPK fertilizers is produced in India. The chronology of fertilizer production provides an idea of the developments that have taken place (Table 1). Nitrophosphates that are highly water soluble have significantly added to the range of fertilizers produced since 1968. In the absence of any commercial source of potash, the entire requirement of potassic fertilizer is imported.

Nitrogen

Production of small quantities of nitrogenous fertilizer in the form of ammonium sulfate as a byproduct from coke oven gas in steel plants of Bengal and Bihar started in 1931. But the first synthetic N factory was set up at Belagula in Karnataka by Mysore Chemicals and Fertilizers Ltd. (MCF) in 1941. It was followed by the establishment of a large-scale production unit of ammonium sulfate by the erstwhile State Government of Travancore-The Fertilizers and Chemicals, Travancore Ltd. (FACT) plant-at Udyogamandal near Cochin in 1947. The first large-size fertilizer plant (ammonium sulfate) went into production in 1951 at Sindri (Bihar).

Table 1. Chronology of the Production of Fertilizer Materials in India

Year When First Produced	Material	Units Manufacturing as of April 1, 1988
1906	Single superphosphate	80
1906	Fertilizer mixtures	577
1933	Ammonium sulfate	11
1933	Byproduct of steel industry	6
1941	Using sulfuric acid	2
1947	Using gypsum	4
1959	Ammonium sulfate nitrate	0
1959	Urea	29
1959	Ammonium chloride	5
1960	Ammonium phosphate	2
1961	Calcium ammonium nitrate	2
1965	Nitrophosphate (30 WS)[a]	1
1967	Diammonium phosphate	10
1968	Urea ammonium phosphate	4
1968	NPK complex fertilizers	4
1973	Pelophos	0
1979	Urea supergranules	[b]
1980	Urea ammonium nitrate solution	[b]
1986	Polyphosphate	[b]
1988	Partially acidulated phosphate rock	[b]
1989	Nitrophosphate (80%-85% WS)	-

a. One of the two grades (20-20-0) later upgraded to 50%-60% water-soluble (WS) P_2O_5.

b. Trial pilot-scale production for experimental purposes.

Source: FAI Fertiliser Statistics for 1986/87.

In the beginning, it was thought that one large-capacity plant at Sindri would be sufficient to meet the requirement of the country. It was soon realized, however, that many more such units would be needed to cope with the growing fertilizer requirements of Indian agriculture, and six additional fertilizer plants were constructed (Nangal, Trombay, Namrup, Rourkela, Gorakhpur, and Neyveli).

The impetus given to the use of fertilizer by the introduction of high-yielding variety (HYV) seed necessitated a suitable backup from indigenous sources to ensure stability and continuity in the supply of fertilizer. To encourage setting up new capacity, the Government of India liberalized policies with regard to fertilizer production and marketing on the basis of a recommendation by the Sivaraman Committee (1965). The 1960s, therefore, saw a rapid growth in the fertilizer industry for the manufacturing of N and NP/NPK complex fertilizers (Table 1).

A number of plants were also established in the private sector during this period, including E.I.D.-Parry in Madras (1963), Gujarat State Fertilizers Company Ltd. (GSFC) in Baroda (1967), Coromandal Fertilisers Ltd. (CFL) in Vizag (1967), Indian Explosive Ltd. (IEL) in Kanpur, and Shriram Fertilisers and Chemicals (SFC) in Kota (1969).

The oil crisis in the early 1970s and consequent problems of procuring the required amount of fertilizers from the international market, related to both limited availability and high prices, provided greater impetus for the process of building up indigenous production capabilities. During the 1970s, a number of plants – Madras Fertilizers Ltd. (MFL); Zuari Agro Chemicals Ltd. (ZACL); The Fertilizer Corporation of India Ltd. (FCI), Barauni, Durgapur; Indian Farmers Fertiliser Cooperative Ltd. (IFFCO), Kandla and Kalol; Southern Petrochemical Industries Corporation Ltd. (SPIC), Tuticorin; Mangalore Chemicals and Fertilizers, Ltd. (MCFL), Mangalore; Sindri Modernisation, Nangal expansion, Bhatinda, Panipat, Ramagundam, Talcher, etc. – were set up; production was based on a wide array of feedstocks, including coal and fuel oil. Significantly, with IFFCO the cooperative sector made an entry into the production of fertilizers.

Feedstock Policy

A brief reference to the feedstock policy of the Government may not be out of place. In the 1960s, most of the capacity was based on naphtha from local refineries supplemented by imports. But towards the latter part of the 1960s, there was a worldwide concern about the long-term availability of petroleum feedstock. It was therefore decided to look at an alternative, such as coal. Two coal-based units (Talcher and Ramagundam) were commissioned.

In the early 1970s, the likelihood of a shortage of naphtha both worldwide and in India, accompanied by relatively easy availability of fuel oil, resulted in a steep rise in the price of naphtha and a lower price for fuel oil in the international market. The Government decided to base some new plants on fuel oil. In the latter half of the 1970s, large quantities of natural and associated gas were discovered offshore in various parts of the country.

Consequently, the feedstock policy was again changed, and capacity during the 1980s has been mainly based on gas.

Phosphatic Fertilizers

Superphosphate (SSP) was the first chemical fertilizer produced in India by E.I.D.-Parry at Ranipet in 1906. The raw material used then was bone meal. Over the years, many new plants were added, and until 1960 the entire production of P fertilizers in the country consisted of SSP only. Presently, 80 SSP units with an installed capacity of 2.13 million tonnes of material exist in the country. SSP is a very good fertilizer, and it can play an important role in also supplying sulfur, calcium, and some micronutrients, particularly where soils and crops demand more of these materials (Biswas et al., 1987). Some units of triple superphosphate (TSP) were established, e.g., Dharamsi Morarji Chemicals Company Ltd. (DMCC)-Ambernath, 1968; Hindustan Copper Ltd. (HCL), Khetri; and FCI, Sindri; at present, however, all the units are closed because of acute marketing problems for this product.

Complex Fertilizers

In the 1960s, it was realized that balanced nutrient dosages were necessary to sustain yields on a long-term basis, particularly when the uptake of all essential plant nutrients increased with intensive agriculture. Consequently, production of NP and NPK complex fertilizers in various standard ratios was encouraged.

Indigenous production of complex fertilizers started in 1963 with FACT and E.I.D.-Parry manufacturing ammonium phosphate sulfate. This was followed by production of various grades, including nitrophosphates at FCI (Trombay-1967), DAP at GSFC (1967), urea ammonium phosphate at CFL (1968), and various NPK complexes at MFL (1971), ZACL (Goa-1973), IFFCO (Kandla-1974), SPIC (Tuticorin-1976), FACT (Cochin-II-1977), and Trombay IV (1978/79). The production of complex fertilizers is largely based upon imported phosphoric acid.

Capacity Utilization

The impetus for indigenous production has resulted in significant improvement in the utilization of plant capacity. In the N sector, the national average increased from 53% in 1980/81 to 79% in 1986/87 while the average in phosphates went up from 65% to 80% during the same period. With a total installed capacity of 7.5 million tonnes N and 2.6 million tonnes P_2O_5 and with capacity utilization rates that are quite commendable by international standards, India has the distinction of ranking fourth and fifth in the production of N and P_2O_5, respectively, in the world (Narayan, 1988).

Narrowing the Gap

The development of an indigenous fertilizer industry has enabled the country to meet an increasingly large percentage of its fertilizer needs from domestic production. Consumption has increased from 0.3 million tonnes (NPK) in 1960/61 to 5.5 million tonnes in 1980/81 and about 9 million tonnes in 1987/88. The interesting fact is that between 1980/81 and 1987/88, the production of NP fertilizer as percentage of consumption has increased from 61% to 90% (Narayan, 1988). No economically viable sources of K are known, and K requirements, therefore, are met entirely from imports.

Future Trends

To meet the increasing need for fertilizers in the years to come, additional capacity is being created, and the capacity utilization of existing plants is being improved by various means such as modernization and providing captive power units. Two gas-based plants at Thal and Hazira (1.5 million tonnes urea capacity each) were commissioned during 1985/86. Three more projects (one each in the public, cooperative, and private sectors), based on gas available from the HBJ pipeline, have already been commissioned. Three more projects based on this gas, apart from the one based on naphtha in the south at Kakinada, Andhra Pradesh, are being developed and are expected to be completed in the next 3 years (Narayan, 1988).

In phosphates, the addition to capacity has been brought about through an ambitious program involving three coastal plants and four expansion projects based on imported ammonia and phosphoric acid. Of the new DAP plants, the GSFC, Sikka; Hindustan Lever, Haldia; and Godavari Fertilizers, Kakinada, have already been commissioned. Besides the completed expansions of MCFL and SPIC, two other expansions, both nitrophosphates, are presently under implementation by Gujarat Narmada Valley Fertilisers Co. Ltd. (GNFC) and Deepak Fertilisers and are expected to be commissioned within 2 years. In addition, a project using available resources of pyrites with a total capacity of 33,000 tonnes of P_2O_5 per annum is coming up at Amjhore (Bihar). The proposed addition in both the sectors will lead to a total installed capacity of 11.5 million tonnes by 1989/90, consisting of 8.4 million tonnes N and 3.1 million tonnes of P_2O_5 (Narayan, 1988).

In addition to the fertilizer materials already discussed, a number of new materials or modified forms of known fertilizers are under development (Table 2). Such developmental work is largely undertaken by the research and development departments of different fertilizer

Table 2. Some Fertilizer Materials Under Development in India and Associated Organizations

Urea supergranules	Indian Farmers Fertiliser Cooperative Ltd.
Neem-treated urea	IEL, Rashtriya Chemicals & Fertilizers Ltd., Maharashtra Agro Industries Corporation, Godrej Soaps
Ureaform	The Fertilizers and Chemicals, Travancore Ltd.
Urea-AN solution	National Fertilizers Ltd.
Urea-gypsum	Madras Fertilizers Ltd.; Projects & Development (I) Ltd.
Rock-P coated urea	Madras Fertilizers Ltd.
Coal-derived N fertilizers	Central Fuel Research Institute
Lac-coated urea	Indian Lac Research Institute
Partially acidulated phosphate rock	Pyrites, Phosphates & Chemicals Ltd.
Polyphosphates	Rashtriya Chemicals & Fertilizers Ltd., Indian Farmers Fertiliser Cooperative Ltd.
Zincated-SSP	Shriram Foods & Fertiliser Industries[a]
Boronated-SSP	Dharamsi Morarji Chemicals Co. Ltd.
Zincated-urea	Gujarat Narmada Valley Fertilisers Co. Ltd.

a. Activity probably now stopped.

Source: Tandon and Biswas (1988).

companies and research institutes. Production of such new fertilizer aims at (1) the development of products that can improve nutrient use efficiency and (2) finding economic avenues for the use of locally available materials (Tandon and Biswas, 1988).

Fertilizer Consumption

Use of fertilizer began in India at the close of the last century on tea and coffee plantations. The use of fertilizer for food crops expanded in the 1940s with free distribution of ammonium sulfate to farmers under the "Grow More Food Campaign."

Although fertilizer consumption increased gradually over the next quarter of the century, the growth rate was not particularly spectacular. For example, consumption went up from 66,000 tonnes in 1951/52 to 785,000 tonnes in 1965/66. The consumption per hectare of cropped area increased from 0.55 kg to 5.05 kg, a ninefold increase during the same period, but still very low in absolute terms.

The introduction of fertilizer-responsive HYV seeds in the mid-1960s, coupled with the Government's favorable policy for fertilizer marketing, resulted in a rise in fertilizer consumption to 1.1 million tonnes in 1966/67, an increase of about 40% over the previous year.

In the 1970s, the growth in consumption lost some of its momentum. To start with, availability was a constraint for about a year. Soon thereafter came the oil crisis, and the price of fertilizer consequently increased by 100%-150%. Farmers just would not accept the use of fertilizer at the price, and in 1974/75, fertilizer consumption went down 9.3% compared with the previous year, the first such decline in many years. The position was alarming. Various corrective measures, such as reduction of fertilizer prices, introduction of price subsidies, and intensification of fertilizer promotion activities revived the upsurge in consumption. Consumption went up by 12.4% and 17.9% in 1975/76 and 1976/77, respectively.

The years 1977/78 and 1978/79 were favorable for fertilizer consumption; growth rates of 25.7% and 19.4% were registered, and total consumption reached 5 million tonnes. The factors conducive to a favorable growth rate in consumption included better and more timely availability of fertilizer, higher benefit/cost ratio for the farmer because of the drop in fertilizer prices and increase in crop procurement price, increased area under irrigation and HYV of crops, better planning and monitoring of input availability and use, and the sustained promotional work by the industry with necessary support provided by the Government.

Consumption Targets

The planning with regard to consumption has, to a certain extent, been vitiated by the experience in the recent past (Narayan, 1988). For almost seven seasons in succession, starting from Rabi 1984/85, the weather conditions have been unfavorable and have resulted in a lower level of consumption in relation to the targets. It can thus be seen that since 1983/84, when India achieved a record consumption of 7.7 million tonnes (NPK), there has not been any appreciable increase in fertilizer use (Table 3). Recognizing the dominating role of weather and the fact that 70% of the cultivated area is under rainfed conditions, the Planning Commission in its mid-term appraisal revised the target of consumption from about 14 million tonnes envisaged earlier to 12 million tonnes for the terminal year of the 7th Plan (1989/90). Although fertilizer consumption is likely to increase this year because of good weather, it may be a difficult task to achieve the target

Table 3. **Fertilizer Production and Consumption and Food-Grain Production 1962/63 to 1987/88**

Year	Fertilizer Production ($N + P_2O_5$)	Fertilizer Consumption (All Nutrients)	Gross Cropped Area	Gross Under HYV Crops	Gross Irrigated Area	Weather (for Purposes of Agriculture Production)	Food-Grain Production
	('000 tonnes)		(million ha)				(million tonnes)
1962/63	283	452	156.8	-	29.8	Average	80.1
1963/64	327	544	157.0	-	29.7	Average	80.6
1964/65	374	773	159.2	-	30.7	Very good	89.4
1965/66	357	785	155.3	-	30.9	Very poor	72.4
1966/67	455	1,101	157.4	1.9	32.7	Very poor	74.2
1967/68	610	1,539	163.7	6.0	33.2	Good	95.1
1968/69	776	1,761	159.5	9.3	35.5	Average	94.0
1969/70	954	1,982	162.3	11.4	36.9	Good	99.5
1970/71	1,061	2,256	165.8	15.4	38.0	Very good	108.4
1971/72	1,240	2,656	155.2	18.2	38.4	Average	105.2
1972/73	1,385	2,768	162.1	22.3	39.1	Very poor	97.0
1973/74	1,374	2,839	169.9	86.0	40.3	Poor	104.7
1974/75	1,517	2,573	164.2	26.3	41.7	Very poor	99.8
1975/76	1,828	2,894	170.9	31.9	45.3	Good	121.2
1976/77	2,341	3,411	167.2	33.6	43.2	Poor	111.2
1977/78	2,669	4,286	172.3	38.9	45.9	Good	126.4
1978/79	2,951	5,117	175.2	40.1	50.6	Good	137.9
1979/80	2,987	6,255	167.2	38.4	52.6	Very poor	109.7
1980/81	3,005	5,516	173.3	43.1	54.1	Poor	129.6
1981/82	4,093	6,067	177.0	46.5	56.0	Poor	133.3
1982/83	4,413	6,387	173.4	47.5	58.1	Poor	129.5
1983/84	4,556	7,710	180.2[a]	53.7	58.6	Good	152.4
1984/85	5,235	8,211	176.0[a]	54.1	60.5	Average	145.5
1985/86	5,753	8,474	-	55.4	62.2	Poor	150.4
1986/87	7,079	8,738	-	56.1	-	Poor	144.1
1987/88	7,131	9,008[a]		51.2[b]	-	Very poor	138.0[a]

a. Provisional.
b. Anticipated achievement.

Source: "Annual Review of Fertiliser Production and Consumption," *Fert. News*, 33(8):71-104.

of 12 million tonnes in 1989/90 and about 20 million tonnes by 2000 A.D. (Table 4), unless we are able to increase fertilizer consumption in the SAT region, particularly in areas where rainfall and irrigation facilities are extremely low.

Fertilizer Use in SAT Region

In India, about 80% of the fertilizer is consumed in irrigated areas; the remaining 20% is consumed in the rainfed areas, which constitute 70% of the cropped area (Venkateswarlu, 1986). Fertilizer use in the SAT region is still lower. The strategy for increasing production of cereals, pulses, oilseeds, and other important crops of the region under rainfed conditions should be based on the use of improved technology, of which the key component is use of N and P. The deficiency of P is limiting crop production more seriously than is generally realized. Deficiency of zinc and sulfur is also being reported in these areas (Kanwar, 1986).

Fertilizer consumption data from a few selected SAT districts (Jodhpur, Bellary, Anantapur, Aurangabad, Banaskantha, and Mehindergarh) in states that have research institutes to provide necessary farm technology to

Table 4. Some Projections of Production and Consumption of Fertilizers in India

Item	1987/88	1989/90	1999/2000
	(million tonnes)		
Nitrogen (N)			
Capacity	7.0	9.2	
Production	5.5	6.5	11.4
Demand	7.8	9.1-9.3	
Gap	2.3	2.5-2.7	
Phosphate (P_2O_5)			
Capacity	2.3	2.9	
Production	1.9	2.2	4.2
Demand	2.7	3.0-3.2	
Gap	0.8	0.8-1.0	
Potash (K_2O)			
Demand	1.2	1.4-1.5	
Gap	1.2	1.4-1.5	
Total ($N+P_2O_5+K_2O$)			
Capacity	9.3	12.1	
Production	7.4	8.7	15.6
Demand	11.8	13.5-14.0	20.0
Gap	4.4	4.8-5.3	4.4

Source: FAI Fertiliser Statistics for 1985/86.

the farmers indicate that fertilizer consumption has increased over the years (Table 5), but the yields have not been affected uniformly (Table 6). Productivity of different crops decreased in 1985/86 compared with 1980/81 except for groundnut and sorghum in Anantapur, wheat in Jodhpur, and chick-pea in Mohindergarh. Rainfall was low and uneven in 1985/86 except in Anantapur, where well-distributed rainfall resulted in higher productivity. The increase in wheat (Jodhpur) and gram (Mohindergarh) yield might be due to the supply of life-saving irrigation.

Table 5. Fertilizer Consumption in Some Selected Districts Receiving Low Rainfall (<750 mm) and Having Low Irrigated Area (<20%)

District	Fertilizer Consumption 1970/71	1975/76	1980/81	1985/86
	(tonnes)			
Jodhpur	937	997	1,396	3,911
Bellary	10,399	22,001	35,133	64,232
Aurangabad	8,598	9,770	22,400	23,329
Anantapur	4,188	6,261	10,161	10,351
Banaskantha	2,881	3,937	9,944	18,311
Mohindergarh	1,111	4,182	4,744	10,495

Source: FAI Fertiliser Statistics for different years.

Table 6. Productivity of Some Selected Districts Receiving Low Rainfall (<750 mm) and Having Low Irrigated Areas (<20%)

District	Crop[a]	Productivity[b] 1980/81		1985/86	
		(kg ha^{-1})			
Jodhpur	Pearl millet	68	Normal	23	Low
	Wheat	969		1,427	
Bellary	K. sorghum	1,430	(477)	1,073	(434)
	R. sorghum	822		627	
Aurangabad	Pearl millet	472	(802)	335	(579)
	R. sorghum	446		183	
Anantapur	Groundnut	369	(429)	647	(387)
	R. sorghum	681		1,556	
Banaskantha	Cotton	220	(512)	124	(322)
	Wheat	2,186		1,916	
Mohindergarh	Pearl millet	320	Normal	28	Low
	Chick-pea	568		696	

a. K = Kharif and R = Rabi.

b. Figures in parentheses indicate annual rainfall in millimeters.

Source: FAI Regional Statistics for 1980/81 and 1985/86.

These data imply that well-distributed rainfall is the most important factor in enhancing the crop productivity of the SAT region. Therefore, moisture conservation and its efficient use are the most important factors in crop management. Use of fertilizer can also play a key role in enhancing the productivity of the SAT region under the condition of required moisture availability (Table 7).

The nutrient requirement to produce a tonne of grain is quite high; crops grown in the SAT region are also removing a huge amount of nutrients, and they are expected to remove much more nutrient (Table 8) by 2000 A.D. to achieve the food production target. Therefore, these areas must also be properly fertilized to obtain the desired results. Fertilizer is a valuable input. Therefore, its use efficiency needs to be increased. Balanced use of plant nutrients increases the fertilizer use efficiency. Use of fertilizer-efficient crops and cropping systems, application of fertilizer through proper methods, and the

Table 7. The Average Yields of Some Important Crops in the SAT and Potential Yield Obtainable Under Rainfed Conditions With Improved Technology and Fertilizer Input

Crop	Average Yield in SAT (30-Year Average)	Yield Obtained at ICRISAT Center Under Rainfed Conditions Low Fertility and Average Management[a]	 High Fertility and Average Management[b]
	(kg ha^{-1})	(kg ha^{-1})	
Sorghum	842	2,627	4,900
Pearl millet	509	1,636	3,482
Chick-pea	745	1,400	3,000
Pigeon pea	600	1,000	2,000
Groundnut	794	1,712	2,572

a. Nutrients added for sorghum and pearl millet, 43 kg N ha^{-1} and 20 kg P_2O_5 ha^{-1}; for pigeon pea and groundnut, 20 kg N ha^{-1} and 20 kg P_2O_5 ha^{-1}.

b. Nutrients added for sorghum and pearl millet, 86 kg N ha^{-1} and 40 kg P_2O_5 ha^{-1}; for chick-pea and pigeon pea 18 kg N ha^{-1} and 46 kg P_2O_5 ha^{-1}; and for groundnut 60 kg P_2O_5 ha^{-1}.

Source: Kanwar (1986).

Table 8. Production and Nutrient Removal (NPK) Estimates of Some Rainfed Crops (by 2000 A.D.)

Crop	Production 1986/87	 2000	Nutrient Removal 1986/87	 2000
	(million tonnes)		(million tonnes)	
Sorghum	8.87	20.40	0.44	1.00
Pearl millet	4.49	15.00	0.13	0.44
Chick-pea	4.46	12.75	0.33	0.94
Pigeon pea	2.32	4.50	0.30	0.44
Groundnut	5.42	13.50	0.95	2.36

Sources: Agriculture Situation in India, June, 1988 and National Commission on Agriculture, 1976.

Table 9. Contribution of Fertilizers and Other Components of Improved Technology to Increase in Yield Over Traditional Systems in Dryland Agriculture

Practice	Increase in Yield Over Traditional System
	(%)
Management	14
Seed	40
Fertilizer	50
Seed + fertilizer	95
Seed + fertilizer + management	130

Source: Singh and Venkateswarlu (1985).

integrated use of all sources of plant nutrients are all factors that increase fertilizer use efficiency by increasing crop productivity.

Crop responses to fertilizer in the SAT region are quite high and also economical. Adoption of a full package of practices gives the best result (Table 9) and therefore needs to be encouraged.

Conclusions

The fertilizer industry in India has registered a rapid all-round growth during the last 35 years; however, we have a long way to go to meet the challenges of increasing fertilizer production and consumption to achieve the food production target of about 235 million tonnes by the year 2000.

In the future, we will have to increase fertilizer consumption in the SAT region, and for that, weather-based agrotechniques need to be developed and adopted at the farm level. This will require adoption of the systems approach, as well as cooperation and coordination at all levels.

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Soil Fertility and Fertilizer Management in Semiarid Tropical India – A Historical Perspective

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Abstract

The development of agricultural research in India is discussed from the period before British rule to the present. Early research focused on the use of manures and other organic amendments, and though yields were moderate, sustainable production was achieved. In the post-independence era, fertilizer use increased greatly as new fertilizer-responsive varieties were introduced. Yield improvements due to fertilizer application resulted in a neglect of manure use for fertility maintenance. Fertilizer use tended to be concentrated in irrigated agriculture to the exclusion of rainfed crops. In the 1970s, high fertilizer prices caused research efforts to focus on defining and refining nutrient recommendations, including consideration of the direct and residual effects of the fertilizers. In addition, research programs have addressed the need for sulfur and micronutrient fertilizers for the major crops. Future research must follow an integrated approach involving scientists of diverse disciplines and must address the problems of the soil-plant-animal system.

Soil is a critical natural resource for supporting the life systems. Agricultural production and productivity have a direct link with the maintenance of soil productivity. Management of nutrients is an important aspect of maintaining soil productivity. This presentation attempts to give a historical perspective of research efforts towards maintaining the fertility of soils of semiarid tropical India.

Although significant advances in the scientific management of soil fertility have been made only in the past few decades, extensive references to maintenance of soil fertility were made and detailed accounts presented in ancient Indian scriptures. Reference to the manuring of soils for the enrichment of plants can be found as early as 1500-500 B.C. in a verse in *Artharva Veda*. The ancient Indian cultivator possessed a fair knowledge of soils, rotation and production of crops, different types of manures, etc. Indeed, one is filled with astonishment and admiration if he looks into the elaborate injunctions that are found in *Arthashastra, Brhat-Samhita (500 A.D.),* and *Agnipurana (500-700 A.D.)* regarding the selection and treatment of seeds and use of animal excreta, fish and bones, beef and fishwashings, minute fishes, and various kinds of mixtures and decoctions as fertilizers. An excellent account of knowledge gained in ancient India on enrichment of crops through manuring has been presented by Raychaudhury (1964). However, the ancient wisdom in the management of soil fertility was gradually forgotten with the lapse of time. This was largely due to the exploitive agriculture followed by successive rulers. Thus, the Turkish ruler Allaudin Khilji was strongly of the view "If an Empire has to stay, farmers should be exploited."

The British Period

Organized research on soil fertility had its beginning following the realization in England and other parts of Europe of the significance of crushed bones as plant nutrients. Von Liebig, a German chemist, was reportedly provoked to accuse the British for extracting, from the battlefields and ancient burial grounds, bones of three and a half million men for production of manure. In India, organized research in the area of soil fertility can be traced to early years of the present century. Following recommendations of the Famine Commission in 1880, Imperial and provincial agricultural departments were formed, which stimulated agricultural research. Dr. J. A. Voelckar, Consulting Chemist, Royal Agricultural Society, London, joined the Imperial Department in 1889 and stayed till 1891. On his advice, the post of Agricultural Chemist was created; Dr. J. W. Leather was the first to assume this position in 1892. Dr. Leather made in-depth studies on the soils of the country and was responsible for establishing permanent manurial experiments at Pusa in Bihar, Kanpur in Uttar Pradesh, and Coimbatore in Tamil Nadu based on the Rothamsted model.

The first serious effort to examine the question of maintenance of soil fertility was that of the Royal Commission on Agriculture (RCA), which submitted its report in 1928. The Commission made several important observations. With regard to the nutrient status of different soils, it observed that red soils, as a rule, are deficient in nitrogen, phosphorus, and humus, but potassium and lime are generally sufficient. Similar observations were recorded for black cotton soils. For alluvial soils, however, the report mentions that the amount of organic matter and nitrogen in these soils varies but is usually low, that potassium is adequate, and that phosphorus, though not plentiful, is generally less deficient than in the other Indian states.

The report also examined in detail the possibility that, on long-cultivated agricultural lands in India, the capacity to yield crops diminished continually because more nutrients in the form of produce were removed than were replaced by nature and the practice of cultivation. Relying on historical information, the report concluded, "while the paucity of records of crop production throughout India over any long period of time make the matter impossible of exact proof, we are of the opinion . . . that an overwhelming portion of the agricultural lands of India long ago reached the condition to which experimental data point. A balance has been established and *no further deterioration is likely to take place under existing conditions of cultivation*."

Between the years 1913/14 and 1925/26, the average yield of rice ranged between 700 and 1,000 kg ha^{-1} and that of wheat from 600 to 780 kg ha^{-1}. A comparison with yields of a few crops currently grown in rainfed conditions is made in Tables 1 and 2 and brings out the contention that sustained yields at low levels can be achieved because of the natural recuperative processes prevailing in the tropical soils.

Table 1. Yield of Rice (1984/85)

State	Percentage of India's Total Land Area	Irrigated Area	Yield
	-------- (%)	-------	(kg ha^{-1})
Orissa	10.7	28.4	969
Madhya Pradesh	12.1	17.7	759
Bihar	13.2	32.7	1039
All India		42.1	1417

Source: Ministry of Agriculture (1986).

Table 2. Yield of Wheat (1984/85)

State	Percentage of India's Total Land Area	Irrigated Area	Yield
	-------- (%)	-------	(kg ha^{-1})
Maharashtra	3.8	48.7	866
Madhya Pradesh	15.6	33.7	1,094
All India		72.4	1,870

Source: Ministry of Agriculture (1986).

The Royal Commission on Agriculture made several other significant recommendations. Those relevant to this presentation include the following:

- The agricultural departments in India are not, at present, in a position to give the farmers definite advice in regard to the economic use of fertilizers.
- The evidence has not suggested any alternative to the use of farmyard manure as fuel where coal and wood are expensive.
- Steps should be taken to promote better preservation of farmyard manure.
- The Indian cultivator has much to learn from the Chinese and the Japanese in regard to the use of compost.
- Greater research is needed on the role of legumes (including those for green manuring) in increasing soil fertility.
- No further investigation under Government auspices of the possibilities of manufacturing synthetic nitrogen in India is at present required.

In the early decades of the 1900s, the British exported large quantities of bones and oilseeds from India to England (Tables 3 and 4). Some people advocated before the Royal Commission that this involved a heavy drain of phosphate and combined nitrogen and left the Indian soils impoverished. They, therefore, pleaded that the large export of these items from the country should be ended by total prohibition of exports or imposition of an export tax.

Table 3. Export of Bones to England from India

Period	Annual Export (tonnes)	Value (million Rs)
1910/11-1914/15	90,452	6.42
1920/21-1924/25	87,297	8.91

Source: Royal Commission (1928).

Table 4. Export of Oilseeds to England from India

Period	Total Yield	Export
	(tonnes)	
1910/11-1924/25	72,518	13,053

Source: Royal Commission (1928).

These suggestions were, however, not agreed to because, according to the Commission, they would deprive one of the poorest sections of society of a source of income and use of bonemeal in general had not shown any increase over the years in India.

The history of fertilizer use in the country is short. Fertilizers were introduced in the early part of this century. During 1906 single superphosphate was produced in Ranipet and was followed by production of ammonium sulfate by Tata Iron and Steel Co. in 1919. Only about 10% of the total production of 4,436 tonnes of ammonium sulfate was used in India, and the rest was exported. The proportion rose to 40% in 1925. Subsequently, with rising demand, ammonium sulfate had to be imported.

Efforts in the Thirties and Forties

Realizing that greater attention must be given to the problems of cultivation of crops that are entirely dependent upon rainfall, the Imperial Council of Agricultural Research financed a scheme launched at five centers in the country. The centers were located at Sholapur, Bijapur, Hagari, Raichur, and Rohtak. The project continued for 10 years and made recommendations for improving agriculture in these areas. Among other recommendations, application of farmyard manure at the rate of five cartloads every alternate year or once in 3 years was recommended. Smaller doses were not effective, and higher doses became relatively uneconomical. The role of legumes in crop rotation for maintaining soil fertility was also emphasized in these investigations.

The Post Independence Era

In the fifties, though the consumption of nutrients increased from about 65,000 tonnes in 1951/52 to about 300,000 tonnes in 1961/62, the overall consumption remained very low, and the increased food-grain production was largely due to an increase in cultivated areas. This was the period when the area covered under irrigation remained nearly constant.

The introduction of an intensive agriculture district program in 12 districts in 1960/61 was the first serious attempt for intensive cultivation based on fertilizers. In the mid-sixties, the availability of dwarf varieties of wheat and rice as well as hybrids of maize, sorghum (jowar), and millet (bajra), all of which were fertilizer responsive, caused a spurt in the demand for fertilizers. Thus, between 1960/61 and 1970/71, nutrient consumption increased nearly sevenfold (Table 5). The increase continued into the next decade when the consumption increased another threefold by 1982/83. The Government responded with various measures including establishment of a high-level team to promote both the production and consumption of fertilizers. Since then, there has been a steady increase in consumption, which rose to 9 million tonnes of nutrients in 1986/87.

Table 5. Growth of Nutrient Consumption Through Fertilizers

Year	Nutrient Consumption (million tonnes)
1955/56	0.131
1960/61	0.292
1965/66	0.785
1970/71	2.177
1975/76	2.894
1980/81	5.515
1985/86	8.737

Source: Ministry of Agriculture (1986).

The early sixties was also the period of rapid expansion of research infrastructure through the setting up of state agricultural universities. The research programs provided full support to the development programs by making recommendations for fertilizer needs of different crops and newly emerging cropping systems. Research efforts were largely confined to defining the optimum dose of nutrients for individual crops, particularly for rice and wheat and their newly released varieties. Scientists and farmers achieving maximum yields were credited. Spectacular yield increases due to application of fertilizers resulted in farmers ignoring the use of small quantities of manure which they were earlier applying for maintenance of soil fertility. The research efforts in the sixties laid little emphasis on the organics and ignored the long-term aspects in arriving at recommendations for new crops. Further, these efforts were largely concentrated in areas with assured supply of irrigation water. Rainfed agriculture, including problems of managing soil fertility, remained largely unattended. In the early years, major emphasis, as would be expected, was directed towards use of nitrogenous fertilizer. However, it was soon realized that for sustained high yields, balanced fertilization was essential. It was further recognized that, in making recommendations, the cropping systems as a whole must be considered and that there was need to carry out fertility experiments over a long period of time to be able to generate results that should be meaningful for maintaining long-term fertility of soils. As a result, the Indian Council of Agricultural Research (ICAR) initiated several coordinated research projects (Table 6). In recognition of the importance of increasing productivity of rainfed areas, an All India Coordinated Research Project on Dryland Agriculture was started in 1970.

Table 6. All India Coordinated Research Projects

All India Coordinated Research Project Areas	Year of Start
Microbiological decomposition and recycling of organics	1967
Soil-test-crop response correlation	1969
Micronutrients in soils and plants	1969
Long-term fertilizer experiments	1970
Dryland agriculture	1970

The Seventies

During the seventies, the net sown area remained almost constant at 140 million ha, but because of improved irrigation facilities, the area sown more than once per year increased from 23.5 million ha in 1969/70 to 32.8 million ha in 1980/81 and 37.6 million ha in 1983/84. Increased cropping intensity resulted in a heavier demand for nutrients, which was reflected in more pronounced nutrient deficiencies. Research efforts were therefore directed to defining and refining nutrient recommendations considering the direct and residual effects (Table 7). Defining management practices including time and method of application for improving efficiency of applied nutrients received more attention. Studies under the All India Coordinated Research Project on micronutrients made significant contributions in bringing out the limiting role of emerging micronutrient deficiencies and in standardizing practices for overcoming these. The interaction effects amongst the nutrients and of nutrients with such factors as water supply were increasingly appreciated and efforts made to quantify these. These efforts were reflected in more balanced use of nutrients, as is reflected in the increased use of P and K fertilizer (Table 8).

Table 7. P Effects in Cropping Sequence

	Grain Yield			
	Average 3 Years		Average 10 Years	
Treatment	Rice	Wheat	Maize	Wheat
	($t\ ha^{-1}$)			
P applied to rice/maize and wheat	6.6	4.2	3.0	4.7
P applied to wheat only	6.6	4.1	3.0	4.5
P applied to rice/maize only	6.5	2.4	3.1	3.8

Source: Gill and Meelu (1983).

Table 8. Relative Consumption of N and P Fertilizers

Year	N/P_2O_5	N/K_2O
1951/52	8.5	-
1961/62	4.1	8.9
1971/72	3.2	6.0
1981/82	3.0	6.0
1985/86	2.8	6.8

Source: Ministry of Agriculture (1986).

A sudden rise in prices of fertilizers in 1974/75 following a rise in oil prices was a reminder of the need for intensifying research to improve fertilizer efficiency and to develop systems of integrated nutrient management involving the use of organics, particularly crop residues and farm wastes. Researchers also looked for plant materials/cultivars that could withstand nutrient deficiencies and toxicities of specific soil disorders. Under the All India Coordinated Research Project on Soil Test Plant Correlations, the concept of achieving targeted yields based on soil test data was evolved. Towards this, quantitative relationships were developed to relate soil test values for important nutrients to the fertilizer requirements for predefined yield targets of important crops. Although the results of these studies have been verified on a large number of farmers' fields, the use of soil tests as a basis for fertilizer recommendations in our country has largely remained a neglected technology.

In the area of rainfed agriculture, increasing efforts were made to define the nutrient requirements of crops, and response functions were worked out for different agroclimatic conditions (Table 9). These studies provided convincing evidence for the need to increase fertilizer use under rainfed conditions.

Table 9. Crop Response to N and P Fertilizer Under Rainfed Conditions

	Fertilizer Dose (kg ha^{-1})	Average Response (kg grain kg^{-1} nutrient)
Nitrogen Response		
Pearl millet	(40)	19.2
Sorghum	(40)	26.7
Maize	(40)	15.5
Mustard	(20)	13.6
Phosphorus Response		
Sorghum	(30-50)	9.0
Pearl millet	(30-50)	7.2
Mustard	(30-50)	5.7
Chick-pea	(30-50)	10.9
Safflower	(30-50)	3.2

Source: Singh and Venkateswarlu (1985).

Recent Efforts

Efforts in recent years have continued to refine nutrient management recommendations based on increasing research information from short- and long-term fertility experiments. The nutrient management needs of oilseeds and pulses and of cropping systems that include these crops became increasingly more important. Sulfur has been reported to be deficient in over 90 districts of the country, particularly where sulfur-free fertilizers have been used over the years (Tandon, 1986). For overcoming the deficiencies, several studies were directed toward defining the sulfur relations of soils and crops for optimum management of nutrients. There has been a renewed interest in economizing fertilizer nutrients through the use of nitrogen-fixing organisms including blue green algae and *Azolla* and through improved *Rhizobial* strains for inoculation of important legumes. Similarly, research efforts have been directed toward maximizing the use of dinitrogen fixed through green manure crops.

In the area of rainfed farming, nutrient management recommendations for promising intercropping systems were worked out. Field studies aiming to integrate nutrient management in agroforestry-based systems were initiated. The role of organics and balanced nutrient application and the need for long-term fertility studies as a basis for recommendations were increasingly realized (Tables 10-12).

Future Needs

India's population continues to grow and is expected to touch the 1 billion mark towards the end of the present century and to stabilize only at 1.6 billion sometime in the next century. The per capita availability of land for cultivation has been continuously decreasing, and in the future there is no likelihood whatsoever of expanding the cultivated area. In fact, all-out efforts are needed to divert some of the marginal soils to alternative uses to check their degradation and to achieve ecological harmony. These projections would emphasize the need for highly

Table 10. Effect of Maize Residue Incorporation on Grain Yield

Treatment	Average Grain Yield (1975-79) (t ha^{-1})
No residue incorporated	1.88
Residue incorporated at 4 t ha^{-1} yr^{-1}	2.35

Source: Hadimani et al. (1982).

Table 11. Crop Responses to Applied Nutrients

Treatment	Pearl Millet		Finger Millet
	Agra	Hissar	Bhubaneshwar
	(t ha^{-1})		
1. Control	0.97	1.34	0.53
2. Recommended fertilizers	1.71	2.01	1.33
3. 1/2 recommended fertilizers	1.35	1.78	1.06
4. Farmyard manure (to compensate N in Treatment 3)	1.30	1.94	0.87
5. Treatment 3 plus Treatment 4	1.62	1.90	1.26
Number of years	4	4	3

Table 12. Long-Term Effect of Selected Treatments on the Yield of Maize Grown in Maize-Wheat Rotation in an Alfisol

	Average Yield			
Treatment	Years 1-12	Years 13-18	Years 19-24	Years 25-28
	- - - - - - - - - - - (kg ha^{-1}) - - - - - - - - - -			
NoPoKo	0.83	0.83	0.55	0.53
N	1.70	1.15	0.04	0.00
NP	2.40	2.85	0.48	0.00
NPK	3.17	3.23	0.82	0.12
FYM (=N)*	2.27	2.59	2.75	2.59
NPK+lime	3.37	3.97	3.79	3.67

Notes: Following year 12, the variety was changed and the N-P_2O_5-K_2O dose increased from 40-40-40 to 100-80-60.

Following year 18, the N-P_2O_5-K_2O dose was increased to 110-90-70.

*Farmyard manure – applied at a level such that the N rate was equivalent to that of the fertilizer treatments.

Source: Lal and Mathur (1988).

intensive agriculture and the need for improving and maintaining high productivity of our resources.

Problems of maintaining and improving soil fertility will get increasingly complex; a high degree of expertise will be required to foresee the problems and to plan and conduct experiments carefully monitoring all relevant environmental changes. Various interactions will need to be quantified so that best use can be made of the favorable ones. Sustainability aspects will need high priority. To achieve these objectives, soil fertility specialists will need to increasingly interact with specialists in other branches, including soil physicists, the microbiologists, the pedologists, and particularly the economists. Long-term field studies will need to be carried out on representative benchmark soils so as to form a sound basis for the transfer of technologies. The problems of whole farming systems will need to be appreciated in planning long-term fertility studies. Thus, soil fertility studies will need to increasingly address the soil-plant-animal system. Rhizosphere biology improvement is another promising area that needs urgent attention from the scientific community. The problems of evolving more profitable nutrient management systems will continue to be the aim of our future research.

I am conscious that, in this presentation, I have touched only the points which I thought were most important. I should like to quote what Hans Jenny wrote in 1961 when reviewing half a century of research in soil acidity. Comparing this to a merry-go-round, Dr. Jenny commented, "When a turn is completed the sight, though familiar, is vastly different from the starting point." We are, more or less, in a similar situation. Although we have made significant advances in understanding and developing solutions to the problems of managing the fertility of our soils, we have, yet, a long way to go.

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Soil Fertility Problems in the Semiarid Tropics of Africa

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Abstract

The region of the African semiarid tropics (SAT) covers an area of approximately 485 million ha and is characterized by a monomodal rainfall distribution as well as a rainy season of 3-4.5 months. Millet and sorghum are the principal crops. Crop yields are very low, due in part to minimal successes in work on varietal improvement and to soil fertility limitations, low organic matter content, and low available N, S, and P-all of which pose serious constraints to sustained crop production. Research undertaken by IFDC, ICRISAT, and their national collaborators suggests that use of fertilizers in combination with organic residues can promote increased crop yields. However, the use of purchased inputs, including chemical fertilizers, in an ecologically fragile environment such as is characteristic of the SAT is highly risk prone. Data are needed to define the right types and amounts of fertilizers for each soil/crop/cropping system combination. Such studies must also define the management practices, including soil conservation measures, needed to maximize nutrient use efficiency and promote sustainable crop production while protecting the environment.

Introduction

The definition of the semiarid tropics (SAT) varies with the classification system of climates. Broadly defined, SAT refers to the region with 2 to 7 wet months (precipitation exceeding potential evapotranspiration) a year. However, for the purpose of this paper we will restrict ourselves to the dry semiarid tropics as defined by Troll (1966) and essentially characterized by a monomodal rainfall distribution with a rainy season of 3-4.5 months. Total rainfall may range from 250 mm to 900 mm, but amounts vary greatly from year to year (Figure 1). Although a broader rainfall range is sometimes used to define the SAT (Kumar, 1977), by our definition the semiarid tropical regions of Africa cover an area of about 485 million ha (Sanchez, 1976). This agroclimatic zone includes the Sahelian belt stretching from Senegal to Sudan, extending into Ethiopia and Somalia and southward into Kenya and Tanzania, and encompassing a region bordering north of the Kalahari Desert (Figure 2). However, this area is reported to be changing rapidly as a result of desertification, which in some areas is progressing at a rate of 5 km/year. In Africa, an estimated 65 million ha of productive land has been lost to desert in the past 50 years. According to the United Nations Environment Program, the livelihood of as many as 50 million people in sub-Saharan Africa has been affected.

The combination of rainfall reliability and total rainfall dictates the predominant crops and cropping systems employed in the region. The principal food crops are millet, sorghum, cowpea, groundnut, and cotton, frequently intercropped with the leguminous crops. The millet and sorghum production areas have remained essentially constant for the past 5 years and in 1981 were approximately as follows: in West Africa, 15.2 million ha for millet and 13.2 million ha for sorghum, along with 5.5 million ha for groundnut; in East and Southern Africa, 2.7 million ha for sorghum and 1.4 million ha for millet, along with 0.9 million ha for groundnut (FAO, 1984).

Millet is grown in the zone with less than 650 mm of rainfall, and sorghum is grown in a zone with 650-900 mm of rainfall. Yields of these crops in Africa averaged 700 and 650 kg ha^{-1} for sorghum and millet, respectively. The low yields are a reflection of a host of biotic and socioecological factors. Varietal improvements have been negligible for the SAT crops. Soil fertility limitations are increasingly recognized as a major constraint to increased productivity of the SAT. It is widely speculated that the severity of this soil fertility constraint is increasing because fallow periods are being decreased as a result of population pressure. However, such a contention is difficult to substantiate. Current millet and sorghum yields as reported by FAO (1987) are equal to or better than those of 10 years back and are substantially better than those

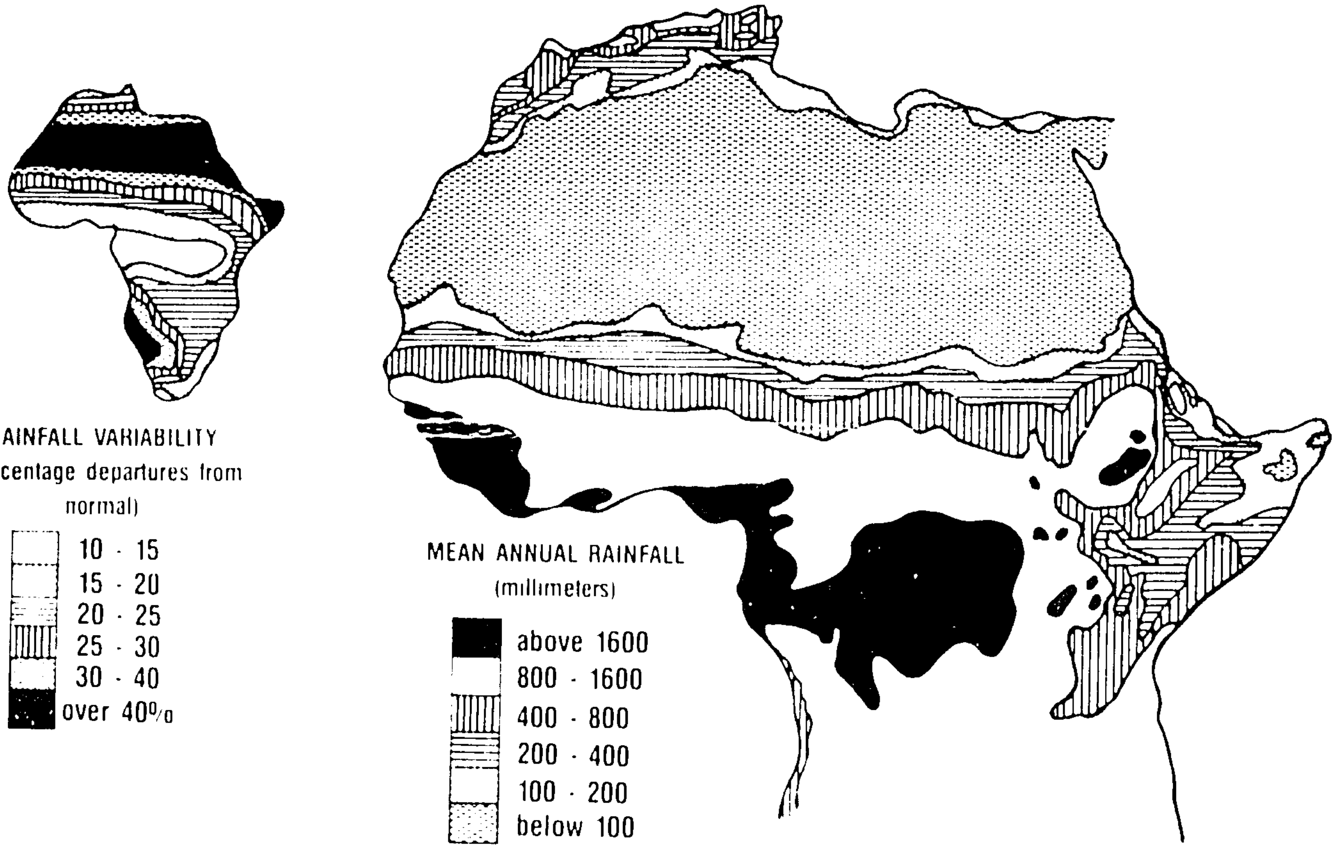


Figure 1. Mean Annual Rainfall and Rainfall Variability of Tropical Africa.

reported for the drought years 1982-84. Most of the yield variation appears related to weather conditions, and long-term soil fertility trends are difficult to discern. The best evidence of the importance of improving soil fertility in the SAT is gleaned from research information accumulated over the years. This paper reviews the soil fertility research for N, P, S, and micronutrients in the SAT, particularly for the Sahelian zone where IFDC and ICRISAT have conducted joint research since 1982. Potassium has been omitted because it has rarely been found to be limiting in these regions, even though it is recognized that K fertilization will be required if intensive agriculture is practiced in the SAT (Iwuafor et al., 1980); Ogunlela and Yusuf, 1988).

Soil Fertility of the SAT

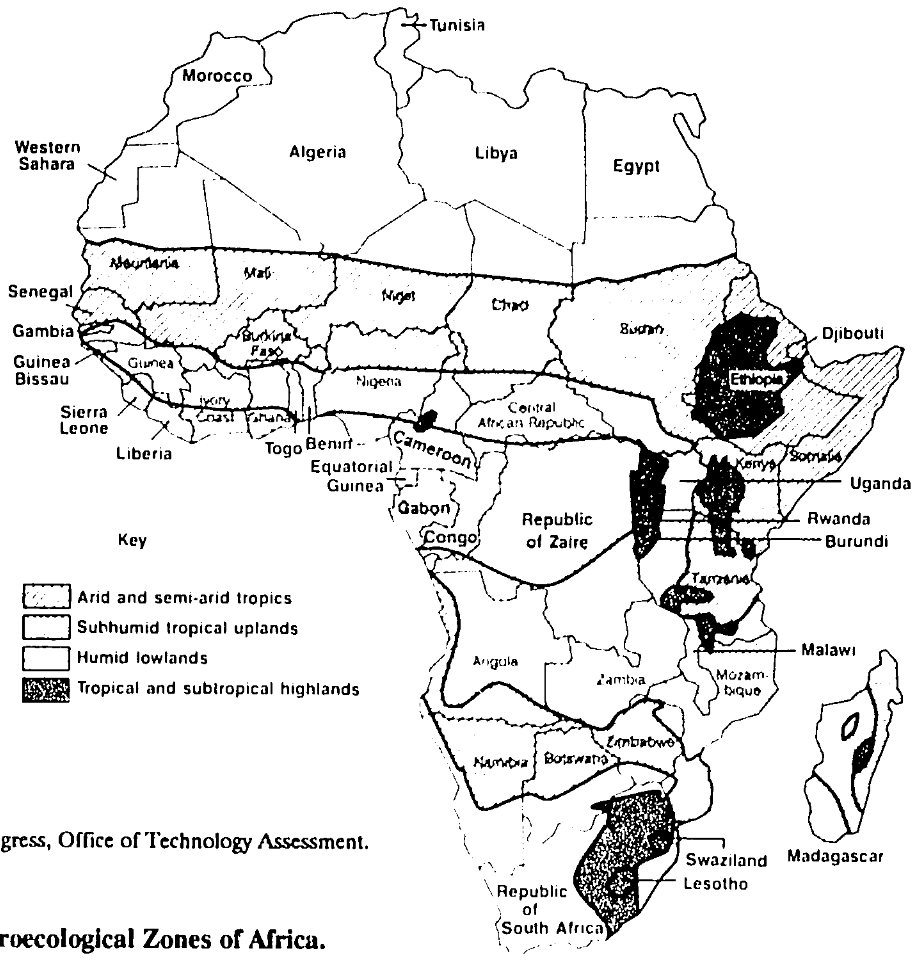
The principal soil types of the West African SAT are the Camborthids of the dryer zones and the Ustalfs of the more humid regions in the south (Charreau, 1977). Similar soils as well as less differentiated Entisols are representative of the SAT fringing the Kalahari Desert. Ustalfs and Ustults are common in the SAT of Eastern Africa. Vertisols are found in the Chad basin, Sudan (20% of the country), and Kenya (5%). The distribution of the principal soil types for Tropical Africa is presented in Figure 3. As a general rule, the soils of the African SAT are not excessively acid. However, most are derived from acidic parent materials and are low in clay and organic matter content, leading to poor buffering capacities and fragile ecosystems (Pichot et al., 1981). In a sampling of 30 soils from West Africa, most of which are from the millet and sorghum growing areas, the organic matter (OM) content was related to rainfall as follows:

$$OM = 0.15 + 0.00085 \text{ rainfall} \qquad (S.E. = 0.20; R^2 = 0.48)$$

with OM contents rarely exceeding 1%. The effective cation exchange capacity (ECEC) is strongly affected by the OM content as shown by the following equation:

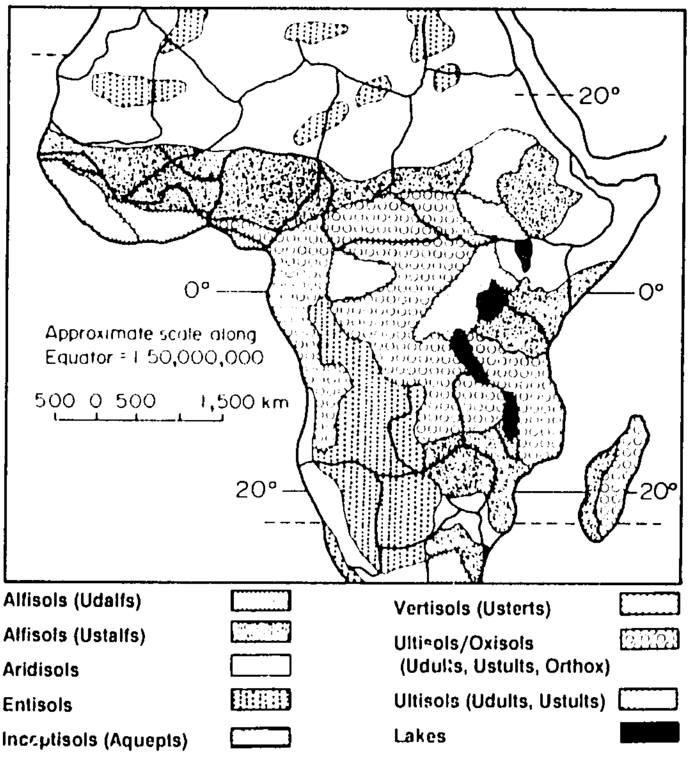
$$ECEC = 0.14 + 3.52\,OM \qquad (S.E. = 1.21; R^2 = 0.75)$$

Continuous cropping can rapidly degrade the soils of the SAT through nutrient depletion and acidification if no measures are taken to counter these processes. Charreau (1972) noted that it took 7 years of fallow to restore a soil in Senegal that was exhausted as a result of continuous cultivation in a millet/groundnut rotation. Soil fertility



Source: U.S. Congress, Office of Technology Assessment.

Figure 2. The Agroecological Zones of Africa.



Source: After Aubert and Tavernier (1972).

Figure 3. Principal Soil Types of Africa.

maintenance measures might consist of intercropping practices, residue conservation, soil amendments, or manuring.

Maintenance of soil fertility as a means to achieve sustained land productivity has become an important issue in the tropics, particularly for the fragile soils of the SAT. Research at the ICRISAT Sahelian Center in Niger has shown that millet yields drastically declined (from about 300 kg ha^{-1} to 100 kg ha^{-1}) as a result of continuous cropping. However, when crop residues were consistently returned, the yields improved gradually to reach 800 kg ha^{-1} by the third and fourth years (1985 and 1986). High yields (around 1,000 kg ha^{-1}) were obtained from the first year with the use of mineral fertilizer. The most promising results were reached with a combination of fertilizer use and residue conservation (Figure 4). Similar results were summarized by Pieri (1985) for various sorghum- and millet-based cropping systems. Because of the value of crop residues for fuel and feed purposes, the restitution of part of the crop residue to the soil combined with the use of moderate amounts of mineral fertilizer may be the best strategy for sustained production.

In addition, the inclusion of legumes in the cropping system may help maintain soil fertility. Pichot et al. (1981) studied the effect of sorghum/peanut rotation on sorghum

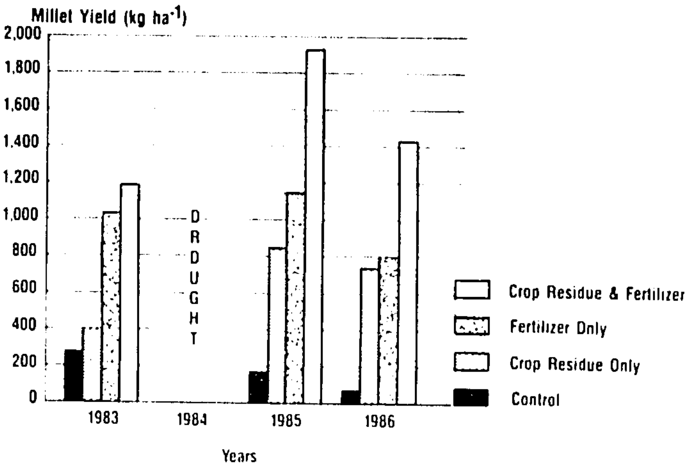
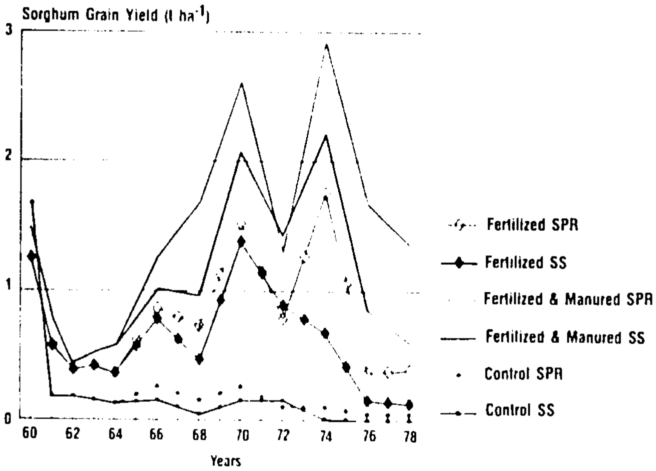


Figure 4. Effect of Combined Fertilizer and Residue Management on Yield (Niger).

yields in Burkina Faso (Figure 5). The effect of the peanut crop on the subsequent sorghum crop was negligible in the case of the control treatment that received neither fertilizer nor organic amendments. With moderate fertilization, some benefits of the legume crop accrued after five rotational cycles. With the annual or biannual addition of moderate amounts (5 t ha^{-1}) of manure in addition to the mineral fertilizer, beneficial effects of the peanut crop were evident from the second cycle onwards.

Various long-term experiments have been conducted to determine the principal reason for the decline in soil productivity. Increasing soil acidity was one suspected problem. The effects of various soil fertility management systems on the acidity of the soil, which were reported by Gigou (1982) for the long-term sorghum experiment referred to in Figure 5, are summarized in Table 1.



Source: Pichot et al. (1981).

Figure 5. The Effect of Rotation and Fertilization and Manuring on Sorghum Yields in Burkina Faso (SPR = sorghum/peanut rotation; SS = sole sorghum).

Table 1. Effect of Fertilizer, Crop Residue, and Manure on Soil pH in Long-Term Sorghum Production

Treatment	pH (KCl) of Topsoil After 6 Years	 18 Years
1. Control	4.2	4.3
2. Light doses of P and N	4.0	3.8
3. Heavy doses of P and N	3.8	3.7
4. As 2 + residues	4.0	3.9
5. As 4 + manure (5 t ha^{-1})	4.4	4.4

Unfortunately, pH values at the onset of the experiment were not recorded. But by 1966, the control yields had dropped from 1,600 kg ha^{-1} to less than 100 kg ha^{-1} (Figure 5), even though there was no indication of a drop in pH. Similarly, results of the first 4 years of the millet experiment at Sadore (Niger) indicate no change in pH (KCl) in the control treatment, which held stable at 4.1, whereas yields steadily declined (Figure 4). In the same experiment, the effect of mineral fertilizer on soil pH was negligible, whereas the return of crop residues tended to increase pH to around 4.4.

Because soil acidity was of limited importance, attention was turned to the problem of soil fertility depletion. Siband (1972) demonstrated that both the organic matter content and sum of exchangeable bases diminished continuously over a 90-year period of cultivation of a soil in southern Senegal. The effect of continuous cropping on available P, one of the most limiting elements in the African SAT, has been documented (Traore, 1972). Data from Sadore demonstrate the critical role of P in the millet growing areas of Niger. After four cropping cycles, the Bray P1 level slightly changed from its initial (low) value of 3.2 ppm to 2.6 ppm in the control treatment. With the practice of returning crop residue, the Bray P1 remained at about 3.0 ppm. Only with fertilization or a combination of fertilization and returning of crop residue did the P status of the soil improve to 7.1 and 8.1 ppm, respectively (Bationo, unpublished). Clearly, continuous cropping tends to deplete the phosphorus reserves of the soil and may be the principal cause for the rapid decline in soil productivity.

One of the first things to be done in a new environment is to use available soil and fertilizer information to assess the principal nutrients limiting crop growth in that environment. The results of one such trial in its second year at Sadore are presented in Table 2. It is obvious that phosphorus is the most limiting nutrient. The rate of phosphorus used was 30 kg P_2O_5 ha^{-1}. One notes, however, that in spite of the importance of phosphorus, there is something to be said for the practice of balanced fertilization, including the use of manures and soil amendments.

Various long-term experiments were conducted in the West African SAT to study the effect of organic matter and fertilizer management on nutrient balances in the soil. Gigou (1982) reports a serious reduction in exchangeable K, Ca, and Mg after 4 years in fertilized cotton/sorghum rotation when straw was not returned. Returning the straw substantially improved the nutrient balances (Table 3).

Estimates by Poulain (1980) of the amount of nutrients returned to the soil under various management systems showed that straw from 1 tonne of a millet crop may add 20 kg N, 10 kg P_2O_5, 5 kg S, 10 kg K_2O, 22 kg CaO, and 30 kg MgO if incorporated without burning. These numbers for sorghum are 60, 20, 7.5, 70, 10, and 7.5 kg, respectively.

Thus, in contrast to soil moisture limitations, which affect yields in the SAT in a stochastic fashion, soil fertility

Table 2. Effect of Various Soil Fertility Management Practices on Grain Yield in Long-Term Trial at Sadore, Niger

	Treatments	Grain Yield ($kg\ ha^{-1}$)
1.	Control	355
2.	P only (SSP)	855
3.	P only (TSP)	838
4.	SSP + N + K	1,071
5.	SSP + N + K + lime every 3 years	1,130
6.	SSP + N + K + Mg + Zn	1,077
7.	SSP + N + Mg + Zn	1,097
8.	Crop residue (2 tonnes ha^{-1}) each year	778
9.	Crop residue (2 tonnes ha^{-1}) each year + ½ SSP + ½ N	1,134
10.	Manure (10 tonnes ha^{-1}) every 3 years	1,035
11.	SSP + N + K + Mg + Zn + lime every 3 years	974
12.	SSP + N + K + Mg + Zn + crop residue each year	1,199
13.	SSP + N + K + Mg + Zn + crop residue each year + manure every 3 years + lime every 3 years	1,283
	SE ± 109	

Table 3. Gains and Losses of Nutrients During 4 Years of Cotton/Sorghum Rotation in Northern Cameroon on Alluvial Soil (0.7% C, 10% Clay)

	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
	(kg of nutrient ha^{-1}														
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^{-1}; F_3 = 100 kg urea ha^{-1}; F_5 = 50 kg urea ha^{-1} + 10 tonnes sorghum straw every 2 years.

All treatments for cotton received 45 kg TSP and 60 kg KCl ha^{-1}; those for sorghum received 90 kg TSP and 90 kg KCl ha^{-1}.

F_3 gave best yields each year followed by F_5.

Source: Gigou (1982).

constraints are a major impediment to sustained crop production. The fragility of the environment necessitates the use of soil and crop management practices that conserve the native soil fertility, supplemented by measures that will enhance the nutritional status of the soils where nutrient supplies are inadequate. The role of fertilizers in this regard is discussed below.

Nitrogen

Response of millet and sorghum in the SAT to nitrogen varies with the weather conditions during the growing season. In 1985, a favorable year in Niger, response to applied urea-N (U) in Sadore was represented by the following regression equation:

$$\text{Grain yield} = 940 + 23\,U - 0.37\,U^2$$
$$R^2 = 0.27 \qquad S.E. = 101$$

whereas for sorghum in Gaya the following equation applied:

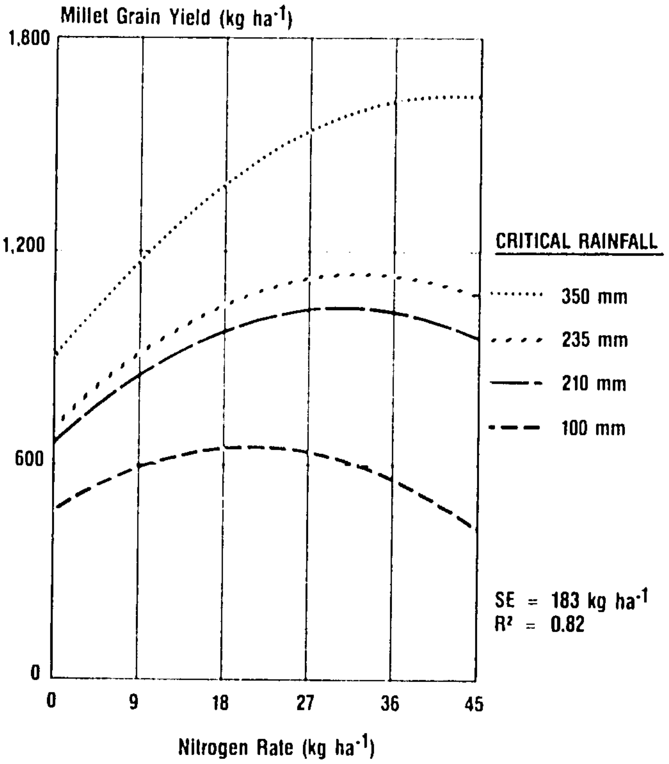
$$\text{Grain yield} = 2{,}000 + 40\,U - 0.28\,U^2$$
$$R^2 = 0.39 \qquad S.E. = 340$$

Sorghum, grown in the higher rainfall zones, has a higher yield capacity than millet, as reflected by the higher grain yield of the control plots. Moreover, in the linear portion of the response curve, grain yield response was 24 kg kg^{-1} N for sorghum and only 14 kg kg^{-1} N for millet. Finally, because of greater year-to-year variability in rainfall, the response to N for millet is less assured.

Analysis of millet yield versus rainfall distribution over the period 1982-85 showed that grain and stover yield were most significantly affected by "critical rainfall"-the total rainfall over a 7-week period in mid-season, starting the second week of July (Rp). A model was developed by Christianson et al. (1990) of the following form:

$$Y_i = \gamma_0 + \gamma_1 Rp + \gamma_2 Ni + \gamma_3 Ni^2 + \gamma_4 Ni\, Rp + \epsilon_i$$

where Y_i is yield of millet grain, γ_0 is control yield, γ_1 is the rainfall coefficient, γ_2 the nitrogen coefficient, γ_3 the quadratic N coefficient, and γ_4 the interaction coefficient for nitrogen and rainfall. The model predicts a response to N at low rates in years of poor rainfall and negative response at higher rates due to "haying off." However, during good years, a strong response to nitrogen is to be expected (Figure 6). The response to N in 1985, a year with high mid-season rainfall, was closely in line with the prediction based on the model. Regression estimates for the model were significant at the 0.01 level (Table 4).



Source: Christianson et al. (1990).

Figure 6. Nitrogen Response of Millet as a Function of Critical Rainfall as Defined in the Text.

Table 4. Regression Estimates for the Effect of Critical Rainfall and Nitrogen Rates on Millet Grain and Stover Yield at Sadore, Niger

Estimate		Grain[a]	Stover
Intercept	γ_0	300.0	1400.0
Rainfall	γ_1	1.70** (0.10)	2.70** (0.27)
N rate	γ_2	10.36** (2.30)	17.31** (6.75)
(N rate)^2	γ_3	-0.41** (0.05)	-0.38** (0.14)
(N rate) x Rainfall	γ_4	0.07** (0.005)	0.05** (0.01)
n		267	164
R^2 Adjusted		0.82	0.63
Sy/x (kg ha^{-1})		183.0	442

* Significant at 0.05 level; **Significant at 0.01 level.

a. Numbers in brackets are standard errors of estimates.

Source: Christianson et al. (1990).

Table 5. Recovery of ^{15}N by the Crop and Estimated Losses From Soil Plant System

Country	Soil	Crop	N Source	N Rate	Plant ^{15}N Recovery	^{15}N Loss
				(kg N ha^{-1})	(%)	(%)
Senegal	Entisol	Millet	Urea	90	32	39
				150	30	45
				90+straw	17	51
				150+straw	21	52
Cameroon	Alfisol	Sorghum	$(NH_4)_2SO_4$	50,100	40-45	40-50

Source: Ganry and Guiraud (1979); Gigou and Dubernard (1979).

Results from 3 years of experimentation in Niger with millet provided some insight into the best N fertilizer management practices (Mughogho et al., 1986). Because urea and calcium ammonium nitrate (CAN) are the most common sources found in the Sahelian region, these sources were compared repeatedly. At rates below 30 kg N ha^{-1}, CAN yielded higher than urea, whereas the reverse was true at rates beyond 30 kg; the differences between the two sources, however, were not significant. Similarly, no significant difference was found between broadcast application versus banding at planting. A comparison of split-applied N with basally applied N showed a slight (15%) advantage in favor of splitting N. Given the uncertainties of the weather in the SAT, the practice of splitting N seems a prudent way of averting risk.

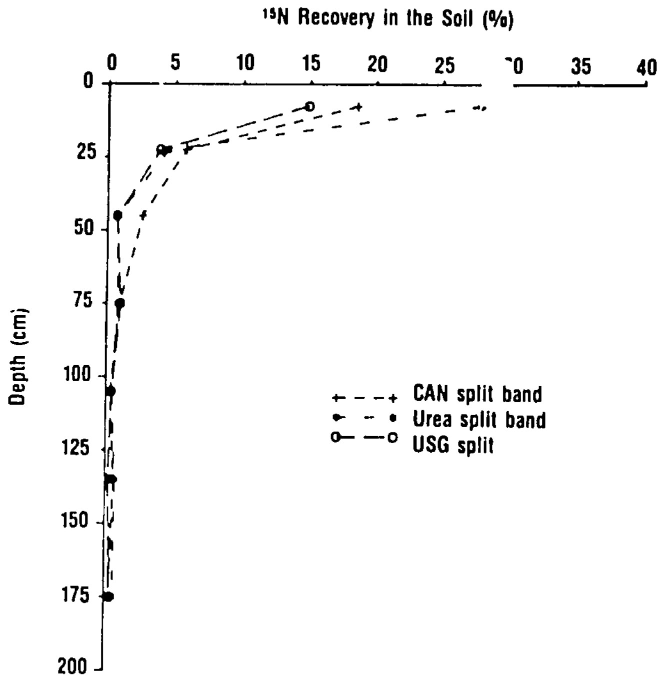
The fate of applied N in the African SAT was studied in Senegal for millet and in Cameroon for sorghum. Findings are summarized in Table 5. Some rates of urea recovery by cotton and sorghum grown on a Vertisol in Sudan were reported by Ayoub (1986). Recoveries by sorghum were low, ranging from 18% to 24%. Recovery by cotton was equally poor unless urea was placed at depths of 10-20 cm, which increased recovery to 37%-45% of the applied ^{15}N. The susceptibility of surface-applied urea in these soils to volatilization of ammonia has been well documented by Musa (1968).

The data in Table 5 indicate that losses can be excessive. Moreover, restitution of plant residues tends to aggravate losses at the expense of plant uptake. Fertilizer N remaining in the soil at the end of the season is surprisingly low. In order to supplement the limited database on the fate of applied N in the SAT, IFDC undertook a series of studies in the Sahel using ^{15}N. The experiments involved sole crop millet (1x1 m spacing) on an extremely sandy (94%) soil in Niger similar to the one in Senegal, and the urea split-banded treatment was used as a reference. The ^{15}N recoveries observed in the 3 years of study are shown in Table 6. These nitrogen balances confirm the high rate of N loss reported by Ganry (Table 5) in Senegal even at the much lower rate of application of 30 kg N ha^{-1}. The mechanism of N loss has not been identified directly. However, in Niger the N distribution in the soil profile at harvest suggests that leaching of applied N is insignificant even in a relatively wet year such as 1983 (Figure 7). Whether the recorded losses are due to wind erosion, volatilization of ammonia, or denitrification remains to be determined. Losses due to denitrification have been reported from desert-type environments following rainfall events (Westerman and Tucker, 1979). Comparison of CAN losses in 1983 (wet) and 1984 (dry), shown in Figure 8, indeed suggests higher losses from CAN in wet years, whereas the losses of urea were relatively unaffected by weather conditions. Because half of the N in CAN is nitrate from the onset and there is no marked tendency of nitrate leaching (Figure 7), an increase in loss tends to indicate that denitrification may act as a loss mechanism. Ammonia loss was identified as the sole cause of N loss in the sandy soils of Senegal (Ganry,

Table 6. Recovery of ^{15}N From Split-Banded Urea Applications to Millet in Niger

	Yield	^{15}N Recovery			Loss
		Grain	Plant	Soil	
	(kg ha^{-1})	- - - - - - - - (%)- - - - - -			(%)
1982	1,070	19.0	31.0	37.3	31.7
1983	1,040	9.8	22.8	39.2	38.0
1984	470	5.5	20.0	40.1	39.9

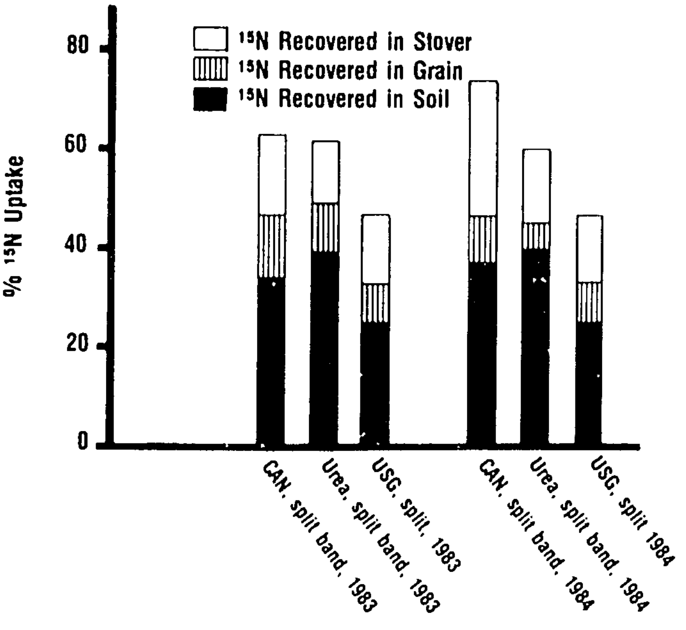
Source: Christianson et al. (1990).



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

Source: Mughogho et al. (1986).

Figure 7. Soil ^{15}N Distribution, Niger, 1983.



Source: Adapted from Mughogho et al. (1986).

Figure 8. ^{15}N Balances in Niger, 1983 and 1984.

personal communication). It is likely that the principal escape route in the acidic soils of Niger was also ammonia volatilization, which was due to localized pH increases resulting from urea hydrolysis to ammonium and bicarbonate or from the $CaCO_3$ present in the CAN. More research on the actual fate of applied N in these environments is urgently needed in order to help design improved management practices for fertilizer N.

It is clear from Figure 8 that deep placement of urea as supergranules (USG) was no safeguard against N loss. Deep point placement of N is sometimes recommended in this environment for crops as widely spaced as millet to increase the availability of N to the crop. There appears to be no justification for this practice in terms of efficiency, in that it resulted in a significant yield reduction and increased loss of N.

Phosphorus

For over 50 years, soil scientists and plant nutrition specialists in the African SAT have recognized that deficiency of phosphorus in the soils is the major constraint to crop growth. In some soils of the West African savannas, the phosphorus deficiency is so acute that plant growth virtually ceases as soon as the phosphorus in the seed is exhausted (Hauck, 1966; Pichot and Roche, 1972). The results of 37 trials involving sorghum in the savanna zones of Nigeria are summarized in Table 7. Even though local sorghum varieties were grown, there was positive response to phosphorus in 92% of the trials.

Table 7. Response of Sorghum to P in Savanna Soils

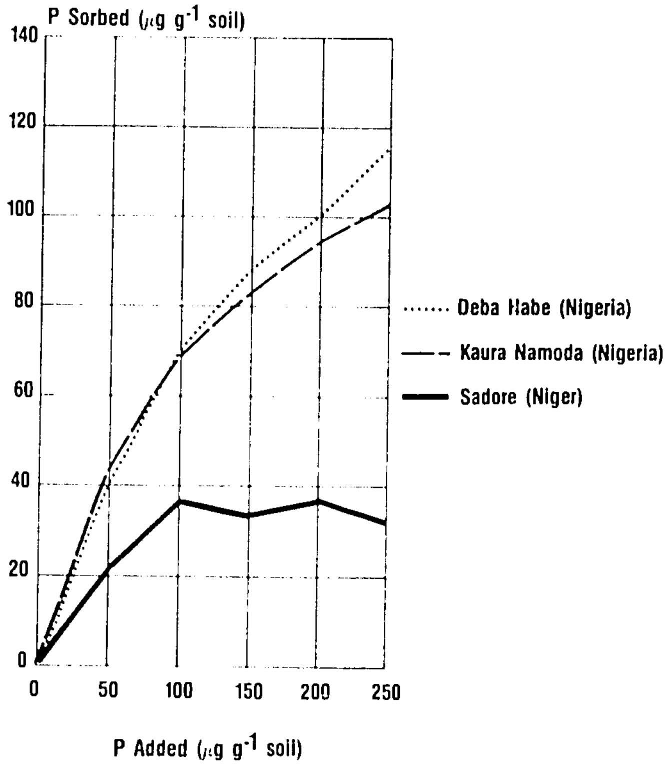
Ecological Zone	Number of Trials	Mean Yield at Lowest Nutrient Level (kg ha^{-1})	Number of Trials With Positive Results
Sudan	11	1,229	8
Northern Guinea	22	1,710	22
Southern Guinea	4	1,559	4

Source: Mokwunye (1979).

Total phosphorus levels in the Entisols and some of the Alfisols of the West African SAT rarely exceed 100 μg P g^{-1} soil. Available P as measured by Bray P1 in the dune sands is usually below 2 μg P g^{-1} soil (Bationo, personal communication). In the wetter zones of the tropics, a substantial amount of phosphorus utilized by a crop in any given year comes from the mineralization of phosphorus contained in soil organic matter. However, organic matter levels in the SAT are exceedingly low, and thus levels of phosphorus from this source are deficient for food crops.

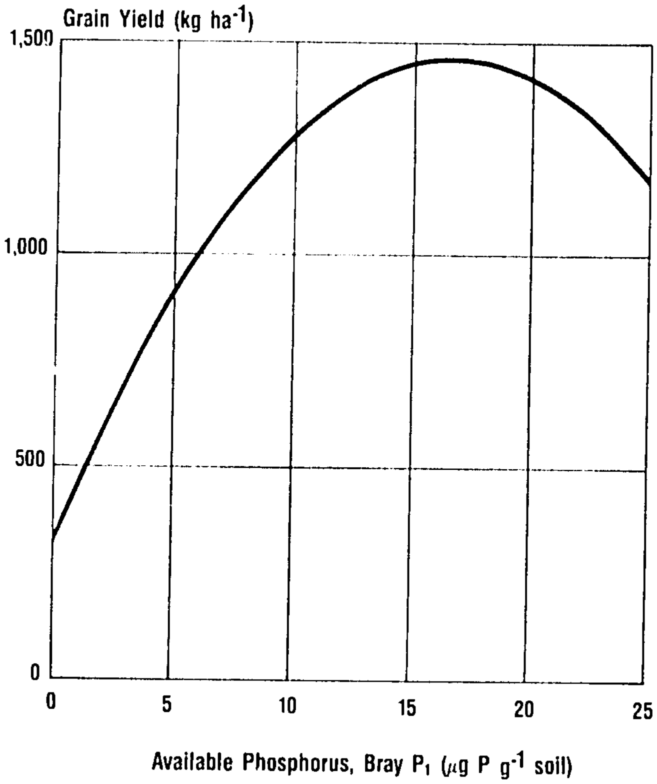
The phosphorus in soil solution that is available for plant uptake is in equilibrium with that adsorbed onto the surfaces of soil colloids. The ability of this adsorbed phosphorus to replenish soil solution phosphorus depleted through plant uptake is a measure of the soil's phosphorus buffering capacity. In a limited number of cases in the African SAT, this principle has been applied in studies to determine the phosphorus fertilizer requirements of crops and in the establishment of phosphorus fertilization practices (Mokwunye, 1977).

The results of a phosphorus sorption study carried out with soils from different areas of the West African SAT are shown in Figure 9. For the very sandy soils such as the Sadore (Niger) soil, maximum phosphorus adsorption occurred at about 100 μg P g^{-1} soil or lower. For most of the soils, phosphorus sorption can be adequately described by the Freundlich, Langmuir, and Temkin equations. Phosphorus sorption maxima for the soils depicted in Figure 9, as calculated from the Langmuir equation, were 36, 112, and 133 μg P g^{-1} soil for Sadore, Kaura Namoda, and Deba Habe soils, respectively (Mokwunye et al., 1986). These relatively low phosphorus sorption maxima imply that the immobilization of phosphorus (P-fixation) in these soils is minimal. Thus, at Gobery, field experiments show that the critical level for 95% of maximum yield of millet as measured by Bray P1 was 12.5 μg P g^{-1} soil (Figure 10). This value is usually attained with the application of less than 35 kg P_2O_5 ha^{-1}.



Source: Adapted from Mokwunye et al. (1986).

Figure 9. Phosphorus Sorption by Some West African SAT Soils.



$y = 327 + 136.9\,P - 4.12\,P^2 \quad R = 0.75 \quad RSE = 301$

Source: Bationo et al. (1989).

Figure 10. Relationship Between Millet Grain Yield (variety CIVT) and Available Phosphorus in Soil at Flowering (Gobery 1987).

A second consequence of the low P-immobilization capacity of sandy soils is the low values of P-buffering capacity associated with those soils. For example, the phosphorus buffering capacity of a sandy loam Alfisol from the northern Guinea savanna zone of Nigeria was more than twice as high as that of an Ustipsamment from the Sudan savanna (13.4 kg P ha^{-1} per 0.1 mg P L^{-1} compared with 5.6 kg P ha^{-1} per 0.1 mg P L^{-1}) (Mokwunye, 1979). A soil with low P-buffering capacity is usually characterized by relatively high soil solution P levels needed for optimum growth of crops, and this is true for soils of the West African semiarid tropics (Fox and Kang, 1978).

As noted above, low phosphorus buffering capacity is a direct result of the low capacity of the soils to sorb phosphorus. Although this low fixation capacity is useful in promoting good residual response from applied fertilizers, it has the potential to result in problems associated with development of economic fertilization practices. Good residual responses encourage the use of phosphorus fertilizers as a long-term investment. Conversely, the low buffering capacity limits benefits from the use of large corrective doses of phosphate by limiting the quantities of phosphorus available to replace that taken up by a crop in a given year. For a soil at Tarna (Niger), Bertrand et al. (1972) found that the application of 75 kg P_2O_5 ha^{-1} saturated the soil with respect to phosphorus. The results also suggested that approximately 1 kg of phosphorus per 100 kg of grain was exported from the soil each year if the stalks of millet were removed from the field. Thus, for a yield of 2 tonnes ha^{-1} it would be necessary to apply about 20 kg P_2O_5 ha^{-1} the following year, simply to avoid excessive depletion of the soil's phosphorus level. In such a situation, the corrective dose of 75 kg P_2O_5 ha^{-1} would not last a long time, and annual application of maintenance doses would be necessary.

Bationo, Mughogho, and Mokwunye (1986) reported that application of the first 10 kg P_2O_5 ha^{-1} as single superphosphate increased millet yield by an average of 17% for each of 3 years at Sadore. Ninety-eight percent of maximum millet yield was obtained at a phosphorus rate of 30 kg P_2O_5 ha^{-1}. Early work in Nigeria (Goldsworthy, 1967) led to the recommendation of 25 kg P_2O_5 ha^{-1} as economic fertilizer rates for sorghum and millet in the Nigerian savannas. Results of carefully supervised field trials and "minikit" trials under Nigeria's National Accelerated Food Production Programme (NAFPP) suggest that improved varieties would respond profitably to higher phosphorus rates (Tables 8 and 9). In Burkina Faso, maximum yield of sorghum was obtained at the phosphorus rate of 60 kg P_2O_5 ha^{-1} (Bationo, Mughogho, and Mokwunye, 1986).

Table 8. Response of Millet in Samaru, Nigeria, to Four Levels of P

P Rates	Yield			
	1973	1974	1976	Mean
(kg P_2O_5 ha^{-1})	(kg ha^{-1})			
0	1,045	1,163	1,648	1,285
66	1,789	2,129	2,459	2,126
99	1,632	1,968	2,042	1,881
132	1,643	1,891	1,842	1,792

Source: Egharevba (1978).

Table 9. Response of Two Sorghum Varieties (L187 and SK5912) to Varying Rates of P at Samaru, Nigeria

	Phosphorus Rates (kg P_2O_5 ha^{-1})				
	0	25	50	75	100
	(kg ha^{-1})				
L187	1,371	2,692	2,896	4,020	4,695
SK5912	1,615	2,532	3,623	3,421	2,447

Source: Mokwunye (1979).

To satisfy the phosphorus needs of the soils and crops of the West African SAT, a number of phosphate fertilizers have been tested. Single superphosphate has been the traditional source of phosphorus. There are, however, several phosphate rock deposits in the West African SAT (Figure 11), and numerous laboratory studies and field trials have been conducted to evaluate the agronomic effectiveness of these phosphate rocks. Fardeau et al. (1983) showed that phosphate rock was effective in soils with pH below 6.1 in Senegal. Both moderately and strongly acid conditions are present in the West African SAT, which should encourage the use of phosphate rock. The work of Binh et al. (1978) suggested that Tilemsi Valley phosphate rock from Mali and Tahoua phosphate rock from Niger possessed chemical and mineralogical characteristics that would permit their use for direct application. This finding was confirmed by scientists at IFDC (Roy and McClellan, 1986) who added Matam phosphate rock from Senegal to the list. The results of several field trials (Nabos et al., 1974; Thibout et al., 1980; Bationo, Mughogho, and Mokwunye, 1986) showed that these rocks serve as efficient sources of phosphorus for crops. For example, in a trial at Gobery (Niger) where Parc W phosphate rock and Tahoua phosphate rock were compared with single superphosphate, the less reactive Parc W phosphate rock was 48% as effective agronomically as single superphosphate, and the Tahoua phosphate rock was 76% as effective as SSP (Figure 12).

In cases where the local phosphate rock is so low in reactivity that it cannot be used for direct application, attempts have been made to improve the solubility of the rock through the chemical process of partial acidulation. The term "partially acidulated phosphate rock (PAPR)" refers to phosphate rock that has been treated with only a portion of the sulfuric or phosphoric acid required to fully convert the insoluble tricalcium phosphate to water-soluble monocalcium phosphate monohydrate (MCP). Sulfuric acid-based partially acidulated phosphate rocks of Niger and Burkina Faso have been extensively tested in

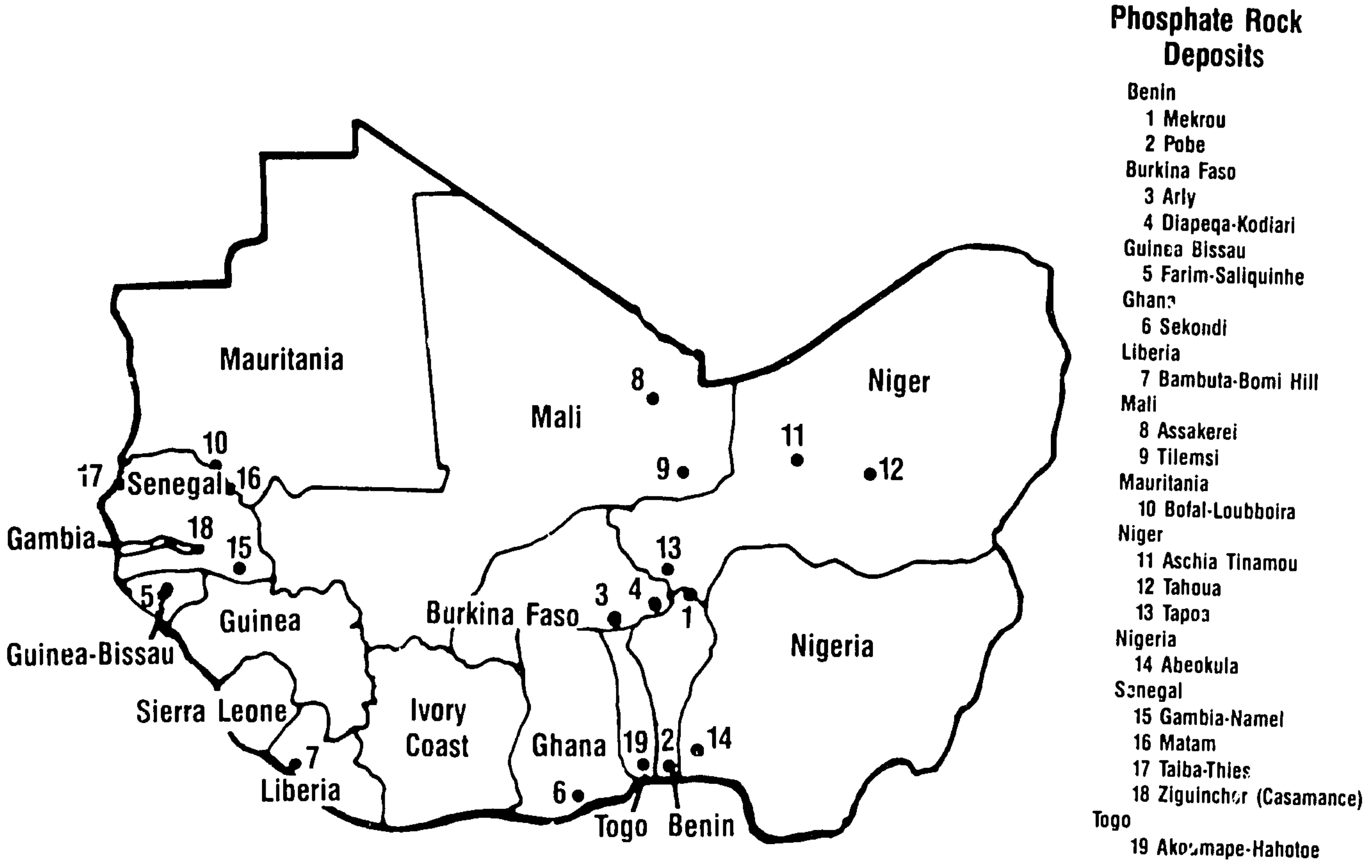
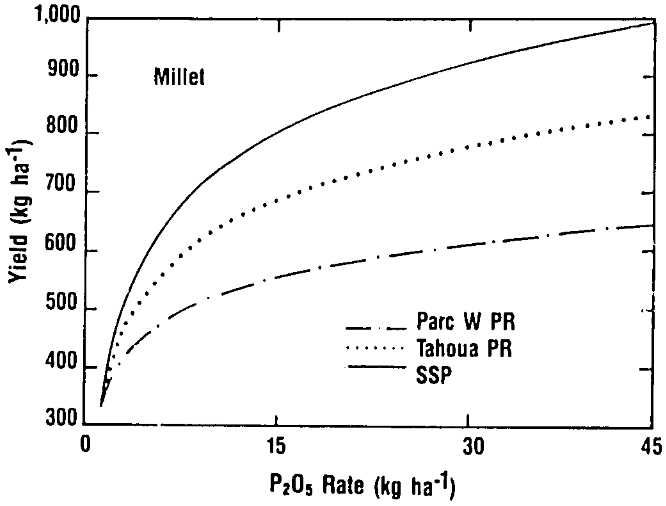


Figure 11. Phosphate Rock Deposits in West Africa.



Source: A. Bationo (unpublished data).

Figure 12. Millet Grain Yield Obtained With Two Phosphate Rocks (PR) and Single Superphosphate (SSP) at Gobery in Niger.

field trials. Results from 5 years of testing at Sadore and Gobery show that 50% partially acidulated Parc W phosphate rock was agronomically as effective on millet as single superphosphate (Table 10). Similar results have been obtained from trials in Burkina Faso with maize and sorghum (Table 11).

Table 10. Agronomic Efficiency Index of Millet at Sadore and Gobery, Niger

P Source	Agronomic Efficiency Index
Parc W phosphate rock	60.3*
PAPR25	76.5*
PAPR50	93.4
TSP	106.1
SSP	100.0

* Significant at the 0.05 level.

Source: Bationo, Mughogho, and Mokwunye (1986).

Table 11. Relative Agronomic Effectiveness (RAE) of Phosphorus Sources Applied to Maize and Sorghum at Farako-ba in Burkina Faso

P Source	Relative Agronomic Effectiveness (RAE)[a] Maize	Sorghum
Kodjari PR	59.8	34.3
Kodjari PAPR 50	84.1	81.3
SSP	100.0	100.0

a. $RAE = \frac{\text{Yield of Test Fertilizer - Control Yield}}{\text{Yield of Standard Fertilizer - Control Yield}} \times 100.$

As mentioned earlier, a direct result of the low phosphate sorption capacity of the soils is the high residual effectiveness of phosphate fertilizers. Data in Table 12, from work done at Sadore in Niger, illustrate that the addition of small amounts of phosphate fertilizers can, in the long run, result in a gradual but steady buildup of the phosphorus fertility of the soils. One way to take advantage of the excellent residual effectiveness of phosphorus fertilizers is to devise a cropping system that would require a single application of phosphorus fertilizers for a number of crops or for a rotation involving several crops. The concept of "corrective fertilization" whereby a large dose of phosphorus fertilizer was initially added to the soil followed by annual additions of smaller doses (maintenance fertilization) was developed by French agronomists in the West African SAT (Bertrand et al., 1972). Several efforts are still underway to refine this methodology. For example, in a trial at Sadore, Niger, small annual doses of the unreactive Parc W phosphate rock were compared with rates that were three times the annual doses over a 3-year period. Millet yields (Figure 13) were significantly higher for the annual application; however, where the large single doses were applied, substantial quantities of phosphorus were still in the soil 3 years after the initial application. Preliminary economic analysis after 3 years indicated that added net return was the same for both systems of fertilization (Table 13). An observation during the life of this trial was that, although the single large phosphorus fertilizer application produced a steady and sustainable yield level for the 3 years, at no time was this level superior to that achieved with the smaller annual applications.

Table 12. Available Phosphorus (Bray 1P) in Soil After Repeated Annual Applications of Phosphate Rock at Sadore, Niger

Annual Rate of Application of Phosphate Rock (kg P_2O_5 ha^{-1})	Bray 1P Measured After 1982 Crop	After 1984 Crop
	--------(μg P g^{-1} soil)-------	
0	3.60	3.40
10	3.65	4.80
20	4.50	5.21
30	4.50	6.05
40	4.85	7.22

Source: Bationo, Mokwunye, Henao, and Hellums (1986).

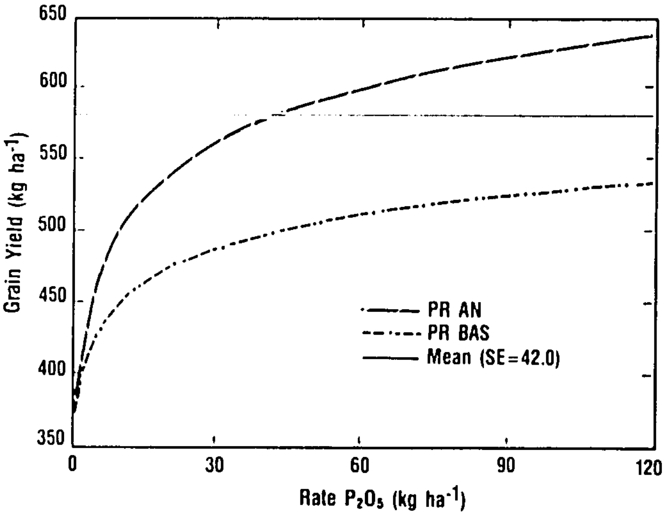


Figure 13. **Response of Millet to Annually and Basally Applied Phosphate Rock After 3 Years, Sadore, Niger.**

Sulfur

Sulfur, a nutrient that was given scant attention in the past, has gradually become recognized as a limiting nutrient in the tropics. Sulfur levels are commonly related to the organic matter content of soils, and the SAT is generally poorly endowed. Yet, because of the limited experience in the temperate zones with S deficiency, the critical role of sulfur in the tropics was recognized only recently. The acuteness of the problem has become more obvious with recent efforts to boost agricultural production in some parts of the SAT while relying on high-analysis, S-free carriers of NPK.

The early reports on S deficiency in the SAT came from studies of cash crops such as groundnuts and cotton

Table 13. Net Added Return to Application of Phosphate Rock Annually or Basally at Sadore, Niger

	Application Rate		Yearly Net Added Return				Present Value of Net Added Return, 1982	
Treatment	Annual	Basal	1982 Annual	1984 Annual	1982 Basal	1984 Basal	Net Return Annual	Net Return Basal
	(kg P_2O_5 ha^{-1})		(US \$ ha^{-1})				(US \$ ha^{-1})	
1	0	0	0.00	0.00	0.00	0.00	0.00	0.00
2	10	30	31.62	20.75	45.11	9.57	52.37	54.68
3	20	60	39.93	25.73	53.28	11.46	64.66	64.74
4	30	90	44.82	27.03	57.75	12.58	71.85	70.33
5	40	120	48.24	28.63	60.66	13.37	76.87	74.03

Source: IFDC (unpublished data).

(Greenwood, 1951). Richard (1972) grouped the S-deficient areas in West Africa as follows:

1. High S deficiency	Burkina Faso, Côte d'Ivoire, Northeast Benin
2. Medium S deficiency	Cameroon, Central African Republic, Central Togo
3. Low S deficiency	Mali, Chad, Southern Togo

Later, the savanna areas of Nigeria were identified as medium to highly deficient (Kang and Osiname, 1976). A summary of some S experiments in selected West African countries on crops typical for the SAT is given in Table 14. Information on S from the East and Southeast African region covers mostly the more humid zones. Bolle-Jones (1964) concluded that 50% of the sub-Saharan plateau soils are deficient in sulfur. He considered soils in regions receiving less than 600 mm rainfall to be less affected.

Table 14. Effect of Sulfur Fertilization on Crop Yield in Selected Countries of West Africa

Country	Crop	% Yield Increase Due to S Fertilization
Senegal	Groundnuts	6
Burkina Faso	Sorghum	14
	Cowpea	38
Niger	Groundnuts	6
	Pearl millet	11
Togo	Groundnuts	45
Benin	Groundnuts	35
	Maize	32
Nigeria	Maize	45

Source: Kanwar and Mudahar (1986).

A research program was initiated by IFDC to improve the understanding of the S constraints in West Africa. In 1985 experiments were set up at three sites. The two trials located in the SAT of Niger failed to respond to S, whereas a maize experiment in the subhumid zone of Togo gave a strong response. In 1986 the program was extended to six sites along a north-south rainfall gradient from the SAT of Niger and Burkina Faso down to the subhumid regions of Togo. Significant grain and/or straw dry matter responses were found in five of the six sites with increases of 22% to 66% (IFDC, 1987). Some of the sites in the SAT that did not respond in 1985 showed a marked response to residual S in 1986 (Figure 14, Gobery). In 1987, the program continued; however, the experiments with sorghum and millet were seriously affected by drought, and deficiencies of S were masked.

In addition to studying the long-term S requirements of various ecosystems, the IFDC program uses radioactive tracing techniques to assess the efficiency of applied S (Friesen, unpublished results). Data from Niger show that from 6% to 25% of the applied S was taken up by the aboveground parts when S was applied as single superphosphate to millet (at Sadore) and sorghum (at Gaya), respectively (IFDC, 1988). Higher recoveries were associated with the more densely planted sorghum crop in a higher rainfall environment. In that environment, recovery of fertilizer S in the soil-plant system was approximately 78% when applied as sulfate (Table 15). The sulfate lost from the system (about 20%) is unexplained but could be due to wind erosion in that sources were only lightly incorporated and early season storms in the region are often accompanied by high winds. Nevertheless, with 53% of the applied sulfate remaining in the soil, substantial residual effects may be expected.

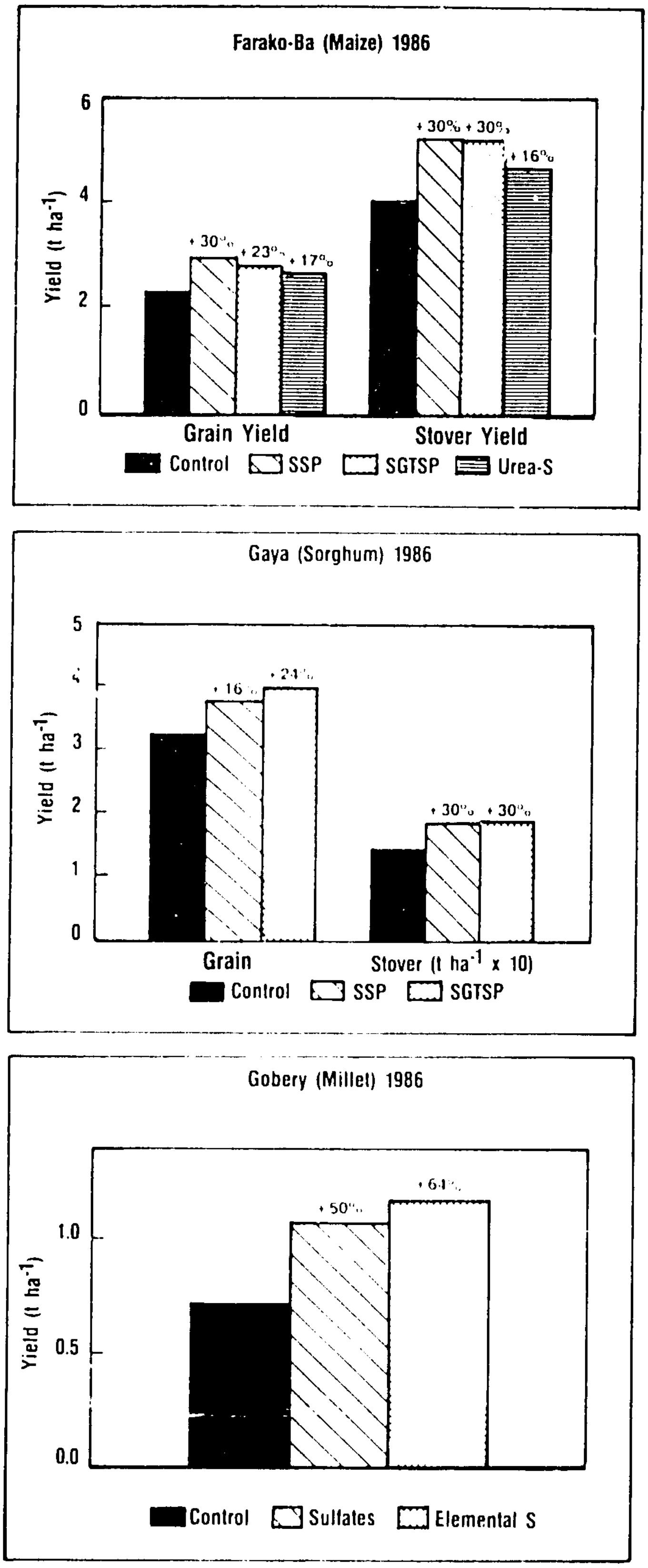


Figure 14. Response to Residual S at (a) Farako-Ba, Burkina Faso, (b) Gaya, Niger, and (c) Gobery, Niger (D. K. Friesen, unpublished).

Table 15. ^{35}S-Balance Under Sorghum at Gaya, Niger (1986)

Sulfur Pool		^{35}S-Recovery	
		SSP[a]	SGTSP[b]
		------ (% applied) ------	
Plants:	Grain	3.9	1.8
	Stover	21.3	7.8
	Roots	-	-
Σ		25.2	9.6
Soil:	Organic-S	29.9	24.7
	Sulfate-S	22.7	2.7
Σ		52.6	27.4
ΣΣ		77.8	37.0

a. Single superphosphate.
b. Elemental sulfur-fortified triple superphosphate.

Source: Friesen, D. K. (unpublished results).

In contrast to recovery from single superphosphate, plant recovery was only 9% when fertilizer S was applied in elemental form to sorghum (Table 15). The recovery of the applied elemental S in the soil was 27%, of which 24% was as organic S and 3% as sulfate S. Apparently, a substantial portion of the elemental S was not oxidized. An analysis of the remaining elemental S will have to be made to complete the S balance in this treatment.

Further research is needed to evaluate long-term S needs in the SAT and address such issues as the rate of oxidation of elemental S as a function of soil ecological parameters, S immobilization and remineralization, minimum S requirements, and optimizing S availability.

Micronutrients

As pointed out in an extensive review of micronutrients in tropical food crop production (Vlek, 1985), it appears impossible to assess the seriousness of micronutrient deficiencies in the semiarid tropics on the basis of presently available data. The data available are too scanty to delineate trends in order to predict areas where problems are likely to arise in the future. Yet, the increases in micronutrient harvesting that are predicted as higher yields are realized (Kanwar and Youngdahl, 1985) may substantially alter existing nutrient balances and may increase the incidence of deficiency symptoms (Table 16).

Some micronutrient deficiencies are common in the semiarid tropics of Africa and are primarily related to the parent materials. Boron deficiency is often reported in cotton. Copper deficiency symptoms have been found in East Africa in wheat, and molybdenum deficiency is a widespread problem in groundnut production in West Africa. Zinc responses are common on the Vertisols of the Chad basin and of the Gezira region in the Sudan (Kang and Osiname, 1985).

The Problems Ahead

If the rural population of the African SAT is to feed itself, food production levels in these regions will have to increase drastically. The FAO estimates that fully 70% of this increase will come from more intensive agriculture including the use of fertilizers. The incidence of micronutrient problems will undoubtedly multiply when these changes are effected.

Much time and effort are often spent on debate as to whether more resources should be devoted to water management studies or to soil fertility studies. This argument as to which is more important – water or fertilizers – need not take place. In a way, lack of water and reduced capacity of the land to produce (reduced fertility) are two sides of the same coin. Where the land is fertile and productive, water-use efficiency is generally high and the natural resource base is preserved. Where the land is unproductive, water is not efficiently captured and used, and marginal lands are brought under cultivation to obtain needed food. This further accelerates the degradation of the soil resource base. There is therefore a strong need to coordinate studies that promote efficient management of both water and fertilizer nutrients.

The use of a purchased input such as fertilizers is highly risk-prone in the SAT. Yet, it is obvious that fertilizers have an important role in promoting land productivity and arresting soil degradation. Studies geared towards a more efficient use of fertilizers are therefore critical. Such studies must define the right types and quantities of fertilizers to use for each crop and cropping system. They must also define what management practices, including soil conservation practices, must be adopted to maximize efficiency. Finally, such studies must examine the long-term effects of the fertilizer treatments on the environment.

In semiarid regions, rapid and deep root establishment is essential to crop establishment. Several studies have demonstrated the strong relationship between root density, weight of roots, and crop yield. There is also a direct relationship between total porosity and root density and hence crop yield. Measures that tend to increase total porosity provide favorable environments for root development. Effective root development translates into more efficient use of the resources of water and nutrients. There is an urgent necessity in the region for intensive studies on factors that improve root development, particularly on the rooting habits of crops in an intercrop.

The bulk of the nitrogen, phosphorus, and sulfur content in soils, crop residue, and manure is bound to carbon. The decomposition of plant (and animal) residue in soil constitutes a basic biological process involving the breakdown of carbon, the release of CO_2 into the atmosphere, and the mineralization of nitrogen (as NO_3^- and NH_4^+), phosphorus, sulfur, and various micronutrients contained in the plant (or animal) material. The rate of carbon loss closely determines the rate of release of these nutrients.

Several studies (Pichot et al., 1981) have demonstrated the value of organic materials in maintaining the productive capacity of the sandy soils of the SAT. The decomposition of added crop residue is generally

Table 16. Estimates of Micronutrient Removal Rates at Current Yield Levels and at Potential Yield Levels

Crop	Yield	Current and Projected Micronutrient Removal					
		Fe	Mn	B	Zn	Cu	Mo
	(t ha^{-1})	(g ha^{-1})					
Sorghum	0.9(5.0)[a]	648(3600)[b]	49(270)	49(270)	65(360)	5(28)	2(11)
Millet	0.6(4.0)	102(680)	12(80)	-	24(160)	5(33)	-
Groundnuts	0.8(5.0)	1200(7500)	94(590)	106(660)	22(140)	12(75)	3(18)

a. Potential high yield levels

b. Projected micronutrient removal rates at high yield levels.

Source: Kanwar and Youngdahl (1985).

accompanied by a concurrent mineralization of native humus. Therefore, additions of large quantities of residue after harvest may not necessarily result in increased organic matter content (Stevenson, 1986). Thus, it may be that the objective of crop residue addition is not to raise the level of soil organic matter but rather to derive benefits (perhaps in the form of the mineralized nutrients) from the decay of organic materials. The rate at which this goal is achieved is important to know.

The research areas discussed are very closely related, and they provide a basis for a meaningful team effort to help the farmer in the SAT. Because of the fragile nature of his soil resource base, this farmer has but one option: to find a way to maintain, if not improve, the productivity of his land. It must be recognized that, given current knowledge and the population growth rate, use of land resources for rainfed agriculture in the region has already exceeded a sustainable level. The scientific community, working with the farmer, must find ways to foster development while maintaining the productivity of these nonrenewable resources.

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Elements of Climate – Their Relevance to Crop Productivity and Fertilizer Use Planning in the Semiarid Tropics[1]

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Abstract

High-yielding varieties, balanced fertilizer application, and adequate water supply are the three important factors for higher crop production. In the semiarid tropics (SAT), water is the primary constraint for crop production mainly in shallower soils having low water-holding capacity. The problem is further aggravated by variability in quantity and distribution of rainfall and by high evaporative demand. Based on the experiments conducted at ICRISAT Center, we have developed a program for N fertilizer application for cereals. Split application of N fertilizer is useful for both Vertisols and Alfisols. In Vertisols, water does not become a limiting factor for N response because of their high water-holding capacity, whereas in Alfisols, water is the main factor dictating crop response to N. Based on an analysis of long-term (1901-87) rainfall received during the crop growing season, the probability of fertilizer N required to optimize sorghum production has been estimated. These data can be used to assess risks to fertilizer N application and differences in fertilizer N needs from year to year in a semiarid tropical environment.

Introduction

In many parts of the semiarid tropics (SAT), great advances in agricultural productivity along with the introduction of modern agronomic practices have been witnessed in the last few decades. These advances have been possible mainly because of a remarkable fusion of the introduction of high-yielding varieties (HYVs) and improved agrotechnology. In particular, controlled use of irrigation and application of balanced amounts of fertilizers have contributed significantly to increased agricultural production. However, this impressive growth has not taken place across all of the semiarid tropics. Unirrigated, dryland areas, which are characterized by uncertain rainfall and a poor resource base, have largely remained neglected. The adoption of improved practices such as the use of HYVs, application of balanced doses of fertilizers, and crop protection measures is fairly low across the SAT. This paper attempts to examine the climatic constraints of some typical SAT locations in relation to their current and potential fertilizer use practices.

Climatic Characteristics of SAT

Seasonality of Rainfall

The SAT regions are characterized by a seasonal rainfall. The rainy season varies from 2 to 4.5 months in the dry SAT and from 4.5 to 7 months in the wet-dry SAT. The distribution of rainfall is generally unimodal in areas lying >15° north and >15° south of the equator; it is bimodal in equatorial regions. The SAT exhibits a wet rainy season followed by a distinct dry season. About 90% of the total annual rainfall is received during the rainy season (Figure 1).

Variability of Rainfall

The amount of annual rainfall received in SAT areas varies greatly from year to year; its coefficient of variability (CV) is 20%-30%. For example, the mean annual rainfall at Hyderabad based on 1901 to 1987 rainfall records is 781 mm with a standard deviation of ±212 mm and a CV of 27%. At Hisar, the mean annual rainfall is 456 mm (1930-70) with a standard deviation of ±149 mm

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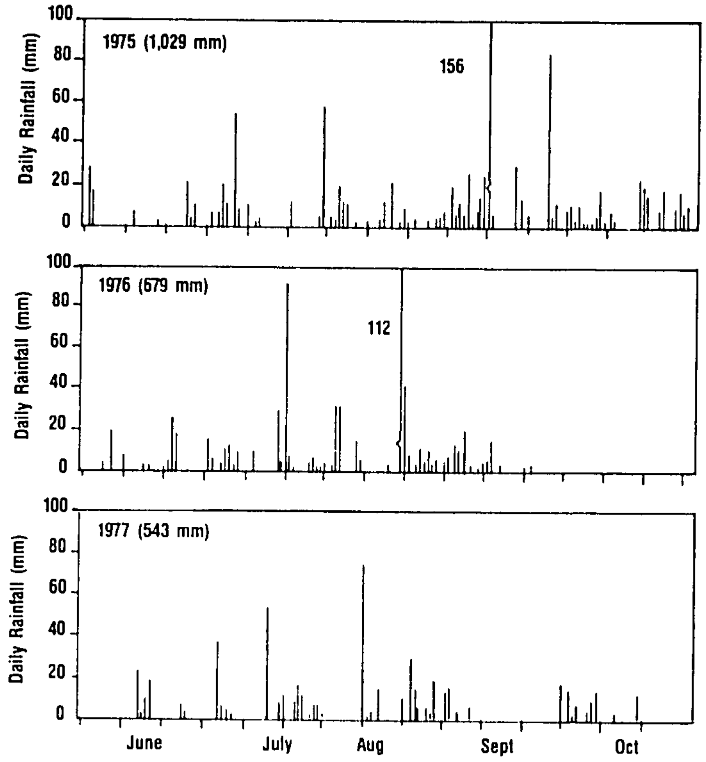


Figure 1. Rainfall Distribution at ICRISAT Center, 1975 to 1977.

and a CV of 33%. Thus, large variations in interannual rainfall are observed. The range of annual rainfall observed at Hyderabad is 950 mm for the period 1901-87. The annual rainfall may be as low as 450 mm or as high as 1,400 mm - about 90% of which is received during the 4-month rainy season.

Another characteristic of tropical rainfall is that the bulk of the seasonal rainfall is received during a few (generally 5-10) rainy days. The 24-hour total rainfall on each of such torrential rainy days may exceed 100 or 150 mm (Figure 1). At ICRISAT Center, it has been observed that in 43% of the rainy days, the rainfall storm intensity exceeded 20 mm hour^{-1}. In Niamey, this characteristic was observed in 72% of the rainy days. In about 10% of the days, rainstorm intensities as high as 120-160 mm hour^{-1} are not uncommon (Hoogmoed, 1981). Hence there is a considerable loss of water due to surface runoff and soil erosion. Miranda et al. (1982) observed that at the ICRISAT Center in traditionally managed Vertisols, 28% of the total seasonal rainfall was lost as surface runoff. This runoff carried away 7 tonnes of surface soil per hectare.

The convective nature of rain-producing storms in the tropics means that the rainy periods are interspersed with dry periods. During the rainy periods, when the soil profile is fully charged, a portion of the soil water is lost as deep drainage. The proportion of total seasonal rainfall lost by this pathway ranges from about 20% in light-textured soils to 10% in heavier soils. Thus the amount of effective seasonal rainfall in the tropics is about 50%-60% of the total annual precipitation.

Evaporation

The SAT areas are characterized by a high water demand due to intense radiation and uniformly high temperatures throughout the year. Sivakumar and Virmani (1987) calculated potential evapotranspiration (PE) statistics for 169 locations in rainfed India and found that the total annual PE was about 1,550 mm with a standard deviation of 196 mm and a CV of 13%. The PE in the months just prior to the rainy season is relatively high - about 200 mm month^{-1}; sometimes the PE exceeds 15 mm day^{-1}. The climatic data for the SAT regions show that the variability in PE is much lower than the rainfall variability and that the atmospheric demand for water is consistently high.

Length and Characteristics of the Growing Season in the SAT

Length of the growing season is defined as the period during which the availability of moisture in the root zone of the crop is adequate to meet the crop's water needs. Because the soil is practically dry prior to the onset of the rainy season, almost all activities related to land preparation for seeding are undertaken when the surface soil is moist enough for ploughing. As a rule of thumb, sowing is done within a week of the onset of the main rainy season in sandy soils and within 2-4 weeks in heavier soils.

The moisture in the soil is enough to sustain crop growth for about 4 weeks after the cessation of rains in lighter soils and about 8-12 weeks in the heavier soils. Thus the length of the growing season in SAT areas receiving rainfall for 2 months will be of the order of 80 days in light-textured soils and about 100 days in soils with clay or clay loam textures. Similarly, in areas with 5 rainy months, the growing season varies between 180 days in light-textured soils and 210 days in clayey soils. Because the amount and distribution of rainfall vary considerably from year to year, the length of the growing season also varies. This variability is higher in the dry SAT than in the wet-dry SAT. The risk to dependable crop production is least for short-duration crops like pearl millet, mung beans in lighter textured soils, and sorghum or maize in heavier soils. The length of the growing season exceeds the average in at least half the years, and the soil water remains relatively underutilized after the harvest of the short-duration crops. In the SAT, therefore, intercropping of short-duration and long-duration crops is recommended. This practice helps stabilize the yield (Willey et al., 1982) and increase rainfall use efficiency (Virmani, 1982).

Climate Analysis and Fertilizer Use Development

Climate analysis is an essential part of technology development and the technology transfer process in the semiarid tropics. For example, by classifying a set of climatic parameters relevant to the definition of adequacy of soil moisture for crop establishment, a region can be defined in which it is assumed that basal dressing of fertilizers would be relatively safe. Virmani et al. (1982) have demarcated the Vertisol region of India into regions with a dependable onset of seasonal rainfall and those with a relatively undependable onset.

The SAT climates encourage surface runoff of rainwater, deep drainage losses, and soil erosion. All of these losses of water lead to fertilizer losses–in particular, losses of applied N. In the SAT, it is best to apply split doses of fertilizers and to adapt the fertilizer applications to the moisture storage capacity of the soil profile and the progress of the seasonal rainfall. The information on rainfall probabilities could be used with advantage in scheduling fertilizer application.

Suggested Fertilizer Use Practices for SAT Dryland Areas

The risks to dependable crop production in the SAT are high. Because fertilizers are costly, the farmers do not use applied nutrients in sufficient quantities. Water is the main limiting factor in the dryland areas of the SAT; therefore, the application of fertilizers will be most advantageous where water conservation methods are used. In the Indian SAT, fertilizer use is currently limited to cash crops like cotton, groundnuts, chilies, etc., and, to some extent, post-rainy-season sorghum. Fertilizer use efficiency, however, is low.

The practice of intercropping is common in the SAT, where about 44% of the cropped area is devoted to intercropping. Legume is one of the important crops in about 50% of the intercropped plots. The practice of intercropping cereals with legume crops leads to the buildup of soil nitrogen. Because intercropping leads to a substantial reduction in risk to dependable crops, the adoption of intercropping encourages fertilizer use for cereal production (Table 1).

Table 1. Some Important Indicators of Fertilizer Use in Three Villages of India's Semiarid Tropics (Average of 1981-83)

Particulars	Nonirrigated	Irrigated	Total
% of total cropped area	81.1	18.9	100
% share of total nutrient (NPK) used	33.7	66.3	100
Fertilizer Use by Crop (%)			
Cotton	39.5	15.3	23.4
Wheat	2.7	32.5	22.4
Paddy	5.2	19.8	14.9
Sorghum	34.0	1.4	12.4
Pearl millet	4.0	13.0	10.0
Castor	6.7	7.5	7.3
Groundnut	3.0	2.7	2.8
Others	4.9	7.8	6.8
Total	100.0	100.0	100.0
Use of Nutrients (NPK) in Relation to Farm Size (kg ha^{-1})			
Small farm	6.1	29.1	8.5
Medium farm	4.8	48.5	14.6
Large farm	6.7	56.8	15.9
All farms	6.3	53.5	15.1

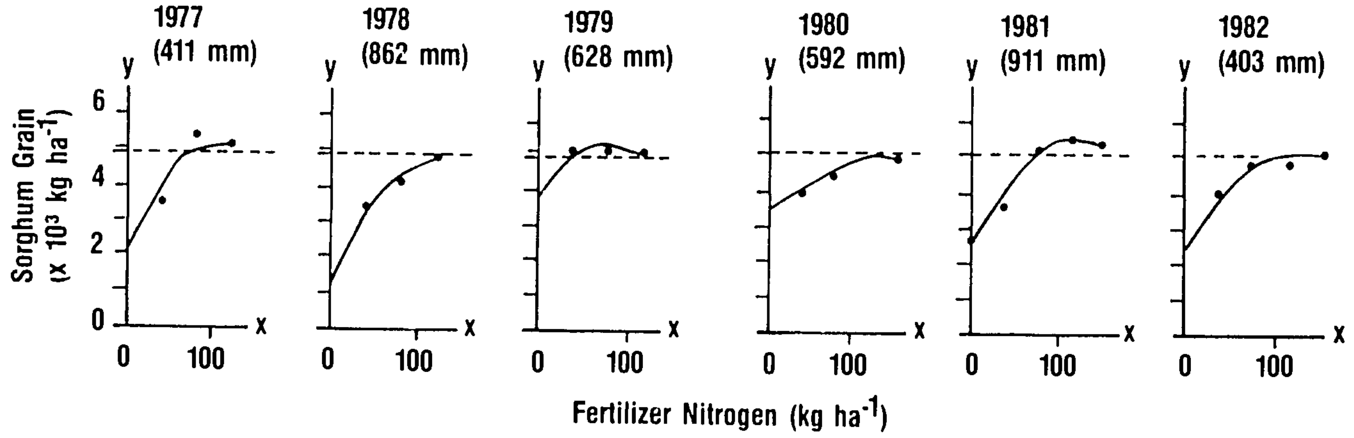
Source: Data collected from ICRISAT's village-level studies.

The production of short-duration pigeon peas is becoming popular. The crop needs application of phosphorus; however, critical soil test values for available P have not been well defined for the various soil orders in India. This is an important area of future research.

Rainfall Amount and Possible Fertilizer Use

Huda et al. (1988) demonstrated the use of agroclimatic analysis for improved soil and water management and efficient fertilizer use in semiarid India. These researchers analyzed seasonal rainfall (June to October) data of Hyderabad from 1901 to 1987 to relate rainfall and possible past fertilizer use. Nitrogen response data at ICRISAT Center from both Vertisols (1977-82) and Alfisols (1979-81) were used (Figures 2a and 2b). In Vertisols, grain yields of rainy-season sorghum (CSH 6) grown in small-plot research experiments at ICRISAT Center exceeded 5,000 kg ha^{-1} in each of the six rainy seasons from 1977 to 1982, provided adequate N was applied. In the absence of added N, grain yields were as low as 1,300 kg ha^{-1}. Seasonal rainfall varied from 474 mm to 907 mm. This did not markedly affect yields, nor were the responses of yields without N closely related to rainfall. For example, the two seasons in which responses were highest (1977 and 1978) were those with extremes in seasonal rainfall. These experiments were conducted on Vertisols nearly 1.5 m deep, which thus had a high water-holding capacity. Variations in nutrient supply apparently are much more important than variability in seasonal rainfall in determining the yields of improved rainy-season sorghum on Vertisols.

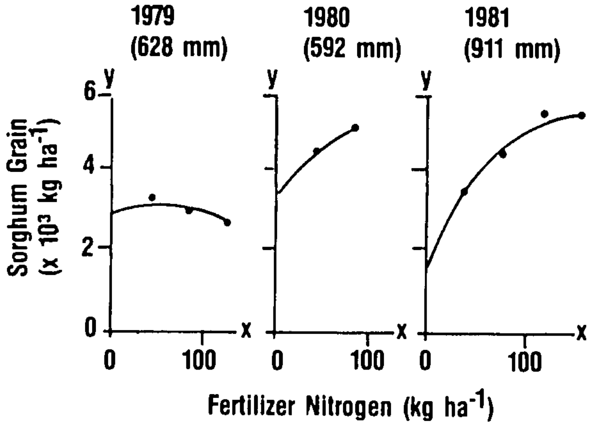
The ICRISAT data base for Alfisols is smaller than that for Vertisols. In the years of moderate and high seasonal rainfall (1980 and 1981), maximum yields exceeded 5,000 kg grain ha^{-1}. But in droughty 1979, the maximum was only 3,400 kg ha^{-1}, and yields were further depressed when applied N exceeded 40 kg ha^{-1}. It seems that maximum yields (when N supplies are adequate) will vary more on Alfisols than on Vertisols. On these Alfisols, which have low water-holding capacity, and on similar soils (in terms of water storage), maximum yields are determined by both rainfall and nutrient supplies. Thus the critical factor determining differences between Vertisols and Alfisols in responsiveness to added N is the moisture-holding capacity of the soil. Alfisols, as well as similar shallow soils, store insufficient moisture to



Regression Equations:

1977: $y = 1{,}920 + 62.4x - 0.28x^2$ $R = 0.81$ rse = 1,063
1978: $y = 1{,}310 + 53.3x - 0.19x^2$ $R = 0.97$ rse = 386
1979: $y = 3{,}920 + 37.8x - 0.23x^2$ $R = 0.92$ rse = 280
1980: $y = 3{,}340 + 19.6x - 0.59x^2$ $R = 0.99$ rse = 123
1981: $y = 2{,}580 + 44.3x - 0.17x^2$ $R = 0.97$ rse = 358
1982: $y = 2{,}340 + 40.8x - 0.15x^2$ $R = 0.91$ rse = 510

Figure 2a. Response of Sole Cropped Hybrid Sorghum (CSH 6) to Applied N on Deep Vertisols, ICRISAT Center, Rainy Seasons 1977-82. Seasonal Rainfall Given in Parentheses After Year.



Regression Equations:

1979: $y = 2,950 + 12.9x - 0.11x^2$
$R = 0.51$ rse = 351
1980: $y = 3,590 + 36.2x - 0.18x^2$
$R = 0.90$ rse = 400
1981: $y = 1,620 + 54.9x - 0.18x^2$
$R = 0.99$ rse = 187

Figure 2b. Response of Sole-Cropped Sorghum (CSH 6) to Fertilizer N on Alfisols, ICRISAT Center, Rainy Seasons 1979-81. Seasonal Rainfall (sowing-harvest) Given in Parentheses After Each Year.

maintain plant growth during droughty, rainless periods, especially when growth is stimulated by addition of fertilizer N. Therefore, if the rainfall is < 500 mm, fertilizer N application is a great risk in these types of soils. For maximum yield of sorghum, the recommended rate of nitrogen application is about 40 kg N ha^{-1} if rainfall is 500-700 mm, about 80 kg N ha^{-1} if rainfall is 700-900 mm, and 120 kg N ha^{-1} if rainfall exceeds 900 mm (ICRISAT, 1984). Analysis showed (Figure 3) that from 1900 to 1941 there were many years when nitrogen would not have been added because of low rainfall, whereas from 1942 to 1987 there was only one such year (1972).

Conclusions

The climatic environment of the semiarid tropics is characterized by variability of amount and distribution of rainfall from year to year. This leads to variations in the length and quality of the growing season. It is suggested that a basal dose of fertilizers be applied in those regions of the SAT where the onset of the rainy season is dependable. Fertilizers should be applied in split doses – not on a fixed schedule but according to the progress of the rainfall and the crop. Practices like intercropping, growing of legumes, and application of fertilizers on the basis of soil test and rainfall probability estimates are likely to lead to the efficient use of applied nutrients in the dryland areas of the SAT.

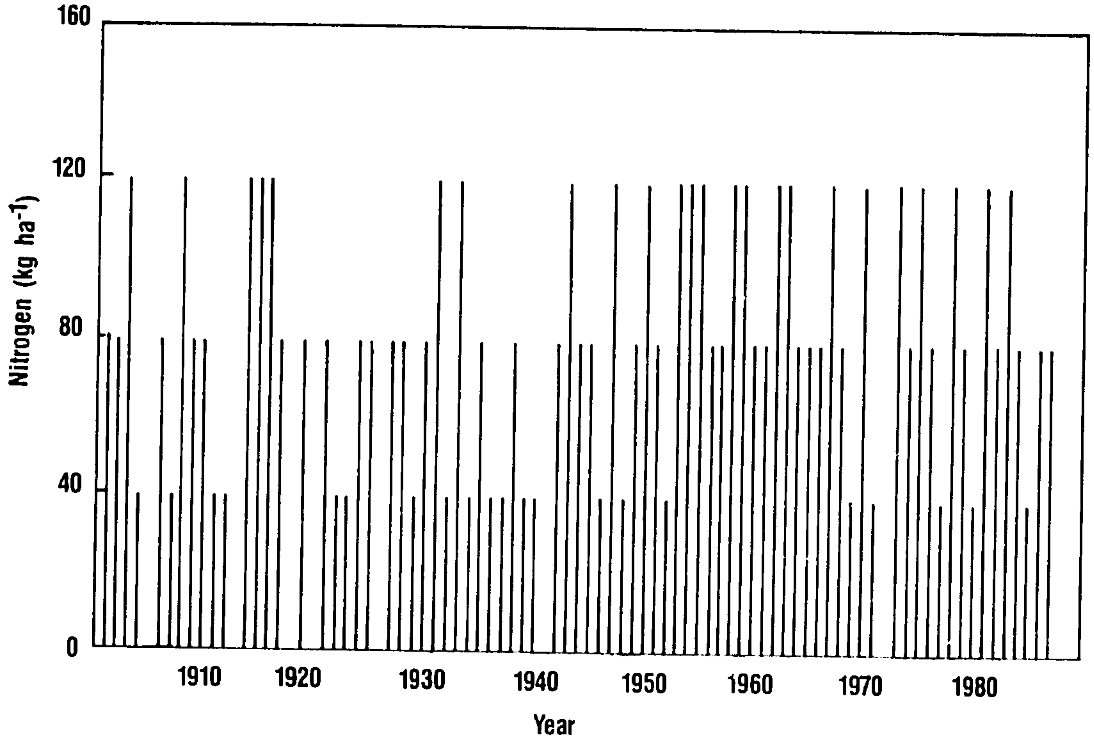


Figure 3. Amount of Nitrogen Fertilizer That Should Have Been Added (based on rainfall analysis) for Sorghum in Hyderabad During 1901-87.

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Nitrogen Availability in SAT Soils: Environmental Effects on Soil Processes

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Abstract

In the past, fertilizer needs of crops in India have been assessed by conducting numerous fertilizer response experiments. Recent advances in crop modeling have led to suggestions that the models based on physical environmental factors may be extended to include descriptions of nutrient behavior. One difficulty in this approach is the harsh environment of the semiarid tropics (SAT) and the effect of this environment on processes affecting nitrogen availability in the soil. Another constraint is the dearth of direct measurements and quantitative descriptions of many processes in the field (e.g., mineralization, urea hydrolysis, leaching, denitrification, and ammonia volatilization). Such measurements are urgently needed, with appropriate attention to methodology, to provide information needed for models that include nutrient terms.

Introduction

Nitrogen deficiency is the most important of the nutrient disorders in India (Prasad and Subbiah, 1982; Randhawa and Tandon, 1982), as shown clearly by the dominance of nitrogen in the fertilizer nutrients used (Biswas, 1989). Although most Indian soils are usually deficient in nitrogen for nonlegume crops, widespread fertilizer N use has been confined primarily to irrigated crops and dryland cash crops. Dryland cereals have received relatively little nitrogen, despite examples of large and apparently highly economic responses (Tandon and Kanwar, 1984). One reason for this is the variability in responses (Table 1) presumably caused in large part by variations in rainfall or its intraseasonal distribution (Jha and Sarin, 1984). Cereal responses to nitrogen are noted for their dependence on an adequate moisture regime (Russell, 1984). How to delineate nonresponsive from responsive locations is thus a major question, deserving perhaps the highest priority.

Under irrigated agriculture, the development of sound fertilizer application recommendations (which, judging from the use of fertilizer in India, have been generally well accepted by farmers) was based on the combination of two main factors: the certainty of responses under assured moisture regimes and the results of many hundreds of empirical nitrogen response experiments. However, it would seem that the number of empirical field experiments could have been greatly reduced if modeling approaches had been used.

The accurate assessment of the fertilizer nitrogen needs of crops requires much greater effort, however, under the variable moisture regimes of dryland agriculture than under assured moisture regimes. The major difficulty is that overall effects of moisture and nutrient

Table 1. Summary of Response of Rainy Season Crops to Fertilizer N

Crop	Range of Response (kg grain kg^{-1} N)
Sorghum	3.4 - 43.4
Pearl millet	2.1 - 24.8
Finger millet	5.0 - 42.4
Maize	4.1 - 67.4
Rice	4.5 - 33.9
Setaria	5.9 - 17.9
Sunflower	1.5 - 22.6
Castor	2.9 - 7.2
Groundnut	1.3 - 6.0
Linseed	1.2 - 11.5
Sesamum	1.3 - 5.0

Source: Rao and Das (1982).

interactions are not known, and their probable complexity indicates that modeling should be a much more efficient means of predicting fertilizer needs. The approaches used in modeling, however, require careful consideration to ensure that major factors in the semiarid tropical environment are fully understood.

Aspects that need particular consideration in the development of models are the harshness of the SAT environment and the marked variations in agroclimate that occur – both through the year and within seasons. Many of the modeling approaches have been developed under temperate climates, with an emphasis on the relationships between crop growth and yield and the physical environment – especially water, light, and temperature. In extending such models to include nutrients, we need to consider the effect of the relatively harsh environment in the SAT not only on plant growth but also on soil processes that influence nitrogen supply. Regrettably, some of these soil processes are somewhat intransigent. Many involve microbiological activity, which is less easy to characterize than physical factors in the environment, and additionally a number of processes present considerable difficulty in the development of quantitative relationships to describe the operation of the process in the field.

The purpose of our paper is not to review the great number of fertilizer response experiments, but instead to indicate some of the past work on processes that affect the supply of nitrogen to plants, especially those processes that may be particularly affected by the SAT environment. These must be considered in any modeling approaches in dryland agriculture where nutrient-water interactions are expected.

Predicting Nitrogen Supply

Organic N commonly accounts for over 90% of the total N in most soils, and this N is made available to plants through the mineralization process. This process, which converts organic N into ammonium, is carried out by a diverse population of heterotrophic soil microorganisms. Only a very small fraction of the total soil nitrogen is mineralized and thus becomes available to a crop during a growing season. In upland soils, ammonium formed via mineralization is further converted to nitrate, which is subject to several loss mechanisms. Fertilizer N that has been incorporated into soil organic N is also subject to these general processes of mineralization and loss.

The amount of nitrogen available for crop uptake is the total N supplied by soil or fertilizer less that which has been subjected to various loss processes. For convenience we shall describe this amount as the net supply. In India, the predominant data available are numerous estimates of the net supply, obtained by the simple method of measuring crop N uptake. Useful as this information has been for providing a general view of the net N-supplying capacity of Indian soils, it has limitations for the development of models; for these, we may need to consider the major factors that influence each of the important processes that contribute appreciably to the net nitrogen supply. These two approaches are discussed for both soil N and fertilizer N supply.

Net Soil N Supply

Determination of soil N uptake by crops is perhaps the most convenient approach for assessing net soil N supply. Crop uptake of N from non-N-fertilized treatments is determined over a number of years to get a reasonable estimate of the average N-supplying capacity of the soil at one particular location. Measurements based on crop uptake should encompass a range of different seasons in relation to seasonal rainfall and its distribution and the effects of temperature on soil processes. From the amount of soil N taken up by the crop, the net amount of mineralized N could be estimated as a fraction of the total N or organic N content of the soil.

Estimates of the N-supplying capacity of soil using this approach would include allowance for the cropping history of the soil, especially the use of legumes in the cropping system, in addition to seasonal effects – such as soil moisture, temperature, and crop. This type of approach is particularly useful for eventual extension applications. However, for the development of the basic research models necessary for such extension applications, it has severe limitations. The major problem is that the causes of the variations in N supply between years will not be known (and usually are assumed by correlation with "likely" environmental factors) unless studies are made to specifically identify them.

Total Soil N Supply

Estimating the total soil N supply, i.e., seasonal or annual mineralization of soil organic N, is much more difficult than assessing the net supply. Nevertheless, in association with estimates of nitrogen losses, these estimates offer a much better understanding of the factors influencing soil N supplies.

The simplest approach is to predict the amount of nitrogen mineralized on the basis of the total nitrogen content of a soil and the known decomposition rates of organic matter, as given by the equation commonly used to describe the annual changes in soil nitrogen:

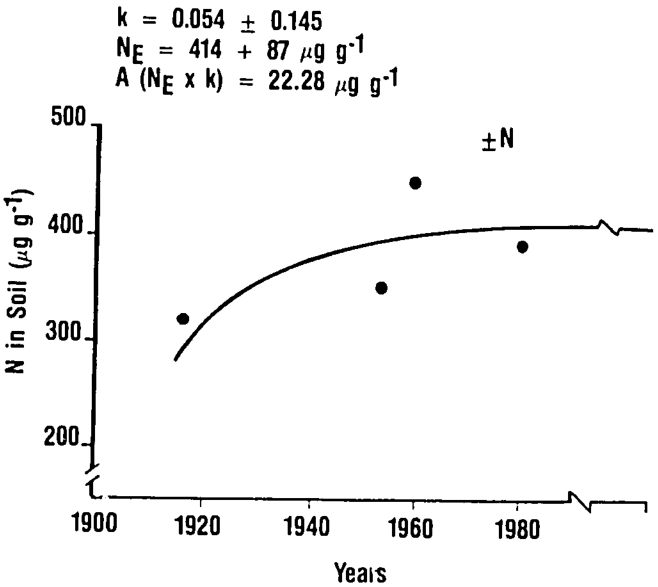
$$dN/dt = -kN + A$$

where k is the decomposition rate.
N is the total amount of soil nitrogen.
A is the annual return of nitrogen.

This equation, of course, is the simplest. Modifications involve the introduction of terms to include the contributions by fertilizer and changes in the annual return of nitrogen with different crops (Russell, 1975).

The use of this basic approach is hindered by the present level of knowledge for SAT soils. Few measurements of the decomposition constant have been made. By examining nine long-term experiments in India, we could get data from only one – the classic Coimbatore Old Permanent Manurial experiment – for making the appropriate calculations (Kausalya, 1982): the result, k = 0.054, appears reasonable for a continuously cultivated soil in the semiarid tropics, but the error term (±0.145) leaves us with no doubt as to the confidence that we can place on this value (Figure 1). The only other serious study in the semiarid tropics (or subtropics) appears to be the recent work of Dalal and Mayer (1986) who obtained good results for a number of soils including Black Earths (Vertisols) in the subtropical Darling Downs area of Australia.

The second impediment is that most measurements of total soil nitrogen are not accompanied by ancillary measurements of fixed ammonium. For at least some Vertisols, fixed ammonium contents are sufficiently high – 22% in the surface soil, increasing to 40% at depth (Table 2) – that the presence of N in this form needs to be recognized. The role of such fixed ammonium is not known, despite many laboratory measurements of fixed ammonium in soil. We presume that this nitrogen is not easily released and that organic N is the source that should be used for calculating mineralization rates.



Source: Kausalya (1982).

Figure 1. N Content of Soil (0-15 cm) in the Old Permanent Manurial Trial (unirrigated) at Tamil Nadu Agricultural University (TNAU), Coimbatore.

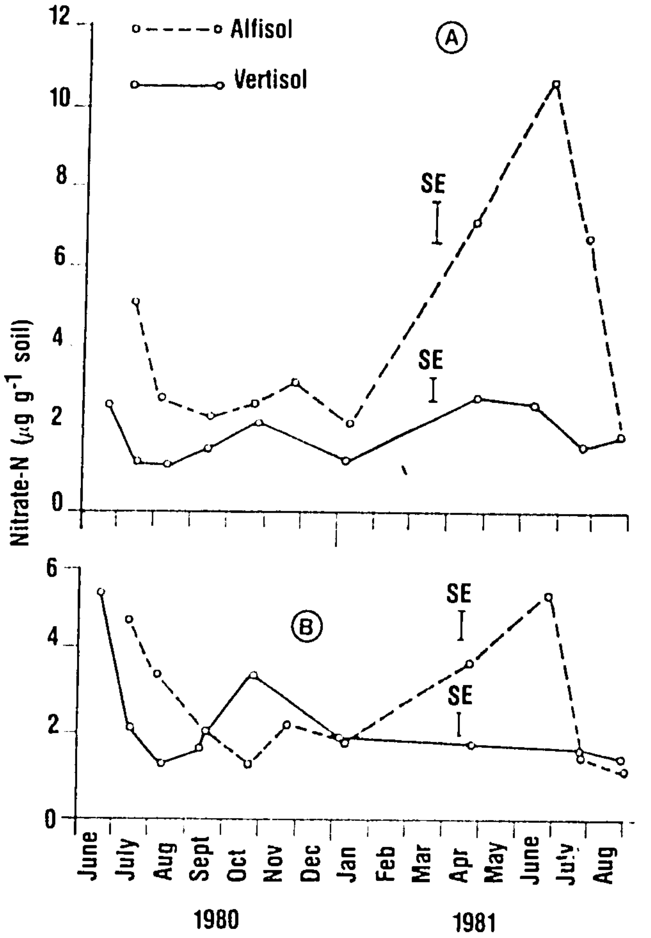
Table 2. Fixed Ammonium in the Kasireddipally Benchmark Profile at ICRISAT Center

Soil Depth (cm)	Fixed Ammonium N	Organic N
	(mg kg^{-1})	
0-15	113	371
15-30	107	278
30-60	100	231
60-90	99	205
90-120	110	208
120-150	102	174
150-170	100	145

Source: ICRISAT (1983).

The third impediment is only an apparent hindrance. The factors that determine N mineralization rates in soils include soil moisture, temperature, drying, nature of organic matter (fresh residues, C/N ratio, etc.), and soil depth (and distribution of organic matter with depth). Unfortunately all these factors act simultaneously to influence the amount of mineral N that is released and thus available to plants. Any soil N modeling exercise has to consider the overall effect of these factors on the release of mineral N. There is a dearth of data on the release of mineral N, not only in the field but also under controlled conditions, as well as on how these factors affect mineralization. Unless such data are obtained, researchers may need to resort to the use of laboratory methods for assessing the N mineralization capacity of soils. Such soil test methods – mainly those based on organic C determination, the amounts of ammonium released from soil organic matter by the oxidative action of alkaline permanganate, and aerobic and anaerobic incubation tests – have been useful for predicting nitrogen supply under controlled conditions (e.g., in the greenhouse or under irrigated agriculture). They have generally been less successful for rainfed agriculture (Indian Society of Soil Science, 1984) where the effects of variable moisture on crop growth and N mineralization have not been adequately characterized.

Although these impediments present a daunting task, selective studies on some aspects will be quite worthwhile. Regardless of whether relatively empirical or basic approaches are used to assess soil N supply, some information will be needed on environmental effects that cause major changes in soil N levels. A good example is our studies on the "Birch effect" - the flush of microbial activity that occurs on the wetting of soil that has been severely desiccated. Such a situation occurs in SAT India at the beginning of the rainy season in June, after the very hot (commonly 40°C maximum) and very dry (to <10% minimum humidity) summer season. The most interesting feature is the marked difference between our two benchmark soils - an Alfisol and Vertisol - in their mineralization following rewetting (Figure 2). The difference is reflected in their biomass (Table 3).



Source: Kausalya (1982).

Figure 2. **Seasonal Fluctuations in the Nitrate-N Contents of Surface 0-15 cm (A) and Subsurface 15-30 cm (B) Depths of an Alfisol and a Vertisol, ICRISAT Center, 1980/81.**

Table 3. **Comparison of Biomass-C Contents of Surface Soil (0-15 cm) of an Alfisol and a Vertisol, ICRISAT Center, 1981**[a]

Measurement	Alfisol	Vertisol
Biomass (μg C g^{-1} soil)	11.4±1.6	3.4±0.3
Total C (%)	0.35	0.60
Biomass-C (% of total C)	0.326	0.056

a. Sampling dates: Alfisol, August 28; Vertisol, August 25. Values are means from uncultivated and deep-cultivated plots.

Source: ICRISAT (1983).

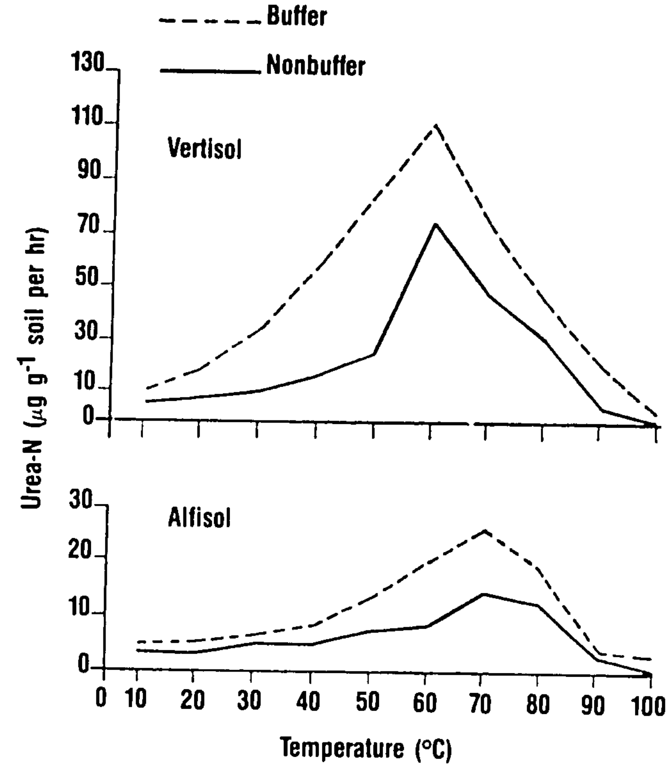
Fertilizer N Supply

The fertilizer N supply term is a much easier one to calculate because we know the total supply (which is the amount that we add). Under favorable environmental conditions, the use of fertilizer by a crop can be relatively efficient because the farmer or researcher can decide when and how to add fertilizer.

Nevertheless, appreciable losses of fertilizer N can occur, and studies of such losses are useful for indicating not only the causes of fertilizer N losses but also the losses of mineral nitrogen derived from soil organic N. These loss mechanisms will be discussed in the next section.

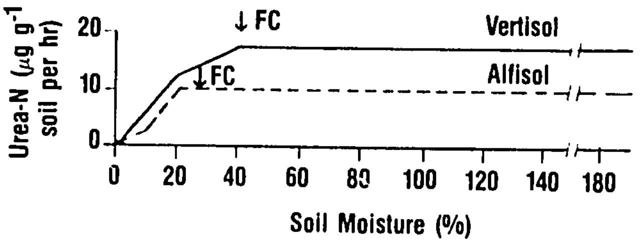
One aspect of fertilizer use needs particular consideration. Urea is the dominant form of fertilizer N used, but its use by plants depends upon the hydrolysis of urea to ammonium and subsequent oxidation to nitrate. Little serious characterization of the rates of these reactions has been made in the field, and such characterization is especially important in developing fertilizer application strategies. Urea and nitrate are readily leached, but ammonium is not; heavy rainfall would cause substantial losses if it occurred immediately after urea application or after conversion of urea entirely to nitrate.

Surprisingly, relatively little information is available on the specific environmental conditions that determine the rate of urea hydrolysis in the field. In the laboratory, urea hydrolysis was found to have a particularly high optimum temperature, 60°-70°C (Figure 3), and the rate was surprisingly constant with increase in moisture content beyond field capacity (Figure 4). Preliminary studies have indicated that laboratory measurements of the hydrolysis rate can be applied to field situations, provided that the soil temperature and moisture conditions in the field are correctly monitored (Jayakumar, unpublished data). The



Source: Sahrawat (1984).

Figure 3. Effect of Temperature on Soil Urease Activity in a Vertisol and an Alfisol. Standard Error for Comparisons at the Same Level of Temperature and Method = 1.9 μg N g^{-1} Soil Per Hour.



Source: Sahrawat (1984).

Figure 4. Effect of Moisture Content on Soil Urease Activity at 37°C. Field Capacity (FC) of Each Soil Indicated by an Arrow.

surprising feature has been the particularly high rate of hydrolysis; 100 kg urea-N ha^{-1} can be hydrolyzed to ammonium within 24 hours. The urea hydrolysis rate is dependent upon the level of urea in the soil up to very high concentrations, i.e., about 2,000 mg urea-N kg^{-1} soil.

Factors Reducing Nitrogen Supply

Around the world, the various loss processes have intermittently attracted enthusiastic attention, primarily because, in some special situations, each of these loss processes can cause substantial reductions in the amount of nitrogen available for crop growth. However, in India, the vast body of literature on crop responses to nitrogen contrasts with the minute number of reports showing that a loss process is important. While the importance of a particular agronomic yield result is frequently attributed to one or more of the soil nitrogen loss processes, almost invariably the evidence is indirect. There is an urgent need for direct measurements of particular loss processes and quantification of the relationships between such losses and environmental and/or agronomic factors. Some of the known data are given below. For these, we draw heavily upon the review by Goswami and Sahrawat (1982) and our own research at ICRISAT Center.

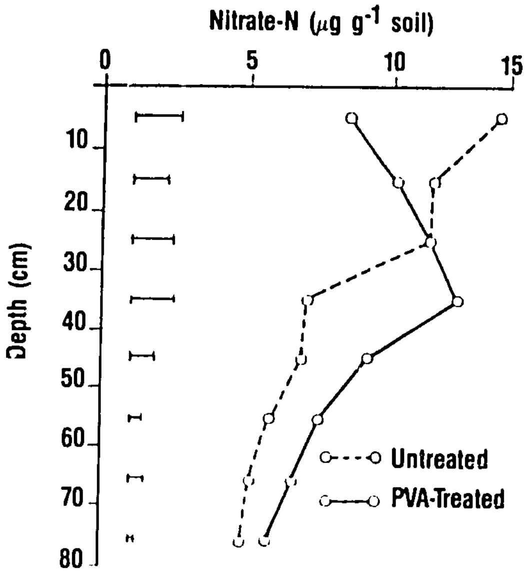
Leaching

Leaching, perhaps the oldest recognized cause of N loss, can result in substantial losses of nitrogen that are neutral (urea) or anionic (nitrite and nitrate) in form. For dryland agriculture in the SAT, losses by leaching depend upon the coincidence of heavy rainfall and the occurrence of high concentrations of such soluble N in the soil. Clearly, the use of some type of probability analysis, in association with knowledge of the forms of soil nitrogen, is required. Of note, however, is the absence of data on leaching losses from dryland agriculture in India. For example, all ten studies cited by Goswami and Sahrawat (1982) on leaching relate to irrigated agriculture or greenhouse studies; not one reported field measurements of leaching under dryland agriculture.

Highly relevant for dryland agriculture is the result of our simple study at ICRISAT Center (Figure 5). The poor structure of Alfisols is well known. Although improvement in structure may increase infiltration, with possible beneficial effects on crops because of better water resources, this additional entry into the soil may cause leaching of nitrate to a greater depth and thus place it beyond the reach of plant roots.

Denitrification

No direct measurements of denitrification have been reported under dryland agriculture in India; this contrasts



Source: ICRISAT (1983).

Figure 5. Movement of Nitrate-N in Nontreated and PVA-Treated Alfisol Under Natural Rainfall, ICRISAT Center, 1982.

with several reports demonstrating appreciable losses under paddy rice culture (De Datta and Patrick, 1986). Deficits in the recovery of ^{15}N-labeled fertilizer N are a common means of indicating losses; losses of almost 30%-from a Vertisol in a particularly wet year-can probably be attributed to denitrification (Table 4).

Substantial losses by biological denitrification can be expected on heavy-textured soils (such as Vertisols) in the higher rainfall areas of India, based on comparisons of this environment with others in which gaseous losses of nitrogen have been directly measured (Burford et al., 1981) or estimated by deficits in ^{15}N recovery (Craswell and Strong, 1976) from similar heavy clay soils in England and Australia. Because the indirect methods of assessing such losses are associated with considerable uncertainty, direct measurements of denitrification losses are urgently needed for the development of models.

Table 4. Effect of Method of Urea Application on Recovery of ^{15}N-Labeled Fertilizer N; Vertisol, ICRISAT Center, Rainy Season, 1981

Method of Fertilizer Application[a]	Recovery of Fertilizer N		Loss
	Plant	Soil	
	------ (%) -----		(%)
Broadcast	31	42	27
Broadcast + incorporated	30	45	25
Split-band	55	39	6
SE±	1.6	2.7	

a. 72 kg N ha^{-1} applied to sorghum (CSH 6).

Source: Moraghan et al. (1984).

Ammonia Volatilization

A priori, many researchers have expected losses by ammonia volatilization to be large in soils of the Indian SAT, especially if urea was applied by spreading granules onto the soil surface. Some Alfisols have a light-textured surface soil, and the increase in pH associated with urea hydrolysis would be expected to promote quite substantial losses, especially if the surface dried. Although Vertisols are heavy textured and have a high cation exchange capacity, and thus would be expected to absorb ammonia, their soil surface is alkaline and would be expected to promote ammonia volatilization. Yet few losses by ammonia volatilization have so far been clearly identified over the past 8 years of research in the IFDC/ICRISAT collaborative project at ICRISAT Center.

To quote from Goswami and Sahrawat's (1982) review, "It should be emphasized that there have been few studies on ammonia loss under field conditions, and these have been hindered by lack of techniques. . . ." We can add that, of these few studies of ammonia loss, most have examined flooded soils. Further, in addition to stressing the need for studies on dryland soils with typical variations of moisture and temperature, we emphasize the need for selecting correct techniques because of the reactivity of ammonia gas.

Direct measurements of ammonia volatilization are needed to determine the importance of this mechanism of nitrogen loss. The relevance to the semiarid environment is shown clearly by the diurnal fluctuations in losses (McGarity and Rajaratnam, 1973).

Immobilization

It is only in recent years that immobilization has been recognized clearly as a major source of N inefficiency in the immediate utilization of fertilizer N added to the soil. The proportion of fertilizer N immobilized can be as high as 40% (Table 4; Jansson and Persson, 1982), which is in agreement with the results of many N-uptake experiments. About 50%-60% of fertilizer N is recovered in a crop where losses are not suspected. Of course such immobilized N will be subsequently mineralized, but at a slow rate as with other organic N.

Interactions

The quantification of the extent and nature of nitrogen mineralization and losses in agricultural soils has been so limited that direct measurement of the various processes must be a first priority for any soil research in this area. Until this has been done and the operation of processes clearly understood in the field situations, hypotheses cannot be developed about the many interactions that we suspect will be very important.

One example of the types of interactions that will require careful consideration involves the mineralization and leaching of nitrogen in an Alfisol at the beginning of the rainy season. The first rain will cause a flush of nitrogen mineralization – the "Birch" effect – resulting in rapid accumulation of nitrate in the surface soil (Figure 2). The next rain, depending upon its amount and timing, may result in some leaching of nitrate. The entry of subsequent rainfall into the soil, and leaching, will depend on the soil surface structure as modified by treatment with the soil conditioner polyvinyl alcohol (PVA) (Figure 5), which in turn will depend upon whether the initial cultivation of the soil has commenced.

Ideally, therefore, any model to calculate fertilizer requirements will take into account the structure of the surface soil in order to determine whether such mineralized N will be accessed by roots growing downwards or whether it will be leached beyond the depth of root exploration.

Many other examples could be given, but that given above provides an indication of the complexity of the interactions involved in modeling nitrogen in the SAT environment. It requires very little imagination to picture the range of weather conditions at the beginning of the rainy season and to ponder the effects that these have on components of the soil N supply in addition to the examples given in Figures 2 and 5.

Concluding Comments

In this paper, we draw attention to the urgent need for direct measurements of a number of processes in field situations, including mineralization, urea hydrolysis, ammonia volatilization, denitrification, and leaching. Failure to quantify these soil processes will result in the inability to build accurate models for describing responses of crops to nitrogen.

One of the reasons for lack of information on nitrogen processes in SAT soils is an emphasis in recent research on agronomic studies or on laboratory studies alone. Inadequate emphasis has been given to the need for linking laboratory research to field experiments so that descriptions of soil processes are available to explain various aspects of responses (or lack of responses) to fertilizer N.

In proposing a sharper focus of research so that we can better understand soil mechanisms, there is a need to stress the importance of attention to methodology. Past research on nitrogen has produced some notable examples of the use of incorrect methods giving results that misled researchers for quite a few years afterwards. For the approaches needed in the future – the quantitative description of processes important for modeling nitrogen – failure to address the issue of methodology could be disastrous. Given an appropriate emphasis on direct measurements of processes, and attention to methodology, a great gap in our current knowledge of the soils of the SAT will be filled. This knowledge is, of course, essential for the development of models of crop behavior in response to the soil, water, and atmospheric environment.

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Nitrogen Fertilizers – Their Use and Management in the Indian Semiarid Tropics

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Abstract

This paper reviews the status of N use in the Indian semiarid tropics (SAT). The main focus of the paper is N use efficiency by crops in the SAT vis-à-vis diversity in the characteristics of the soils and striking inconsistencies in rainfall across the years and the seasons. Historically, N fertilization of crops in the SAT has been considered to be a risky investment. Research over the last 15 years has dispelled this belief. Now it is clearly established that fertilization of soils in the SAT with N is highly profitable. The extent of benefits from the use of N fertilizers fluctuates with soil depth and seasonal rainfall. With deep soils which exhibit good moisture-holding characteristics, response to N is higher, and it is stable across contrasting rainfalls. With shallow soils, which exhibit poor moisture-holding characteristics, response to N is low, and it decreases with increasing rainfall. The decrease in N use efficiency with the latter group of soils is a result of N loss, mainly through denitrification. A high N loss from shallow soils is accompanied by a low crop N recovery. Split applications of N over the growing season and their placement at a depth in bands are management strategies that can maximize N use efficiency and minimize risks of total fertilizer loss during years with aberrant weather.

Introduction

Fertilizers have played an undisputed dominant role in the burgeoning of India's food-grain production from 71 million tonnes during 1965/66 to nearly 150 million tonnes during 1985/86 (FAI, 1986). Among the major plant nutrients, nitrogen has had a principal influence on this impressive record in food-grain production, apparently because crop needs for N are high and it is universally deficient in Indian soils. With a consumption of 5.7 million tonnes of N during 1986, India ranks fourth in N consumption only after China (13.4 million tonnes), U.S.S.R. (11 million tonnes), and the United States (9.5 million tonnes) (FAO, 1987). Uninterrupted expansion in fertilizer N use is crucial in maintaining agricultural productivity because (1) high yields of modern crop varieties remove more nutrients from soil, particularly N, and (2) many Indian soils are incapable of maintaining N in adequate amounts without fertilization. Semiarid tropical soils are exceptionally low in organic matter, the main source of soil-available N. Compared with the 2% to 4% organic carbon content of semiarid soils of the temperate environments (Dudal, 1965), SAT soils contain less than 1% organic carbon, and their total N content seldom exceeds 0.1% (Tandon and Kanwar, 1984). Fertilization with N is therefore necessary for efficient use of SAT soils. This paper reviews the status of N use in the Indian SAT. Different elements of the SAT environment and their interaction with N use and efficiency are discussed. Management options are viewed from the point of diversity in the characteristics of soils and contrasts in rainfall across the years and the seasons.

Current Status of N Use in SAT

With the currently available fertilizer consumption statistics, it is not possible to pinpoint the rate of fertilizer N use by rainfed SAT crops in that fertilizer use figures do not distinguish fertilizer use between rainfed and irrigated crops. Thus, fertilizer use data on rainfed crops are severely vitiated by the fertilizer use data on the preferentially fertilized irrigated crops grown within the unirrigated districts. According to a survey by Jha and Sarin (1980), mean consumption of major plant nutrients (NPK) in 112 rainfed SAT districts with less than 25% irrigated area was 18.5 kg ha^{-1}. The corresponding mean nutrient consumption was 57.5 kg in 78 irrigated SAT districts. At a given level of irrigation, fertilizer use fluctuates with the amount of seasonal rainfall and type of crops grown. For example, fertilizer N use in the Kutch district with a mean annual rainfall of less than 322 mm and irrigated area less than 10% has been static at between 4 and 6 kg N ha^{-1} over the last 18 years (FAI fertilizer use statistics for Western India). The corresponding fertilizer N use in Amreli district (irrigated area also less than 10%) with a mean annual rainfall of 511 mm ranged between 15 and 25 kg N ha^{-1}. Because of the high value of cash crops (cotton), fertilizer N use on these crops generally exceeds that on noncash crops (Parmar, 1979). As a result of the existing apathy towards fertilizer use, the soils of the SAT are being continuously depleted of their nutrient reserves, including N. In order to attain the projected improvements in levels of productivity, expansion in fertilizer N use in the Indian SAT is necessary.

Response of Crops to N Application

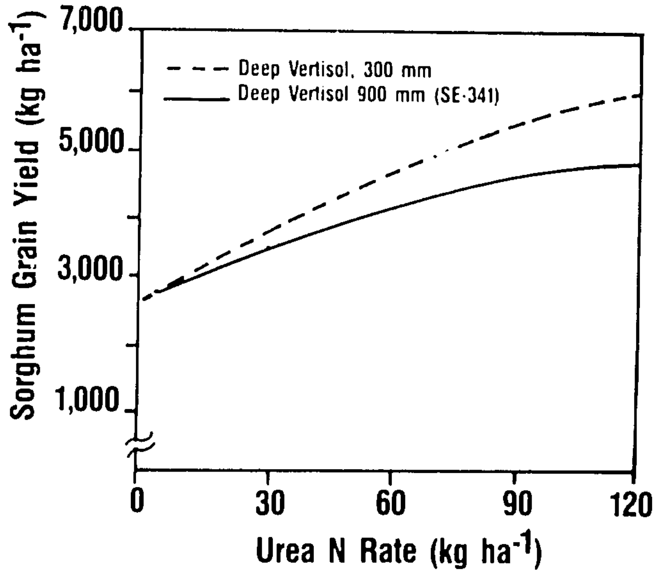
Historically, benefits from applications of organic manures (farmyard manure [FYM], compost, and green manure) to rainfed crops were explored (Kanitkar et al., 1960). A series of experiments on rainfed crops involving organic manures (5.0 tonnes ha^{-1} FYM or 2.0 tonnes ha^{-1} fresh green manure) was conducted over a decade (1928-38) at the five then-established dryland research stations – Sholapur, Raichur, Hagari, Bijapur, and Rohtak. As a consequence of organic manure treatment, crop yields improved by 20% to 50% (over no manure grain yield of 150 to 400 kg ha^{-1}). Mineral fertilizers were neglected because their application was considered ineffective in yield improvement on several soil types and across most of the seasons. During the 1950s, the attention in dryland regions focused on soil conservation measures. It was only in the late 1960s or early 1970s that serious efforts on fertilizer use research in dryland regions started. Since then, a positive and significant response to fertilizer N (generally in conjunction with P) with rainfed crops has been reported from the Indian SAT (IARI, 1970; Kanwar et al., 1973; Mahapatra et al., 1973; Venkateswarlu and Spratt, 1977; Spratt and Chowdhury, 1978; Randhawa and Venkateswarlu, 1980; Kanwar and Rego, 1983; Tandon and Kanwar, 1984; and El-Swaify et al., 1985). Sorghum, millet, oilseeds, cotton, and wheat were the test crops of this research. Each kilogram of fertilizer N was able to produce an additional grain yield of 10 to 30 kg across sharply differing rainfall environments and variable soil types.

Results of a 7-year research study conducted jointly by the International Fertilizer Development Center (IFDC) and the International Crops Research Institute for the Semi-Arid Tropics (ICRISAT), conclusively established that fertilizer N offers considerable potential for increased yield of sorghum on Vertisols and Alfisols in dryland regions (Table 1). Invariably, rainfed crops with fertilizer application could withstand drought longer because of healthy growth and a more extensive root system.

Table 1. Agronomic Efficiency of Urea-N as Influenced by N Rate, Rainfall, and Depth of SAT Soils (kg sorghum grain kg^{-1} N)

Soil	Rainfall (mm)	Check Yield (kg ha^{-1})	Agronomic Efficiency 30-40 kg N ha^{-1}	Agronomic Efficiency 60-80 kg N ha^{-1}
Deep Vertisol	913	1,500	26	29
	907	2,720	24	34
	674	3,380	14	14
	516	2,870	0	40
	322	3,270	33	31
Deep Alfisol	907	1,590	51	38
	674	5,230	0	11
	516	3,240	49	28
	322	1,490	15	25
Shallow Vertisol	913	670	14	21
	485	1,310	31	37
	322	3,390	30	18
Shallow Alfisol	485	1,440	23	17
	322	2,120	19	9

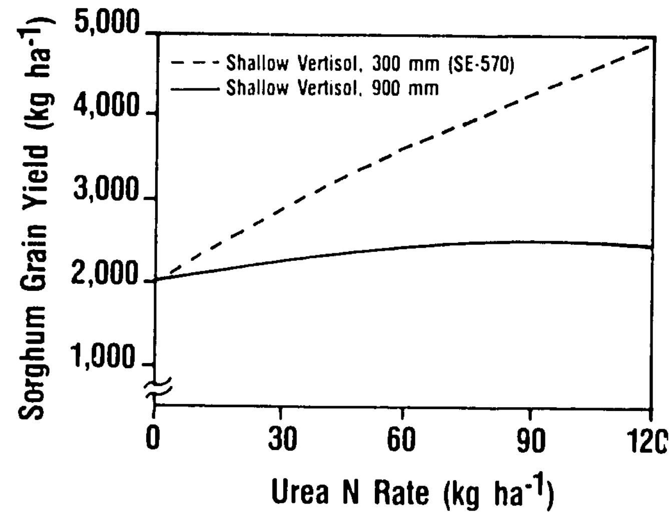
Source: IFDC/ICRISAT Joint Project.



Source: IFDC/ICRISAT Joint Project.

Figure 1. Grain Yield Response of Sorghum to Nitrogen on Deep Vertisols as Affected by Rainfall.

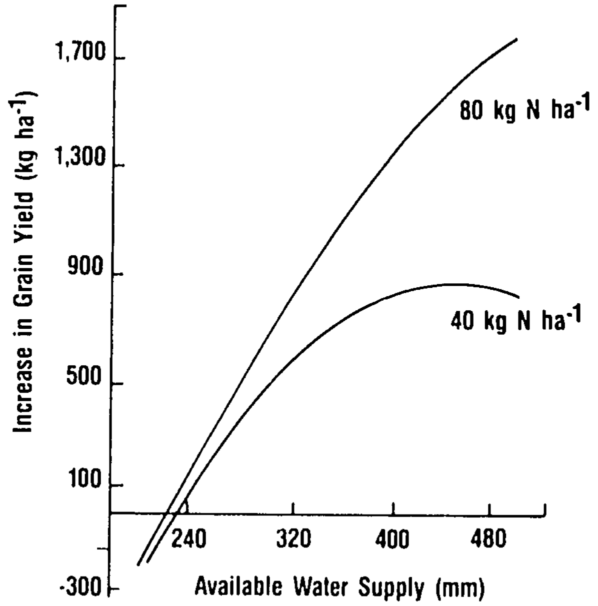
In these studies, as shown in Figures 1 and 2, crops responded to applications of up to 60 kg N ha^{-1}, and yields leveled off at about 90 kg N ha^{-1}. Shallow soils (depth <50 cm) were exceptions in that grain yields leveled off at



Source: IFDC/ICRISAT Joint Project.

Figure 2. Grain Yield Response of Sorghum to Nitrogen on Shallow Vertisols as Affected by Rainfall.

N application rates higher than 30 kg N ha^{-1} (Katyal et al., 1987). With post-rainy-season crops (Rabi season), the levels of application and response are governed by the moisture stored in the soil (Figure 3) (Prihar et al., 1981). Computations relating stored water with fertilizer use were provided by Singh et al. (1975). In general, post-rainy-season crops produced less response to N fertilizers than that obtained in the rainy season (Table 2).



Source: Prihar et al. (1981).

Figure 3. Response of Rainfed Wheat to Added Nitrogen as a Function of Available Water Supply.

Table 2. Agronomic Efficiency of Urea-N in Wet (Kharif) and Dry (Rabi) Seasons (kg sorghum grain kg^{-1} N)

Kharif		Rabi	
N Rate (kg N ha^{-1})	Yield Response (kg grain kg^{-1} N)	N Rate (kg N ha^{-1})	Yield Response (kg grain kg^{-1} N)
40	27	30	14
80	24	60	15

Source: Venkateswarlu (1979).

Fallowing, an age-old practice in the Indian SAT, is an important strategy to conserve soil fertility and moisture. As a consequence of fallowing, the productivity of crops is generally augmented. Recent research (Table 3 and Katyal et al., 1987) confirmed the benefits of fallowing to a post-rainy-season crop provided the rainfall during the rainy season was normal to low. Excessive rainfall during the rainy season severely limited the benefits of fallowing. During high-rainfall years, erosion, runoff, percolation, and NH_3 volatilization led to a considerable loss of topsoil and nutrients (Kanwar and Rego, 1983). The implication is that the extent of advantages from fallowing is not universal and will vary with the rainfall during the rainy season.

Table 3. Seed Yield of Rabi Season Safflower as Affected by Preceding Crop, Kharif Rainfall, and N Rate

Kharif Rainfall (mm)	N Rate (kg N ha^{-1})	Grain Yield Fallow-Safflower	 Sorghum-Safflower
		------- (kg ha^{-1})	------
516	0	1,470	630
	60	1,960	-
SEM		90	
913	0	530	690
	60	1,460	-
SEM		108	

Source: IFDC/ICRISAT Collaborative Research Project.

Fertilizer N Use Efficiency

Fertilizer N use efficiency assumes different meanings for different purposes. From a practical standpoint, fertilizer N use efficiency is defined as the capacity of the fertilizer N to increase yield over that of plots with no N application. This is also referred to as "agronomic efficiency" and is usually expressed as kilogram grain yield (more appropriately economic yield) increase per kilogram of fertilizer N. Agronomic efficiency refers to a particular rate of N application.

Because N is capable of permanently escaping from the soil-plant system, soil scientists are often interested in quantifying the proportion of fertilizer N (1) absorbed by the crop and (2) lost from the crop's point of use. The fertilizer N fraction absorbed by the crop connotes fertilizer N recovery, or apparent N recovery (ANR) if the "difference method"[1] is the basis for computation. ANR includes a part of soil N that is absorbed because applied N can influence the transformation of native soil N and because it also improves plant growth, leading to a higher recovery of soil N. In order to exclude the contribution of soil-N to the growing crop, ^{15}N-labeled fertilizers are employed. With that approach, it is possible to ascertain more exactly the fertilizer N recovered by a crop (^{15}N recovery). The ability of the fertilizer N absorbed by the crop to increase yield is referred to as physiological efficiency. Physiological efficiency reflects the efficiency with which fertilizer N absorbed by a crop is translated into grain yield. In effect, agronomic efficiency is a function of N recovery and physiological efficiency (Novoa and Loomis, 1981). Factors influencing the plant's ability to recover N and its ability to utilize this N for grain formation exert a major control on agronomic efficiency.

Chemical makeup of N fertilizers (whether the N is in the form of nitrate, ammonium, amide, or a combination of these) and the plant-usable forms arising from their transformations in soil strongly influence the fertilizer N recovery by a crop. The site in the soil where the fertilizer N transformations take place determines (1) the accessibility of usable forms of N to plant roots and (2) exposure of those forms to various N loss processes. Precipitation, the only source of water in the SAT, moderates N uptake and recovery by influencing plant growth. It also plays a dominant role in fertilizer N recovery via fertilizer N transformations (urea hydrolysis and nitrification), mobility, and loss. Soil temperature regulates the rate of these processes.

Thus, the following essential elements predominantly control N use efficiency by crops grown in the SAT:

1. Precipitation and, associated with it, the soil's moisture-holding characteristics, which are influenced by soil texture and depth (Table 4).
2. Form of N source.
3. Method of application.

Table 4. Moisture Storage Capacity of Different SAT Soils

Soil Group	Subgroup (depth in cm)	Moisture Storage (mm)
Vertisols	Shallow (<45)	135-145/45 cm
	Deep (>90)	300/m
Alfisols (Luvisols)	Shallow (<45)	40-70/45 cm
	Deep (>90)	200-220/m
Sierozam	Medium to deep (up to 90)	80-90/90 cm

Source: Randhawa and Sinha (1985).

The SAT soils are extremely dry before the onset of the southwest monsoon. Urea, the principal N fertilizer in India (FAI, 1987), does not hydrolyze when applied to air-dry soils (Sahrawat, 1984). As moisture and temperature increase, the rate of hydrolysis increases. This suggests that urea application coinciding with dry seeding–a management practice recommended by ICRISAT for SAT Vertisols (Virmani et al., 1981)–will not lead to significant N loss in that urea has to hydrolyze to NH_4^+-N before it is subject to loss (unhydrolyzed urea can leach, though this is a remote possibility in the SAT).

Results from studies conducted jointly by IFDC and ICRISAT (Table 5) suggest that high recoveries of ^{15}N-labeled urea can be achieved by the plant (≈55%) with

Table 5. Fate of Fertilizer N (^{15}N-Labeled Urea Placed by Split Band Method) in SAT Soils (Crop: Sorghum)

Soil	Rainfall	Apparent N Recovery	^{15}N Recovery Plant	^{15}N Recovery Soil	^{15}N Loss
	(mm)	(%)	- - (%)- - -		(%)
Deep Vertisol	907	58	56	37	7
	516	74	56	35	9
	322	78	56	37	7
Deep Alfisol	907	88	64	29	7
Shallow Vertisol	913	37	36	35	29
	485	54	41	29	30
Shallow Alfisol	485	44	46	25	29

Source: IFDC/ICRISAT Collaborative Research Project.

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[1] $$\text{Apparent N recovery} = \frac{\text{N uptake with nitrogen fertilizer} - \text{N uptake without fertilizer}}{\text{Fertilizer N applied}} \times 100$$

Table 6. Effect of Urea-N Application Methods on Grain Yield of Sorghum, ^{15}N Recovery by Sorghum Crop, and ^{15}N Loss (Deep Vertisol)

Treatment	Rainfall = 516 mm[a]			Rainfall = 907 mm[b]		
	Grain Yield	^{15}N Recovery	^{15}N Loss	Grain Yield	^{15}N Recovery	^{15}N Loss
	(kg ha^{-1})	(%)		(kg ha^{-1})	(%)	
Control	2,870	-	-	2,720	-	-
Split band	5,270	56	9	5,220	56	6
All basal broadcast	5,650	44	18	4,260	31	28
Surface incorporation	-	-	-	4,110	29	26
SEM	180	-	-	225	-	-

a. IFDC/ICRISAT Collaborative Research Project.

b. Moraghan, Rego, Buresh, Vlek, Burford, Singh, and Sahrawat (1984).

limited losses of N (<10%). This trend was particularly pronounced in the deep soils when urea was applied in split bands (half of the N applied at the time of seeding and the remaining half 1 month later; each N split placed in bands 5-7 cm deep and 5-7 cm away from the seed row and covered with soil).

Methods of Application

As shown in Table 6, in a year of average rainfall (seasonal rainfall 516 mm), urea application on the surface did not lead to excessive N loss when compared with its placement in bands (18% versus 9%). In contrast, in a good-rainfall year (rainfall 907 mm), surface-broadcast urea suffered a heavy N loss (28%), whereas the N loss from urea placed in bands continued to be low (6%). It is possible that low soil moisture in an average-rainfall year restricted urease activity (Sahrawat, 1984) and consequent buildup of NH_4^+-N and its volatilization at the surface of the soil. A similar argument was advanced to explain the lack of ammonia (NH_3) volatilization from surface-applied urea in Northern Australia (Myers, 1978). In variance with dry soils, surface placement of urea on wet soils aggravates NH_3 volatilization. Despite limited urea hydrolysis, leading to low N loss, there is little justification for recommending broadcasting of fertilizers on the surface of drylands. In a sole cereal system with wide row spacing, broadcasting of fertilizers will allow weeds better access to the fertilizer. In the cereal/legume intercropping situations, which are very common in the tropics, broadcasting of N fertilizers will provide N to the legume component, which is unnecessary. Subsurface banding near the crop row will increase the N efficiency because of better access to the roots and less chance of losses via NH_3 volatilization, runoff, and immobilization. The bulk of the evidence generated thus far favors the soundness of placing N fertilizers in the moist subsurface (Table 7).

Table 7. Placement Versus Broadcast: Grain Yield Gains

Crop	Yield Gain (kg ha^{-1})	Source	Remarks
Pearl millet	668	IARI (1970)	Sandy loam (774 mm)[a]
Sorghum	1,130	Venkateswarlu (1979)	Mean of five experiments
Sorghum	1,100	Moraghan, Rego, Buresh, Vlek, Burford, Singh, and Sahrawat (1984)	Vertisol (786 mm)
Sorghum	1,500	Moraghan, Rego, and Buresh (1984)	Alfisol (766 mm)
Sorghum	660	IFDC/ICRISAT	Vertisol (512 mm)
Sorghum	340	IFDC/ICRISAT	Shallow Vertisol (397 mm)

a. Figures in parentheses indicate seasonal rainfall.

Deep placement of fertilizers is of utmost significance in a receding moisture situation (post-rainy-season cropping) where the root activity declines in the rapidly drying surface layers. Chaudhary and Prihar (1974) reported that, compared with broadcast application, placement of fertilizers 20 cm below the seed rows produced more than a twofold increase in wheat yield. Deep placement also led to greater extraction of water from layers below 60 cm (Prihar et al., 1977). Katyal et al. (1987) reported a significant improvement in agronomic efficiency with decreasing distance of the fertilizer row from the seed row.

Past research on N use efficiency reviewed by Katyal et al. (1987) showed that the situation with shallow soils (soil depth <50 cm) was strikingly different from that with deep soils. Nitrogen-15 recovery was low (≈40%), and loss was high (≈30%) (Table 5). Differences in soil moisture regimes (J. C. Katyal and L. S. Holt, unpublished report), following a rainfall event, predominantly explain the variable N loss from shallow and deep soils. Because of poor water-retention characteristics (Table 4) arising from textural discontinuity, i.e., hard pan, (Pratt et al., 1972), a shallow soil is likely to become saturated more often, and with that, anoxic conditions set in (Firestone, 1982). Consequently, (1) nitrification – an aerobic process – is obstructed and (2) denitrification – a process of anaerobic environment – is likely to be promoted. Thus, shallow soils are more likely to lose N through denitrification. Denitrification in SAT soils, which are deficient in organic carbon (1.0%), may be sustained by crop root exudates (Firestone, 1982). A high N loss from shallow soil parallels the lower agronomic efficiency with which N is used (Tables 1 and 5). Apparently, the contribution of denitrification to N loss is likely to increase with increasing rainfall, and thus agronomic efficiency will decline. Agronomic efficiency (Figure 1) in a high-rainfall year was significantly lower than in a low-rainfall year. In contrast, fluctuations in rainfall had less influence on agronomic efficiency (Figure 2) in deep soils.

Sources of N

The forms of fertilizer and their transformation products respond differently to moisture fluctuations in SAT soils. It has already been mentioned that urea hydrolysis does not proceed under air-dry conditions. Contrarily, nitrification of ammonium, the hydrolysis product of urea, will be decelerated when saturated (anaerobic) conditions prevail. Under those circumstances, nitrate-containing fertilizers will tend to denitrify, whereas urea may be protected. As explained earlier, denitrification is less likely a problem with deep soils, which exhibit better water-holding characteristics. Therefore, it is logical to believe that the efficiency of urea and potassium nitrate (KNO_3) – a source vulnerable to denitrification – will not vary with rainfall when both these N sources are tested on deep soils. Results presented in Table 8 confirm this contention in an average-rainfall year (rainfall 516 mm), and further support to this hypothesis is provided by the findings that even in a good-rainfall year (rainfall 733 mm) agronomic efficiency and ^{15}N recovery were identical for urea and sodium nitrate.

Urea and KNO_3, however, performed differently when tested on shallow soils (Table 8). Results of a 2-year study

Table 8. Effect of Source of N Application to Sorghum on Grain Yield, ^{15}N Recovery by Crop, and ^{15}N Loss

	Rainfall = 516 mm[a]			Rainfall = 733 mm[b]		
Source of N	Grain Yield	^{15}N Recovery	^{15}N Loss	Grain Yield	^{15}N Recovery	^{15}N Loss
	(kg ha^{-1})	------- (%) --------		(kg ha^{-1})	---------- (%) ----------	
Deep Vertisol						
Control	2,870 b	-	-	3,380 b	-	-
Urea	5,280 a	56	9	4,470 a	53 a	-
KNO_3	5,390 a	66	8	4,480 a	61 a	-
	Rainfall = 485 mm[a]			Rainfall = 370 mm[a]		
Shallow Vertisol						
Control	1,310 c	-	-	1,690 b	-	-
Urea	3,560 a	41	36	4,060 a	39 b	21 a
KNO_3	2,870 b	26	64	4,340 a	55 a	18 a

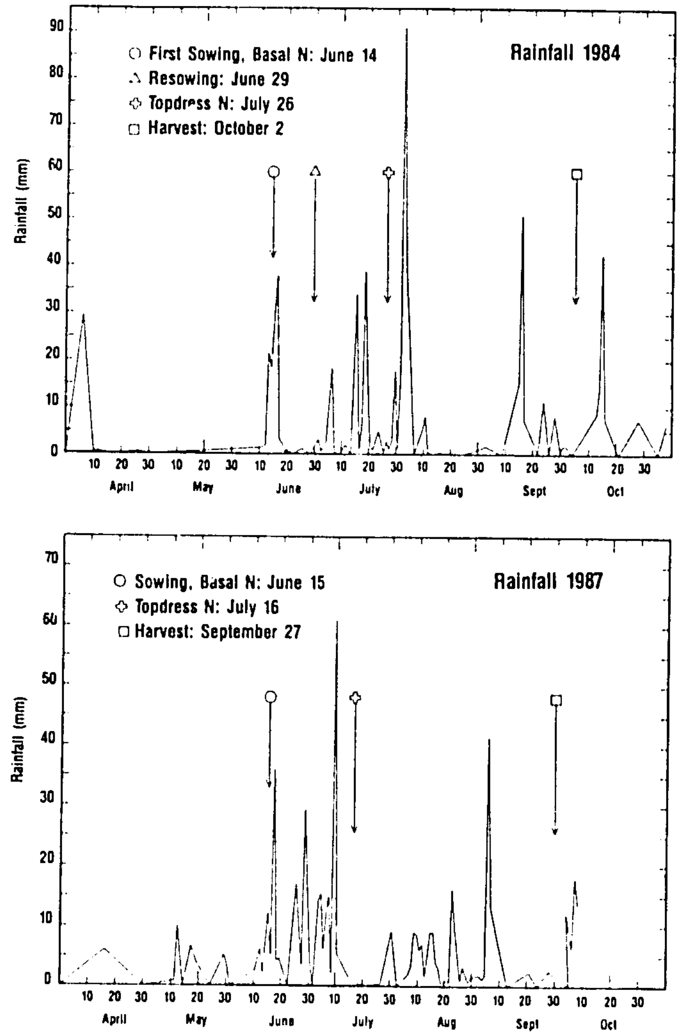
a. IFDC/ICRISAT Collaborative Research Project.

b. Moraghan, Rego, Buresh, Vlek, Burford, Singh, and Sahrawat (1984) - $NaNO_3$ substituted for KNO_3.

Note: Means followed by the same letter are not significantly different ($P = 0.05$).

involving urea and KNO₃ explicitly explain the interaction of moisture and form of fertilizer.

The rainfall during the two cropping seasons varied: 485 mm during 1984 and 370 mm during 1987. The rainfall distribution also differed between the 2 years (Figure 4). During the high-rainfall year, urea outperformed KNO₃, whether the criterion was agronomic efficiency or ^{15}N recovery (Table 8). Potassium nitrate-N suffered a loss of 64%; the corresponding loss of urea-N was 36%. In the low-rainfall year, total N loss and the pattern of N loss diverged markedly from those observed in the high-rainfall year; agronomic efficiency, ^{15}N recovery, and loss were at par for KNO₃ and urea (Table 8). Regardless of source, the N loss was lower in the year of below average rainfall.



Source: IFDC/ICRISAT Joint Project.

Figure 4. Rainfall Distribution (April-October) During 1984 and 1987.

Rainfall events, specifically those coinciding with fertilization, explain the inconsistent performance of KNO₃ or urea (Figure 4). During 1984, a heavy rainfall followed fertilization both at seeding and at topdressing 1 month later. With that, conditions necessary for denitrification developed, and KNO₃ – a source vulnerable to denitrification – suffered an excessive N loss. In variance, it is possible that, because of the low and evenly distributed rainfall during 1987, the soil did not become saturated. Consequently, KNO₃ did not become prone to denitrification, which explains the parity between KNO₃ and urea in agronomic efficiency, ^{15}N recovery, and loss.

Research under controlled conditions (J. C. Katyal and L. S. Holt, unpublished report) has established denitrification as the principal mechanism of N loss from saturated SAT soils. The contribution of ammonia volatilization to overall N loss is minimized with placement. The possibility of runoff also decreases when N fertilizer is placed at a depth in bands. Present evidence, though limited, does not support leaching as a significant avenue of N loss from SAT soils.

Time of Application

Because of sharp contrasts in rainfall patterns across the years and seasons and the unstable and risky nature of agriculture in the SAT regions, there is no justification for a single application of N fertilizers to rainy-season crops. Furthermore, the bulk of the evidence supports the superiority of divided applications of N in two or three splits (Table 9) to a single application. Apart from agronomic

Table 9. Effect of Time of N Application (One-Time Application Versus Split Applications) on Grain Yield of SAT Crops

Crop	Time of N Application	Grain Yield (t ha^{-1})
Finger millet (*Eleusine coracana* Goertn.)	All at planting	2.5
	Three splits	2.8
Maize (*Zea mays* L.)	All at planting	3.5
	Three splits	3.8
Sorghum (*Sorghum bicolor* L.)	All at planting	0.9
	Two splits	1.3
Pearl millet (*Pennisetum americanum* L.)	All at planting	0.9
	Three splits	1.4

Source: Spratt and Chowdhury (1978).

superiority, split application is a viable fertilizer management strategy because it allows the farmer to make midseason adjustments: (1) in a year with poor rainfall to withhold further fertilizer application and (2) in a season with good rainfall to apply an additional dose to make use of the rainfall that was not foreseen at planting time.

Standard Agronomic Practices

Irrespective of the proper selection of fertilizer sources and their methods and timings of application, N use efficiency cannot be maximized without proper attention to a standard set of agronomic practices. These include proper tillage methods, application of other limiting nutrients, choice of disease- and pest-resistant modern varieties, maintenance of intra- and interrow plant spacing, weed control and moisture conservation practices (mulching).

Conclusion

In conclusion, N fertilization of SAT crops is a sound practice because it minimizes the element of uncertainty by improving crop growth and promoting better use of limited water. Fertilization of SAT crops, in fact, is highly economical (Katyal et al., 1987) in that fertilizer use efficiency is high and losses are low. Placement of fertilizers and their split application are necessary elements of good fertilizer management. Because of variability in rainfall and the associated wide spectrum of moisture regimes, choice of fertilizer N sources will depend upon the depth of soil. Nitrate-containing fertilizers are a poor choice for shallow soils, which tend to develop conditions conducive to N loss through denitrification. Urea (or ammonium-containing fertilizers) should be the preferred N source for shallow soils. For deep soils, the choice of fertilizers is less important. The role of nitrification inhibitors in preventing denitrification of fertilizer N is an important area of research for the future.

An intensive cultivation approach, involving a package of improved crop husbandry, is essential to maximize benefits from N fertilization.

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Management of Fertilizer Nutrients Other Than Nitrogen in the Semiarid Tropics of India

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Abstract

Available information on the management of fertilizer nutrients other than nitrogen in the semiarid tropics (SAT) of India (about 96 million ha) is reviewed. Crop responses to fertilizer nutrients are high under dryland conditions. Phosphorus and then zinc are of major importance for the nonirrigated SAT, but significant yield responses to potassium and sulfur, in addition to P and Zn, are also obtained under dryland conditions in the reddish brown lateritic soils of the Bangalore area. Iron chlorosis is increasingly being mentioned as a problem in the SAT. Available information on P, K, S, Zn, and Fe has been reviewed by continuously searching for information applicable to rainfed systems in irrigation-oriented overall research in nutrient management and soil fertility even for major dryland crops. Suggestions for further research have been made for the nutrients reviewed.

Introduction

The SAT cover nearly two-thirds of the 143 million ha net cropped area in India. Two-thirds of the SAT area does not have access to conventional irrigation, and farming systems are mostly rainfed/dryland. The SAT areas are spread over ten states (Andhra Pradesh, Gujarat, Haryana, Karnataka, Madhya Pradesh, Maharashtra, Punjab, Rajasthan, Tamil Nadu, and Uttar Pradesh). The nonirrigated SAT areas occur primarily in central Andhra Pradesh, Gujarat, Karnataka, Madhya Pradesh, Maharashtra, and eastern Rajasthan.

Improving the productivity of the nonirrigated SAT is crucial for the future development of Indian agriculture, the well-being of millions of farmers who live off these lands, and the production of high-value crops such as pulses, oilseeds, and cotton. Three statements concerning the SAT/drylands are often made: (1) the drylands are more hungry than thirsty; (2) lack of water management, not lack of water, is a key constraint in many areas; and (3) by growing suitable varieties and adopting improved soil-water-fertilizer management practices, crop yields can be increased substantially without irrigation.

This paper reviews available research on the management of fertilizer nutrients other than nitrogen in the semiarid tropics of India. The nutrients covered are phosphorus, potassium, sulfur, zinc, and iron because these are considered to be of sufficient practical importance at present and/or in the near future. Results discussed pertain mostly to nonirrigated conditions. Discussion on N is included only where it is a component of nutrient interactions or for the complete description of a system.

Research Scenario and the Development of Fertilizer Use

Soil fertility and fertilizer use have been important components of agricultural research in India. However, specifically for rainfed/dryland systems, apart from field experiments to study fertilizer responses, research has always been and continues to be glaringly weak. This is because research on SAT soils or crops grown on them often includes liberal application of water. Research programs that have studied crop responses to nutrients under nonirrigated conditions have not gone into nutrient dynamics, balances, or soil fertility/crop response correlations. Virtually the entire research effort of otherwise well-developed, coordinated research programs such as on soil test/crop response correlations, long-term fertilizer experiments, and secondary and micronutrients is under irrigated conditions.

The net result of the above scenario is that, except for data on field responses to nutrient applications, detailed information on nutrient management, transformations, balances, and interactions is either lacking, piecemeal, or derived from data pertaining to fully or partially irrigated conditions. It is important to recognize this feature in order to initiate realistic, in-depth research programs aimed at providing answers to questions on nutrient management that are specific to the unirrigated SAT agriculture.

It is a well-known fact that fertilizer use in India, which is at present 9 million tonnes nutrients, continues to be confined largely to irrigated areas or to nonirrigated cash crops. Fifty percent of the total fertilizer is consumed in only 69 of the more than 350 districts. In a general analysis, the mean fertilizer consumption in predominantly nonirrigated SAT districts was 31% of that in the predominantly irrigated SAT districts (Jha and Sarin, 1984). Since irrigated and nonirrigated holdings coexist in a given district or village, small pockets of irrigated lands in predominantly rainfed areas can dominate the fertilizer-use pattern.

Dryland cereals, millets, pulses, and oilseeds probably receive very little fertilizer other than some N on the high-yielding varieties (HYVs) and some P on groundnut. A fertilizer demand study had projected that the share of sorghum and pearl millet in the "effective demand" in 1986/87 could be 3.0% of the total demand for N, 2.2% for P, and 1.7% for K, even though these two crops occupy 15% of the gross cropped area (NCAER, 1978).

There is a lack of systematic surveys and monitoring of fertilizer application rates and management practices actually used by the farmers. The application of P is recommended for most dryland crops while recommendations for K, S, and Zn are gradually emerging for specific soil-crop conditions.

Role of Nutrients in Dryland Crop Production

At the research level, the importance of fertilizer nutrients is well recognized for increasing the yields of dryland crops. With improved technology, including the use of N and P in Vertisols, Alfisols, and Inceptisols, crop production in the SAT can be substantially increased (Kanwar, 1986). Crop responses to fertilizer are high under dryland conditions (CRIDA, 1987). Deficiencies of P and Zn are quite widespread, whereas those of K, S, and Fe occur on a much smaller scale; where they do occur, however, the application of these fertilizer nutrients results in significant yield increases, as discussed later.

Nutrient uptake and removal by crops per unit yield may not be much different under irrigated and nonirrigated conditions. An idea of the amounts of nutrients absorbed by important crops to produce a tonne of economic yield is provided in Table 1, primarily as background information. The nutrient drain caused by common dryland crops is no less than the drain by irrigated crops. Application of fertilizer plus improved management techniques can increase the yield of dryland crops three- to sevenfold (Table 2).

To understand the importance of fertilizer, it must be seen as a component of the package of improved practices and not in isolation. Under well-managed conditions, using proven sorghum hybrids, grain yields of 5-6 tonnes ha^{-1} and dry-matter yields of 11-12 tonnes ha^{-1} can be

Table 1. General Estimates of Total Uptake of Nutrients Per Tonne Economic Yield

Crop	N	P_2O_5	K_2O	Ca	Mg	S	Zn	Fe	Mn	Cu	B	Mo
	(kg)						(g)					
Rice	20	11	30	7.0	3.0	3.0	40	153	675	18	15	2
Maize	26	14	36	5.4	7.8	3.8	130	1,200	320	130	-	-
Wheat	25	9	33	5.3	4.7	4.7	56	624	70	24	48	2
Sorghum	22	13	34	6.4	4.8	2.8	72	720	54	6	54	2
Pearl millet	42	23	91	-	-	-	40	170	20	8	-	-
Chick-pea	46	8	50	-	-	-	38	58	30	14	-	-
Pigeon pea	64	18	42	-	4.0	3.3	24	40	14	14	-	-
Groundnut	58	20	30	28.0	7.3	5.7	28	1,500	118	15	133	4

Source: Compilations by Kanwar and Youngdahl (1985), Kemmler and Hobt (1987), Munson (1982), Tandon and Sekhon (1988).

Table 2. Impact of Fertilizer Application on Grain Yields Under Rainfed Conditions at the ICRISAT Center

Crop	Average SAT Yield (30 Years) kg ha^{-1}	Average SAT Yield (30 Years) Base	Fertilizer Level A kg ha^{-1}	Fertilizer Level A Relative to Base	Fertilizer Level B kg ha^{-1}	Fertilizer Level B Relative to Base
Sorghum	842	100	2,627	312	4,900	582
Pearl millet	509	100	1,636	321	3,842	755
Chick-pea	745	100	1,400	188	3,000	403
Pigeon pea	600	100	1,000	167	2,000	333
Groundnut	794	100	1,712	216	2,572	324

Fertilizer Level A: 43 kg N + 20 kg P_2O_5 ha^{-1} for sorghum and millet, 20 kg N + 20 kg P_2O_5 ha^{-1} for other crops.
Fertilizer Level B: 86 kg N + 40 kg P_2O_5 ha^{-1} for sorghum and millet, 18 kg N + 46 kg P_2O_5 ha^{-1} for chick-pea and pigeon pea, 60 kg P_2O_5 ha^{-1} for groundnut.

Source: Kanwar (1986).

attained without irrigation (Sivakumar and Huda, 1983). Taking sorghum again, multi-location research has shown that the yield gap between the crop planted early and that planted during the traditional (late) period can be as much as 1.1-3.7 tonnes ha^{-1}, with obvious impact on fertilizer efficiency (Spratt and Chowdhury, 1978). Trials with grain legumes show that 25%-35% of achievable yield can be lost if fertilizer is not applied (Chandra and Ali, 1986).

The importance of nutrients in dryland agriculture needs to be seen from several angles, such as the role of P in enabling crops to grow deeper roots and absorb water from the subsoil during periods of drought, the role of K in regulating transpiration losses and bringing about water economy, the role of S in increasing total oil yield per unit area by improving seed yield as well as oil content, to cite a few examples.

Table 3. Generalized P and K Fertility Status of Some SAT Areas

State	Available Phosphorus Number of Districts Low	Available Phosphorus Number of Districts Medium	Available Phosphorus Number of Districts High	Available Potassium Number of Districts Low	Available Potassium Number of Districts Medium	Available Potassium Number of Districts High
Andhra Pradesh	17	4	0	2	13	6
Gujarat	5	13	1	0	0	19
Karnataka	15	4	0	3	9	6
Madhya Pradesh	15	30	0	3	9	30
Maharashtra	15	10	0	0	13	12
Rajasthan	1	22	3	0	5	14

Source: Ghosh and Hasan (1976, 1979).

Phosphorus

Phosphorus Status of Soils and Crops

Widespread phosphorus deficiency in the Indian SAT is one of the most limiting factors for producing high yields (De, 1988; Kanwar, 1986; Rao and Das, 1982; Tandon, 1987; Venkateswarlu, 1987). In six states that together have a cropped area of 98 million ha, 80% of which is rainfed, soils in 44% of the districts have been categorized as low in available P and those in 55% of the districts as medium in available P (Table 3). An analysis of 24 districts, which accounted for 50% of the total sorghum area, showed that the P-fertility rating was low in 15 districts and medium in 9 districts (Tandon and Kanwar, 1984).

In a survey of the P status of standing crops, the percentage of samples found deficient in P was as follows: 98% for groundnut, 24%-52% for sorghum, 28% for maize, 94% for finger millet, and 6% for pearl millet (Singh and Venkateswarlu, 1985). In Maharashtra State, a survey of 74 sorghum fields showed that the percentage of P-deficient ($<0.2\%$ P) samples was 58% in shallow soils, 42% in medium deep soils, and 27% in deep black soils (Narkhede et al., 1981). Some workers from the same state have reported that P responses are obtained only on shallow black soils (Patil et al., 1981), whereas others have reported significant responses to P on medium black soils (Nagre, 1982).

The relative abundance of common forms of inorganic P is governed largely by the degree and intensity of weathering and can be reasonably predicted by the prevailing pH. In neutral-alkaline soils, Ca-bound forms of P dominate, whereas in very acid soils, Al- and Fe-bound forms are more abundant along with the reductant-soluble and occluded forms. In a Vertisol of pH 7.5-8.2 and containing 60%-69% clay, the Al-, Fe-, and Ca-bound forms accounted for 56% of the total P and individually for 5%, 15%, and 36% of total P (Bapat et al., 1965). In the Alfisols, the order of dominance can be Fe-P > Ca-P > Al-P (Goswami and Sahrawat, 1982). The chemical/surface reactivity of the Al- and Fe-P forms has been shown to be greater than that of Ca-P, and thus the Al- and Fe-P forms are capable of making a contribution to available P that is greater than their relative abundance. Lack of data on P transformations as affected by soil and crop systems under field conditions is a missing link (Goswami and Sahrawat, 1982).

Crop Responses to Phosphorus

There is a considerable volume of data on the responses of crops to P application under a wide range of soil-climatic conditions in India (Tandon, 1987). It is necessary to mention at the outset that (1) field response data are available from both "on-station" and "on-farm" experiments and (2) yield responses by themselves may not provide the complete picture because dryland crops vary threefold in their unit market value, and thus an agroeconomic perspective is necessary while evaluating fertilizer responses. This is illustrated in Table 4.

Table 4. Break-Even Response Ratios for Some Important SAT Crops to the Application of P, K, Zn, and S

Crop	Official Procurement Price (Rs/tonne)	Kilogram Grain Needed to Pay for 1 kg Input			
		P_2O_5	K_2O	S	$ZnSO_4$
Sorghum	1,320	4.5	1.7	1.5	4.6
Chick-pea	2,800	2.1	0.8	0.7	2.1
Pigeon pea	3,250	1.8	0.7	0.6	1.8
Groundnut pods	3,900	1.5	0.6	0.5	1.5
Mustard	4,150	1.4	0.5	0.5	1.4

Procurement prices announced for 1986/87.
US $1 = Rs 14 approximately.
Prices of input: Rs 6.0 per kg P_2O_5 through SSP/DAP, Rs 2.2 per kg K_2O through MOP; Rs 2 per kg S and Rs 6 per kg zinc sulfate.

Cereals and Millets–Experiments by the All India Coordinated Research Project on Dryland Agriculture (AICRPDA) show that 30-50 kg P_2O_5 ha^{-1} increased sorghum grain yield by 9 kg per kg P_2O_5 (Singh and Venkateswarlu, 1985), and trials by the Coordinated Sorghum Project suggest a mean optimum level of 40 kg P_2O_5 ha^{-1} for sorghum HYVs in the rainy season (Singh et al., 1981). In a review of fertilizer research on sorghum, responses to P at the research stations in the rainy season were found to range between 7.3 kg and 34.3 kg grain per kg P_2O_5 (Tandon and Kanwar, 1984). The magnitude of response was generally in the order red soils > alluvial soils > black clay soils. It was also observed that (1) at similar levels of available P, a black soil could support a higher yield level than a red soil; (2) sorghum varieties exhibited differential response to P application, and their ranking for responsiveness to P was similar to their ranking for yield potential; and (3) P application increased grain yield by producing 16%-46% more grain per ear and also resulted in a 5%-22% improvement in the harvest index.

Estimates of nutrient responses based on a large number of "on-farm" fertilizer experiments without irrigation have been periodically summarized. Table 5 is

Table 5. Average Crop Responses to the Application of P and K in a Large Number of "On-Farm" Experiments in India During 1977-82, Under Unirrigated Conditions

Crop	Season	Kilogram Grain Response Per Kilogram of P_2O_5	Kilogram Grain Response Per Kilogram of K_2O
Sorghum	Kharif	7.0-10.6	5.1-8.8
Sorghum	Rabi	5.3-11.1	3.7-6.9
Pearl millet	Kharif	3.2-8.1	2.1-8.2
Blackgram	Kharif	3.0-6.2	0.8-8.4
Blackgram	Rabi	3.9-6.6	2.9-4.7
Chick-pea	Rabi	3.7-11.4	0.7-5.7
Pigeon pea	Kharif	4.6-10.7	0.3-5.6

Responses are average values of experiments in a state.
Responses for P are to 30 kg P_2O_5 ha^{-1} over 90 kg N for cereals and millets and to 40 kg P_2O_5 ha^{-1} over 20 kg N for legumes.
Responses to K are to 30 kg K_2O ha^{-1} over 60 N and 60 P_2O_5 for cereals and millets and to 20 kg K_2O ha^{-1} over 20 N and 40 P_2O_5 for legumes.

Source: Randhawa et al. (1985).

based on data reported by Randhawa et al. (1985). Unit responses to P range from 3 to 11 kg grain per kg P_2O_5. This wide range includes many dryland crops. Yields of finger millet and maize in the P-deficient reddish brown lateritic soils of Bangalore can be increased by 1-2 tonnes ha^{-1} without irrigation as a result of P application (AICRPDA, 1983b).

Pulses – Chick-pea and pigeon pea together occupy about 11 million ha, that is, nearly half of the total area under pulse crops. Low soil fertility and lack of weed control have been identified as two major constraints to improving the yield of pulses (Chandra and Ali, 1986). Among nutrients, P-deficiency is stated to be the major cause for low yields (Saraf and Ganga Saran, 1986). Grain yields of 2.5-4 tonnes ha^{-1} can be obtained with optimum fertilizer use when combined with other improved practices. Reviewing the results of about 2,200 trials, Tandon (1987) reported an average response of 7.8 kg grain per kg P_2O_5. In addition to response data summarized in Table 5, some responses of chick-pea to P application under rainfed conditions are given in Table 6. Phosphorus application increased yield by 13%-42%. Optimum rates of P application for rainfed chick-pea range from 20 kg to 75 kg P_2O_5 ha^{-1} (AICRPDA, 1983a).

Table 6. Responses of Chick-Pea to Fertilizers Under Dryland Conditions in Rajasthan

Application Rate			Response to Treatment			
			Alwar District		Chittorgarh District	
N	P_2O_5	K_2O				
- - - -(kg ha^{-1}) - - -			(kg ha^{-1})	(%)	(kg ha^{-1})	(%)
0	0	0	(1,338)	-	(927)	-
20	0	0	+470	35	+215	23
20	40	0	+638	48	+598	65
20	40	20	+954	71	+689	74
Number of trials			48 (1975-77)		58 (1978-82)	

Sources: Rawal and Yadava (1986), Rawal and Bansal (1986).

Responses of pigeon pea to P application have been obtained both at research stations (Ahlawat et al., 1985) and on farmers' fields (Table 5). These are, in general, similar in magnitude to those for chick-pea, and optimum application rates recommended are in the range of 40-60 kg P_2O_5 ha^{-1} (AICRPDA, 1983a). In certain situations, such as the Vertisols at the ICRISAT Center, responses of pigeon pea to P application have not been obtained (Kanwar, 1986). Possible reasons stated for this nonresponsiveness include role of mycorrhiza, low P requirement of the crop, and ability of the crop to absorb P from very low concentrations.

Oilseeds – The P requirement per unit yield is highest for oilseeds as compared with other field crops. Yield responses of oilseeds to P have been summarized by several workers (Ankineedu et al., 1983; DOR, 1984, 1985; Kanwar et al., 1983; Kulkarni et al., 1980b; Singh and Venkateswarlu, 1985; Tandon, 1987). Results of 2,462 fertilizer experiments on the response of groundnut to P in 11 soil types are given in Table 7. The unit response ratios varied from 4 to 15 kg pod per kg P_2O_5. Responses were highly significant in the red, red and yellow, coastal alluvial, red loamy, and laterite soils. At research stations as well as in trials on farmers' fields, 20-60 kg P_2O_5 ha^{-1} has been found remunerative for oilseeds under a variety of conditions (AICRPDA, 1983a; Ankineedu et al., 1983; Kulkarni et al., 1980b). In some situations, either no or little response of groundnut to P has been observed. Restricted soil moisture has been reported to be the prime factor for low/erratic response in such cases (Patel and Kanzaria, 1985). Correlation of available P with pod yield and nutrient uptake indicated that subsoil fertility made an important contribution to nutrient uptake by groundnut (Patil and Patel, 1982).

Table 7. Response of Groundnut to Phosphorus Application in "On-Farm" Experiments Conducted Between 1959 and 1970

Soil Group	Number of Trials	Mean Response (kg kg^{-1} P_2O_5)
Red and yellow (Vertisol)	226	15.4
Coastal alluvial (Entisol)	39	9.8
Red loams (Oxisol)	62	9.6
Alluvial soil (Inceptisol)	1,065	8.3
Red sandy soil (Alfisol)	842	5.6
Medium black soil (Vertisol)	381	5.5
Deep black soils (Vertisol)	313	4.8
Response needed to pay for P		1.5

Source: Kanwar et al. (1983), Kanwar (1986).

From 1,014 farm field trials, Pillai et al. (1984) reported an average increase of 300 kg seed ha^{-1} for rapeseed mustard in response to 40 kg P_2O_5 ha^{-1}. Based on a large number of "on-farm" trials, the economical P_2O_5 rates for various oilseeds were reported to be 30-40 kg ha^{-1} for mustard, 40 kg ha^{-1} for safflower, and 15 kg ha^{-1} for niger (Kulkarni et al., 1980b).

Factors Affecting Crop Responses to Phosphorus

The importance of crop variety in affecting the quantum of yield response to P has been stated. The following factors are also briefly discussed.

Available P Status of Soil – It is a common observation that higher responses are obtained in soils that are low in available P than in high-P soils. This general trend is evident also in the drylands (Tandon and Kanwar, 1984). Much of the soil test/crop response correlation research in India is applicable to irrigated systems. Results with dryland wheat in Punjab show that the response to applied P was determined largely by the soil's available P status and the stored soil moisture (Singh et al., 1979). Grain response was 10 kg per kg P_2O_5 where available P_2O_5 was 31-47 kg ha^{-1} and 18 kg per kg P_2O_5 in soils testing 13-15 kg ha^{-1} available P_2O_5. Based on the ICRISAT experience, critical levels of P are reported to be lower in the Vertisols than in the Alfisols (El-Swaify et al., 1985). Mycorrhiza has been shown to modify the critical level of P for pearl millet (Krishna and Dart, 1984).

Methods of P Application – Drilling or placement of fertilizer P below the soil surface is a proven practice for improving the efficiency of P. It is almost universally recommended for the dryland crops (AICRPDA, 1983a; De, 1988; Kanwar, 1986; Singh and Venkateswarlu, 1985). Subsurface drilling of P brings about 23%-69% increase in yield as compared with a broadcast application (Tandon, 1987). Results with finger millet show that drilling of seed + DAP mixture to provide 40-50 kg P_2O_5 ha^{-1} was a feasible practice (Hegde and Reddy, 1984). In rainfed soybean, mixing of DAP with seed was satisfactory at 40 kg P_2O_5 ha^{-1} but caused loss in yield at higher rates of P application (Singh and Singh, 1986).

Interactions of Phosphorus

Three major interactions involving P are those with genotype, nitrogen, and moisture. In commonly conducted field experiments, it is reasonable to assume that a part of the response attributed to P is in fact due to the positive N x P interaction. The N x P interaction is very important for dryland agriculture. It can account for 50%-60% of the combined response to an NP application, as shown in Table 8 for sorghum and finger millet. Nutrient interactions have also been discussed by Kanwar (1986) in general and by Tandon and Kanwar (1984) for sorghum in particular.

Table 8. The Significance of N x P Interaction in Dryland Agriculture

	Response			Estimated Contribution of		
Crop	N	P	N+P	N	P	NP Interaction
	----- (kg ha^{-1}) ----			--------- (%) --------		
Sorghum	110	490	1,570	7	31	62
Finger millet	390	170	1,300	30	13	57

Source: Singh and Venkateswarlu (1985).

The interaction effect of P with plant population produced a yield advantage of 26% in pigeon pea (Ahlawat and Saraf, 1981). Interaction of P with weed control also added 26% to chick-pea yields (Saraf and Ganga Saran, 1986).

Sources of Phosphorus

In general, fertilizers containing most of their P in water-soluble form are preferred for field crops in the SAT (Kanwar, 1986). In the acidic P-deficient soils of Bihar, powdered rock P has been found useful for pulses and oilseeds if (1) applied 20-25 days before seeding, (2) at double the usual rates at seeding, or (3) in suitable combination with a water-soluble source (Mohsin et al., 1984). About 95% of all fertilizer P distributed in India is in water-soluble form. Single superphosphate, by virtue of its having S and Ca in addition to P, is usually favored for groundnut (Reddy, 1985).

Phosphorus and Water Use Efficiency

Efficient use of available water deserves as high a priority as efficient use of nutrients in dryland agriculture. A number of findings on the role of P in improving water use efficiency (WUE) are given in Table 9. The application of P increased water use efficiency by 15%-20% in dryland wheat, 22%-25% in finger millet, 41%-99% in chick-pea, 17% in linseed, and up to 19% in mixed chick-pea + wheat stands. Increase in water use efficiency due to P application is greater on coarse-textured soils than on fine-textured soils (Singh et al., 1985). This characteristic is quite important because it provides extra production support to soils that have low moisture storage capacity. Such results also underscore the role of P in promoting extensive and deeper root growth, which makes the water stored in deeper soil layers accessible to them. This can be very important during droughty periods when the surface soil dries up. Work with transpiration suppressants has shown that spraying of CCC or Atrazine on spring sorghum increased water use efficiency by 31%-53% and P uptake by 17%-21% (Boobathi Babu and Singh, 1984a, 1984b).

Table 9. Effect of Phosphorus Application on the Water Use Efficiency (WUE) of Dryland Crops

Crop (Soil)	Input (kg P_2O_5 ha^{-1})	Grain Yield (kg ha^{-1})	CWU (cm)	WUE (kg grain cm^{-1})	Reference
Finger millet	0	1,336	29	46	AICRPDA (1983b)
(Red)	50^a	2,223	31	72	
Chick-pea	0			72	Singh and Tiwari (1985)
(Alluvial)	40			143	
Wheat	0	1,630	22	76	Singh et al. (1983)
(Alluvial)	40	2,140	24	91	
Wheat + chick-pea	0	1,697	26	65	Singh et al. (1985)
(Alluvial)	20	2,057	27	77	

a. Combined NP effect due to the application of 50 kg ha^{-1} of N and P_2O_5.

CWU = Consumptive water use; WUE = Water use efficiency.

Phosphorus Management in Cropping Systems

Research on nutrient management in cropping systems focuses mostly on N and very little on other nutrients. A number of recent reviews underscore this general lack of research on nutrient management in systems involving major crops of the SAT (ISA, 1985).

A sorghum/pigeon pea intercropping system removed 31% more P than did a stand of sole sorghum (Kanwar, 1986). Results obtained by AICRPDA suggest that in cereal-legume intercropping, application of P to the cereal components is satisfactory (Singh and Venkateswarlu, 1985). A 6-year research study of sorghum/pigeon pea intercrop followed by castor shows that the total productivity of the system was highest when 50 kg P_2O_5 ha^{-1} was applied to the main system and castor was raised on residual fertility (Venkateswarlu et al., 1986). Other reports emphasize that, in intercropping systems, P recommendations should be able to meet the needs of all the component crops (Ahlawat et al., 1985; Mohsin et al., 1984; Singh and Upadhyay, 1985). There is a dearth of long-term experiments in this area.

Phosphorus Recommendations for Dryland Crops

Phosphorus application is recommended for most dryland crops (AICRPDA, 1983a). Tandon (1987) analyzed the P recommendations generated by the 23 research centers of AICRPDA and found that, of 113 soil-crop situations, the quantities of P_2O_5 recommended per hectare were 15-30 kg for 35%, 30-45 kg for 56%, and 45-60 kg for 9%. Some general recommendations per hectare for P_2O_5 were in the range of 20-50 kg for sorghum, 20-40 kg for millet, 20-75 kg for chick-pea, 30-60 kg for pigeon pea, 25-50 kg for groundnut, 15-60 kg for mustard, 15-40 kg for wheat, 25-50 kg for finger millet, and 40-60 kg for soybean.

Areas for Future Research

1. Strengthening of soil fertility research in dryland research programs and of dryland research in soil fertility-oriented projects operating in the dryland areas.
2. Establishment of long-term fertilizer experiments on adequately characterized sites under rainfed conditions and detailed monitoring of the fertility dynamics and balances.
3. Field verification of critical limits of soils and crops that originated from pot experiments.
4. Nutrient-indexing surveys of standing crops and relating the results to soil fertility status.
5. Extension of soil test/crop response correlation work to rainfed areas.
6. Evaluation of the P fertility status of high-clay soils on the basis of effective root zone and specific surface area of the soil rather than on a per-hectare basis.
7. Expansion of research on interactions of P with N and water.
8. Initiation of field-based research on mycorrhiza, its contribution to the P nutrition of SAT crops, and its role in solubilizing the relatively less available fractions of soil P.
9. Expansion of research on P management in intercropping systems.
10. Strengthening the plant physiology input in soil fertility research.

Potassium

Potassium Status of Soils and Crops

Soil deficiencies of potassium in the unirrigated SAT are important only in certain coarse-textured soils, in some red soils, and at high yield levels obtained without K application for a period of time (AICRPDA, 1983b, 1988; Venkateswarlu, 1987). Some possible areas of K deficiencies are soils of the Anantapur and Karimnagar area in Andhra Pradesh (Venkateswarlu, 1984), red soils of the Bangalore area (AICRPDA, 1983b), and several alluvial soils in Uttar Pradesh (Ghosh and Hasan, 1976). Soil test ratings may not always agree with the K status of standing crops. In Kurnool and West Godavari districts of Andhra Pradesh, rated as medium-high in available K, 29%-60% of the groundnut crop samples were reported to be deficient in K (Subba Rao, 1975).

According to Sekhon (1985), much of the work on K has concentrated on determination of forms of K and that too in soils which cannot be properly correlated because information on soil classification and mineralogy is generally lacking. In soils of the semiarid and arid areas, the K-bearing minerals may be relatively less weathered and therefore potentially capable of releasing more K into the system. However, moisture stress during the crop season may impose a limitation on the extent of actual K release (Sekhon, 1983).

As an average over 19 benchmark soils, of the 1.82% total K_2O in surface soils, 92% was found to be present as mineral K, 6.3% as nonexchangeable K, 1.6% as exchangeable K, and 0.2% as solution K (Tandon and Sekhon, 1988). By now, it is also well recognized by research workers that the nonexchangeable fraction makes a significant contribution to the K taken up by crops and that some measure of this fraction should be included in K-fertility evaluation.

Crop Responses to Potassium

Conclusions about the response of dryland crops to potassium application based upon "on-station" research can be markedly different from those based on "on-farm" experiments. Although responses to K at the research station are indeed not common, responses on farmers' fields are common enough to merit attention (Table 5). It is irrelevant that these are lower than the responses to other major nutrients because the per-unit price of potash is also 30%-40% that of N and P.

Cereals and Millets – Unit responses to K in a large number of on-farm trials were 2-10 for cereals and millets (Table 5). Among major dryland systems, the reddish brown lateritic soils of the Bangalore area are most interesting from the point of view of multiple nutrient deficiencies. The surface soils have a pH of 5.0, available K_2O of 150 kg ha^{-1}, and cation exchange capacity (CEC) of 7.1 me/100 g. Yield responses of dryland maize and finger millet to potassium, along with other nutrients in these soils, are summarized in Table 10. Yield increases per unit K_2O were 7.3-8.7 for finger millet and 15-21 for maize.

Table 10. The Nutrient Response Profile of Acidic Reddish Brown Lateritic Soils (Oxic Haplustalf), Bangalore, Under Dryland Agriculture

Nutrient	Crop	Years Studied	Input (kg ha^{-1})	Yield (kg ha^{-1})	Response (kg kg^{-1} input)
N	Finger millet	4	0	1,820	
			25	2,620	32.0
			50	2,850	20.6
			75	3,060	16.5
N	Maize	2	0	1,950	
			50	4,170	44.4
			75	4,460	33.5
P_2O_5	Finger millet	4	0	1,960	
			30	2,450	16.3
			60	2,840	14.7
P_2O_5	Maize	2	0	2,900	
			30	3,390	16.3
			60	4,170	21.2
P_2O_5	Pigeon pea	2	0	1,550	
			30	1,750	6.7
			60	2,040	8.2
K_2O	Finger millet	3	0	2,860	
			30	3,080	7.3
			60	3,380	8.7
K_2O	Maize	3	0	3,770	
			30	4,220	15.0
			60	5,030	21.0
$ZnSO_4$	Maize	4	0	4,120	
			5	4,490	74
			10	4,630	51
S	Groundnut	3	0	1,310	
			10	1,547	23.7
S	Sunflower	2	0	910	
			10	1,165	25.5

Compiled from data in AICRPDA (1983b). Response to the application of the indicated input is over the general application of other major nutrients at recommended rates.

Kharif sorghum responded significantly to 30 kg K_2O ha^{-1} in 697 trials conducted in Andhra Pradesh, Madhya Pradesh, and Maharashtra States. Responses to potash were inferior in the post-rainy season in all states (Tandon and Sekhon, 1988). Rainfed finger millet responded to 30 kg K_2O ha^{-1} in Karnataka and Orissa with a mean response of 10 kg grain per kg K_2O. Of 247 trials with pearl millet, responses were obtained only in Andhra Pradesh. The yield increase was 7 kg grain per kg K_2O.

Pulses – In fertilizer experiments on farmers' fields, the responses to potash were variable, but application of 20 kg K_2O ha^{-1} was beneficial in a large number of cases for chick-pea, pigeon pea, and blackgram in the presence of 20 kg N and 40 kg P_2O_5 (Kulkarni et al., 1980a). In a set of 16 field trials, highest yields of chick-pea were obtained with an application per hectare of 18 kg N, 46 kg P_2O_5, and 20 kg K_2O (Chandra and Ali, 1986). In soils rated as high in available K, potassium application increased chick-pea grain yield by 9%-23% (Table 6). It is important to view the yield responses of high-value crops in terms of economics in order to have the correct picture. As an example, a physical yield increase of 9 kg grain per kg P_2O_5 for sorghum is as profitable as a yield increase of 1.6 kg grain per kg K_2O for chick-pea, as illustrated in Table 4. In Andhra Pradesh, responses of pigeon pea to potassium application in on-farm trials were 5.5 kg grain per kg K_2O (Tandon and Sekhon, 1988).

Oilseeds – The remunerative doses of potassium for various oilseeds varied from 20 kg to 40 kg K_2O ha^{-1} in a large number of "on-farm" trials with groundnut, mustard, sunflower, safflower, and castor (Kulkarni et al., 1980b). Responses of groundnut to potassium both in Kharif and Rabi were significant in Andhra Pradesh, Karnataka, and Tamil Nadu with an average of 3 kg pods per kg K_2O applied at 40 kg ha^{-1}.

Method of Potassium Application

The most commonly advocated method of applying K_2O is to apply the recommended rate by drilling or placement as a part of the basal dose before planting.

Potassium and Moisture Stress

Potassium may improve water use efficiency and help to maintain crop yields under moisture stress or reduce the extent of crop loss under such conditions (Saxena, 1985). The mechanism of the role of K may be osmotic adjustment, and it is different from that of P, which largely influences root development. Because drought occurrences are quite common in the SAT, intensive research in this area might be very valuable for increasing and stabilizing production.

Potassium Dynamics Under Continuous Cropping

There is a real dearth of long-term fertilizer experiments under nonirrigated conditions. In the Alfisols at ICRISAT Center, an 8-year experiment was conducted using a 2-year rotation of improved cropping system (T. J. Rego, 1987, personal communication). The exchangeable K at the site was 59 ppm initially. It was found that sorghum grain, sorghum stalk, millet stalk, groundnut pods, and pigeon pea grain did respond to applied K but the responses were small. In sorghum grain, these ranged from 10% to 28%. The experiment indicated that, though the site was marginally deficient in available K for all the crops, the severity of K deficiency did not increase with time. Further, the exchangeable K in the soil changed very little after 8 years indicating significant supplies from the nonexchangeable pool. Because the nonexchangeable pool is large, one may not expect a big response to applied K in the near future in spite of harvesting moderately good yields.

In contrast to the ICRISAT site, the exchangeable potassium status of the red soil at Bangalore dropped from 160 kg K_2O ha^{-1} to about 65 as a result of continuous cropping without K application from 1977 to 1987 (AICRPDA, 1988). In response to a range of K levels applied in 1987, grain yield of finger millet increased by 994 kg ha^{-1} as an average of three varieties at an application rate of 75 kg K_2O ha^{-1}. Both the local and the improved varieties of finger millet responded significantly to potassium application. Potash application is recommended for dryland cereals in Bangalore.

Areas for Future Research

1. Establishment of long-term experiments on well-characterized sites under rainfed conditions, with priority on red soil areas.
2. Research on the role of K in drought tolerance of crops, its effect on water economy, and its impact on water use efficiency (with adequate plant physiology input).
3. Assessment of the contribution of leaf fall and other recycled residues in adding K to the SAT soils.
4. Development of methodologies for evaluating the K-fertilizer status of soils by integrating the exchangeable and nonexchangeable fractions.
5. Effect of different rainfall patterns on the distribution of various forms of potassium in soils of varying texture and mineralogical composition.

Sulfur

Sulfur Status of Soils and Crops

Research on sulfur is much less than that on other important nutrients (N, P, K, Zn). Sulfur has recently been included in the mandate of the coordinated research program of the Indian Council of Agricultural Research (ICAR), which was earlier confined to micronutrients. It is now being recognized that sulfur deficiencies are widely scattered and not confined to the coarse-textured alluvial soils as traditionally thought. Although these may occur to a varying degree in 90 districts, the available database is grossly inadequate to delineate S-deficient areas (Takkar, 1988; Tandon, 1986). The following assessments are particularly relevant for the SAT:

1. On an average, 17% of the soils in Gujarat State are considered to be deficient in sulfur (Patel, 1988).
2. Sulfur deficiencies are considered to be limiting crop production in many parts of Karnataka (Badiger and Shivraj, 1988).
3. In Madhya Pradesh, results of 1900 soil analyses from 12 districts indicated that [illegible]%-88% of the samples in different districts were deficient in sulfur (Shinde, 1984).
4. In Maharashtra, very meager information is available on the sulfur status of soils under different climatic conditions (Karle et al., 1985).

Although 10 ppm available S is commonly employed as the critical limit for delineating S-deficient/responsive sites, these levels can vary from 8 ppm to 30 ppm depending upon the soil, crop, and the analytical method used (Goswami, 1988; Takkar, 1988). Field-based critical limits and field verification of pot-based critical limits are fit subjects for future research. In the Kurnool and West Godavari districts of Andhra Pradesh, 70%-90% of the groundnut plants were reported to be deficient in S in a survey conducted during the 1970s (Subba Rao, 1975).

There is lack of information on sulfur transformations, particularly under dryland conditions. In general, these may resemble nitrogen transformations. Mineralization of organic S may lead to a flush of sulfate S in soils after a prolonged drought or during normal dry periods (Kanwar and Mudahar, 1986). Depending upon soil texture and intensity of rainfall, part of this mineralized S can leach.

Crop Responses to Sulfur

Although responses to sulfur application have been reported for over 30 crops under field conditions, most of these are obtained under irrigation (Tandon, 1986). Without irrigation, some information is available for oilseeds. As a broad indication for the tropics and subtropics, amounts of S absorbed per tonne of yield production have been given as 3-4 kg for cereals, 5-8 kg for millets, 8 kg for pulses, and 12 kg for oilseeds (Kanwar and Mudahar, 1986).

Significant responses of groundnut to the application of S either through gypsum or elemental S have been reported from Andhra Pradesh (Raman and Subba Rao, 1979). For rainfed groundnut in coarse-textured well-drained, neutral to slightly alkaline soils, application of 40 kg S ha^{-1} through gypsum has been found useful (Pasricha and Rana, 1985). In a medium black soil analyzing 8.7 ppm available S and 0.38 ppm available B, groundnut responded up to 120 kg S ha^{-1}. Sulfur application increased pod yield by 927 kg ha^{-1}, which was further increased by 387 kg ha^{-1} as a result of the application of 15 kg borax ha^{-1} (Karle and Babula, 1985). In this single-season trial, the S + B application increased groundnut yield by 1.5 times and oil yield by 1.8 times. In the red soils of Bangalore, application of 10 kg S ha^{-1} increased pod yield of groundnut by 237 kg ha^{-1} or 18% (Table 10).

Some responses of rainfed mustard to S have been summarized by Ankineedu et al. (1983) and by Aulakh and Pasricha (1988). Sulfur increased seed yields by 17%-28% at moderate yield levels (Table 11). Results with rainfed mustard that received preplanting irrigation show that a combined P + S application increased grain yield by 564 kg ha^{-1}, of which 49% could be attributed to P, 41% to S, and 10% to the P x S interaction (Rauth and Ali, 1985).

Table 11. Response of Mustard to Sulfur Application Under Nonirrigated Conditions

State	Input	Grain Yield Without S	Increase With S
	(kg S ha^{-1})	(kg ha^{-1})	(%)
Orissa	20	960	17
Punjab	30	400	124
Rajasthan	20	1,090	28
Rajasthan	50	1,420	25
Uttar Pradesh	30	1,600	18

Sources: Ankineedu et al. (1983), Aulakh and Pasricha (1988).

Five years of field experiments with taramira (*Eruca sativa*) on a soil testing 7 ppm available S in Haryana showed that S application increased seed yield by 400 kg ha^{-1}, primarily by increasing the number of silique per main shoot from 16 to 22. It also increased water use efficiency by 60% (B. P. Singh, 1983). In assessing the practical value of S responses, it was computed that each unit of S applied to S-deficient soils could augment by three units the supply of edible oils, a commodity in which India is facing a severe deficit (Tandon, 1986).

Recent agronomic studies have demonstrated that S application can improve the yield and quality of pulses (Saraf, 1988). Much of the evidence for this at present is based on irrigated experiments.

Sources of Sulfur

There is very little research on the comparative evaluation of sulfur sources for the unirrigated SAT. The most commonly recommended sources for groundnut are either gypsum or single superphosphate. For nonlegumes, ammonium sulfate can provide N as well as S while ammonium phosphate sulfate (APS) can provide N, P, and S.

Sulfur Recommendations

The most common recommendation is for the application of gypsum or of N and P through S-containing sources. On S-deficient soils, the application of 20-40 kg S ha^{-1} from most of the S-containing fertilizers is highly economical and essential for boosting crop production, particularly of oilseeds and pulses (Takkar, 1987). In the red soils of Bangalore, 10 kg S ha^{-1} is now recommended for rainfed groundnut. For rapeseed and mustard, 20 kg S ha^{-1} is recommended in S-deficient soils (DOR, 1984).

Areas for Future Research

1. Delineation of S-deficient/responsive areas by a two-pronged approach of soil analysis and plant analysis.
2. Determination of the S requirement of SAT crops in relation to productivity under Indian conditions.
3. Monitoring of the S input through rainfall and residues.
4. Study of sulfur responses in dryland cropping systems, particularly ones that include pulses and oilseeds.
5. Standardization of plant composition parameters to generate data applicable to Indian SAT conditions.
6. Study of sulfur transformations in SAT soils in relation to changes in moisture status.
7. Field verification of critical levels of S in soils and plants based on pot experiments.
8. Initiation of fertilizer experiments on cultivators' fields with an S treatment, as has been done for NPK for a quarter of a century. A small beginning in this direction has been made by the FAO sulfur network.

Zinc

Zinc Status of Soils and Crops

Among the micronutrients, research on zinc has received maximum attention, for which the major input has been provided by ICAR's coordinated scheme on secondary and micronutrients. Zinc deficiencies have been found to be widespread. These are considered to be more frequent in arid and semiarid soils than in the humid or subhumid zones (Katyal and Vlek, 1985).

A summary of about 93,000 soil analyses shows that 47% of the soil samples contained less than 0.6 ppm DTPA-extractable Zn and were therefore categorized as deficient in Zn (Table 12). The proportion of Zn-deficient samples in major states of the SAT varies from 26% in Gujarat to 77% in Haryana. In general, the extent of Zn deficiency increased with increase in soil pH and decreased with a decrease in organic matter and clay content (Takkar and Nayyar, 1986).

Table 12. Distribution of Soil Samples Deficient in Micronutrients in Major SAT Areas

	Zinc		Copper		Manganese		Iron		Boron		Molybdenum	
State	TSA	PSD	TSA	PSD	TSA	PSD	TSA	PSD	TSA	PSD	TSA	PSD
Andhra Pradesh	4,405	51	3,197	0	3,197	1	3,197	1				
Gujarat	21,994	26	21,994	4	21,994	1	21,994	8	1,715	1	1,715	11
Haryana	14,472	77	13,739	4	12,435	7	12,778	33				
Karnataka	2,318	24	2,318	4	2,318	1	2,318	1				
Madhya Pradesh	7,643	63	6,786	1	6,801	4	7,070	5	1,249	3	927	18
Punjab	13,341	53	12,531	4	12,421	1	12,564	15				
Tamil Nadu	7,540	36	7,545	10	7,254	11	7,064	19				
Uttar Pradesh	6,093	69	5,098	1	4,774	1	5,710	8				

TSA = Total soil samples analyzed; PSD = Percent samples deficient.

Data Source: ICAR Micronutrient Project Results compiled by Katyal (1985).

Critical limits for DTPA-extractable Zn may range from 0.35 for chick-pea to 1.2 for sorghum (Table 13). The impressive number of soil analyses carried out, however, does not provide an all-India picture. For example, it cannot be concluded that because 47% of the samples analyzed were deficient in Zn 47% of India's cropland is zinc-deficient. This is primarily because micronutrient research continues to be concentrated in nine states, and within these, 54% of all soil analyses originate from three states that account for 12% of the agricultural area, that is, Gujarat, Haryana, and Punjab (Tandon, 1988). In Maharashtra, a major SAT state, it has recently been concluded that studies on Zn are restricted to a few areas and most of the conclusions drawn are based on pot experiments (Malewar, 1987).

Table 13. Critical Levels of Available Zinc Used in India

DTPA-Extractable Zn (ppm)	Crop	Soil	State
0.35	Chick-pea	Red and black	Madhya Pradesh
0.40	Groundnut	Alluvial	Andhra Pradesh
0.50	Raya[a]	Alluvial	Haryana
0.50	Pigeon pea	Alluvial	Haryana
0.50-0.60	Groundnut	Red	Andhra Pradesh
0.52	Finger millet	Alluvial	Madhya Pradesh
0.60	Chick-pea	Alluvial	Bihar
1.0-1.2	Sorghum	Red and black	Tamil Nadu

a. Raya is *Brassica juncea*.

Source: ICAR Micronutrient Project data from Takkar and Nayyar (1986).

The two main climatic factors affecting micronutrient transformations are temperature and moisture. Little work on their effect on the SAT crops has been reported. Dry soil conditions can reduce the uptake of micronutrients (Kanwar and Youngdahl, 1985). The reactions of Zn added to soil proceed rapidly, and a substantial proportion may be converted into relatively unavailable forms. The absorption/desorption reactions of Zn are pronounced in fine-textured alkaline soils and least in coarse-textured acid soils (Katyal and Deb, 1982).

Crop Responses to Zinc

On a gross basis, there is a considerable volume of field data on crop responses to Zn (Katyal, 1985; Takkar and Nayyar, 1986; Randhawa and Nayyar, 1982). However, for the major crops of the SAT, there is very little information without irrigation. In Madhya Pradesh, for example, 80% of the 204 experiments on the response to Zn were on rice and wheat (Rai and Rathore, 1987). In Andhra Pradesh, application of 5 kg Zn ha^{-1} (25 kg zinc sulfate) increased the grain yield of rainfed sorghum by 80-410 kg ha^{-1} (Subba Rao, 1975). In the red soils of Bangalore having an initial 0.33 ppm available Zn, application of 10 kg zinc sulfate ha^{-1} increased the yield of dryland maize by 510 kg ha^{-1}, returning Rs 12.8 for every rupee invested in Zn (Table 10). According to Joshi et al. (1987), there is immense scope to increase groundnut yields through correction of micronutrient deficiencies.

Differential Response of Genotypes to Zinc

It is well known that varieties of the same crop may respond differentially to a given level of soil or applied Zn. Several crop varieties have been listed for their relative tolerance or susceptibility to Zn deficiency by Kanwar and Youngdahl (1985) and by Kaur (1987). The review by Kaur (1987) lists chick-pea genotypes P 6628 and N 59 and groundnut genotypes M-13 and TG-3 as relatively tolerant to zinc deficiency. Very little work has been conducted under field conditions, and the hazards of screening under protected environments are depicted in Table 14, taking wheat as an example. Sorghum hybrid CSH-1 has been reported to be more susceptible to zinc deficiency than Swarna (Subba Rao, 1975). A field experiment with six finger millet varieties in Bihar has shown that yield responses to 5 ppm Zn varied from 2% to 59% among varieties. Zinc uptake per tonne of grain production varied from 101 g to 151 g Zn, but the ranking of genotypes for this parameter remained the same with or without the application of Zn (Sakal et al., 1985).

Table 14. Susceptibility of Wheat Varieties to Zinc Deficiency According to Screening System Used

System	Susceptibility to Zn Deficiency	
	Variety Kalyan Sona	Variety WG 357
Sand culture	High	Low
Pot culture (soil)	Medium	Medium
Field	Low	High

Sources: Randhawa and Takkar (1976), Kaur (1987).

Sources of Zinc

The most commonly tested, advocated, and available source of Zn in India is zinc sulfate heptahydrate containing about 21% Zn. Mahendra Singh (1983) has dealt with the desirability of incorporating Zn into suitable phosphatic carriers in view of the widespread deficiencies of P and Zn in Indian soils.

Zinc Recommendations

General recommendations are to apply zinc sulfate as a basal soil application at the rate of 25 kg ha^{-1} in coarse-textured soils and 50 kg ha^{-1} in fine-textured soils once in 1-3 years in Zn-deficient soils. Recommendations specific to dryland conditions are still to emerge (AICRPDA, 1983a) except for the application of 10 kg zinc sulfate ha^{-1} for rainfed maize at Bangalore. For groundnut, the Directorate of Oilseed Research recommends 25 kg zinc sulfate ha^{-1} once in 3 years (DOR, 1985).

Areas for Future Research

1. Characterization of the available zinc status of SAT soils in relation to soil properties and climatic parameters.
2. Research on transformation of Zn and other micronutrients under typical dryland conditions.
3. Investigations on important interactions involving Zn such as with N, P, S, and moisture.
4. Field verification of critical limits for soils and crops.
5. Field-based research on the differential response of crop varieties to micronutrient stresses. To make such research productive, coordination with seed production agencies will be necessary.
6. Field data on the uptake and removal of micronutrients in relation to yield under dryland conditions.
7. Studies on the role of root systems of different crops in responding to micronutrient stresses.
8. Correlation of on-farm data with soil test data. Although a large number of on-farm experiments are conducted, the yields obtained are not correlated with soil test data. Such correlations can provide field-tested critical levels.
9. Effect of climatic features that are characteristic of the SAT (wet spells, droughty periods) on changes in micronutrient availability in the soils.
10. Information on the residual effects of Zn in order to determine the optimum rates and periodicity of application.

Iron

Iron Status of Soils

Iron is the most abundant micronutrient in soils and also the one taken up by most crops in largest amounts (Table 1). Yet iron deficiencies are next only to those of Zn. In general, iron deficiencies may be one-fourth as extensive as those of Zn, but an examination of district-level data shows that, in many areas, these may be as important as Zn (Table 12).

In the highly alkaline soil, under drought conditions and long dry spells, iron deficiency is a possibility in Andhra Pradesh (Subba Rao, 1975). Recent reports show that groundnut variety TMV-2, which is extensively grown in the state, is particularly sensitive to iron deficiency under dryland conditions even in red soils (Venkat Raju et al., 1987). It was reported that the iron content of leaves did not reveal any deficiency, but the yield was increased as a result of spraying iron compounds.

The commonly used critical levels of available iron in soils vary from 3.2 to 7.2 ppm of DTPA-extractable Fe (Table 15). In the Vertisols of Karnataka, DTPA-extractable iron was significantly and negatively correlated with calcium carbonate content (Murthy and Viswanath, 1987). These workers suggested that Fe-deficiency in these soils could be due to the precipitation of iron on the carbonate surfaces. The problem of iron chlorosis has manifested itself on several crops in large areas of Maharashtra (Daftardar, 1987). Although research on Fe is well behind that on Zn, the nutrient is worth watching in the coming years.

Table 15. Critical Limits of Available Iron Used in India

DTPA-Extractable Fe (ppm)	Crop	Soil	State
3.2	Wheat	Alluvial	Haryana
4.0	Maize	Black	Gujarat
4.4	Sorghum	Alluvial	Haryana
6.0	Sorghum	Black	Madhya Pradesh
7.2	Chick-pea	Alluvial	Bihar

Source: ICAR Micronutrient Project data from Takkar and Nayyar (1986).

Although research on iron application to unirrigated SAT crops is yet to be fully undertaken, iron should not be allowed to be unduly overshadowed by zinc. Kaur (1987) has listed some genotypes of chick-pea (T-1, BD-9-3, Chaffa, G-20) and groundnut (TG-1, TG-7, TG-17, Kadiri) reported to be relatively tolerant of iron chlorosis. Research on combating iron deficiencies needs to be pursued. This will require the joint efforts of plant physiologists, breeders, and agronomists/soil scientists.

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Significance of Biological Nitrogen Fixation and Organic Manures in Soil Fertility Management[1]

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Abstract

A review of the literature on the role of leguminous crops and organic manures in soil fertility management confirmed that they can enhance soil productivity. The leguminous crops, either intercropped or in rotation, benefited the associated or succeeding crops. N_2 fixation by leguminous crops is one of the most beneficial effects; the amount of N_2 fixed by a few legume species has been estimated by various measurement methods.

The effect of legume crops is discussed primarily from the viewpoint of the transfer of N to associated and succeeding crops. Evidence obtained by using ^{15}N-labeled legumes suggests that the amount of N transferred from the legume crop to an associated crop is not substantial and that a major part of N in legume residue is not made available to the succeeding crop. The beneficial effect of legume could not be ascribed solely to N mineralization, and the acidifying effect of legume roots may be an additional benefit.

The extent of crop response to organic manure, i.e., farmyard manure (FYM), undecomposed crop residue, and green manure, varies with locations, time and method of application, and environmental conditions. Organic manure influences soil productivity through its effect on physical, chemical, and biological soil properties. Several long-term experiments in India have shown that organic manure improved the soil physical properties by reducing bulk density, increasing water-stable aggregates, and increasing field capacity. Continued application of organic manure increased organic carbon and nitrogen content and cation exchange capacity, as well as the population of bacteria, fungi, and actinomycetes. Increased N_2 fixation by associative N_2-fixing bacteria was noticeable.

Introduction

Biological N_2 fixation and organic manures occupy an important place in the soil N cycle. Under arable upland conditions, legumes are a major source of N_2 fixation; the source of organic manure is plant residue and FYM. The growing of crops that fix N_2 and the application of organic manures maintain soil fertility by minimizing the loss of N and other nutrients from the soil.

The beneficial effect of a legume crop on soil fertility or on other nonleguminous crops in association or in rotation with the legume has been a subject of interest among research workers. It is generally accepted that N_2 fixation by legumes reduces the rates of soil N depletion and that a major part of N_2 fixed by a legume crop becomes available directly or indirectly to the associated or succeeding crops. However, there is much variation in assessing the extent of these benefits and much controversy concerning the mechanism of N transfer from the legume to associated or succeeding crops.

Organic manures are generally applied to the land in order to recycle nutrients, improve soil structure, and accumulate organic matter in the soil. It has been recognized that efficient and effective use of organic manures provides benefits to crop productivity by immobilizing nutrients that are otherwise susceptible to leaching and by enhancing the activity of soil microorganisms and fauna.

The use of legumes and organic manures as a means of returning nutrients to the soil and enhancing soil productivity has declined in the countries with intensive agriculture and in the areas where chemical fertilizers are abundantly applied. However, in the humid tropics and

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the semiarid tropics (SAT) where the use of chemical fertilizer is limited, biological N_2 fixation by legumes, grown in rotation or intercropped with cereals, and addition of organic manures are very important factors in achieving good crop yields and in maintaining adequate nutrient levels in the soil.

The emphasis in this review is on the improvement of the nutrient status of the soil; therefore, the review will focus mainly on the quantity of N_2 fixed and the fate of that N_2 fixed by legumes and in legume residue, as well as the effects of organic manures on improving productivity of the soil and the soil properties.

Biological Nitrogen Fixation

Benefits of Legumes

The fact that legumes are a common component of crop rotation, intercropping, or mixed cropping has led to the thought that N_2 fixed by legumes contributes to maintaining soil fertility, particularly soil N, and that it may be directly or indirectly used by associated or succeeding crops. There are several reports and reviews on the advantages of including legumes in a cropping system over sole cropping of nonlegumes; however, only some of the recent results obtained in India are discussed here.

Legume-wheat and fallow-wheat sequences have been compared with a sorghum-wheat sequence for 3 years (Shinde et al., 1984). Generally, the former two sequences performed better than did the latter one at a medium level of N fertility management, but at a higher level of fertility management, the advantages of legumes on succeeding wheat were not clearly evident. Pearl millet (*Pennisetum glaucum*) yielded more when sown after fallow, cowpea (*Vigna unguiculata*), or greengram (*Vigna radiata*) than after maize (*Zea mays* [L.]) (Narwal and Malik, 1987). After 4 years of continuous crop rotation, the total N increased in soil under all rotations in which legume was included but not in a maize-wheat-fallow system, with the maximum buildup of N observed in rotations with groundnut (*Arachis hypogaea* [L.]) (Thind et al., 1979). Rainy-season grain legumes showed appreciable residual and cumulative effects on N concentration in an unfertilized wheat crop when phosphorus was applied (Dhama and Sinha, 1985). Winter grain legumes increased the N and P status of the soil compared with cereal or fallow and increased the yield and N uptake of maize following legumes (Ahlawat et al., 1981).

Yield was significantly increased when wheat was grown following sorghum intercropped with cowpea or groundnut compared with following sole sorghum in the previous season (Waghmare and Singh, 1984). Grain yield was significantly increased for maize intercropped with blackgram (*Vigna mungo* [L.]), cowpea, and mungbean (*Phaseolus aureus*) as compared with sole maize and maize intercropped with groundnut (Das and Mathur, 1980). Intercropping of maize with blackgram, greengram, groundnut, or cowpea was found to increase the soil N content more than did maize alone; in general, in soils with lower levels of N, inclusion of legumes resulted in increased soil N content (Gangwar and Kalra, 1980). The All India Coordinated Millet Improvement Project compiled the results of intercropping pearl millet with pulses and oilseeds from 1974-80, and the consolidated data showed that the pearl millet-greengram system was consistently more productive than pure pearl millet (Borse et al., 1983).

Estimation of Nitrogen Fixation

A leguminous crop acquires N through absorption of soil N and through fixation of atmospheric N_2. The ratio of N acquired through each of the two processes to total N in the plant varies with plant species and environmental conditions. Accurate measurement of the amount of N_2 fixed under various environmental conditions is a prerequisite for assessing the role of leguminous crops in crop and soil management.

The following techniques are commonly used for estimating N_2 fixation in the greenhouse and the field:

1. Acetylene (C_2H_2) reduction.
2. ^{15}N gas incorporation.
3. ^{15}N isotope dilution.
4. Natural abundance of ^{15}N.
5. N difference method.
6. N balance.

Acetylene Reduction – The acetylene reduction assay makes use of the fact that the enzyme responsible for N_2 fixation, nitrogenase, can reduce acetylene (C_2H_2) to ethylene (C_2H_4) as well as N_2 to NH_3 (Hardy et al., 1973). Acetylene and ethylene can be easily and rapidly analyzed by a gas chromatograph. The technique requires incubation of plants in a closed chamber along with acetylene. Ethylene formed by the enzyme is estimated by using gas chromatography. Because a closed chamber is used, this technique is not suitable for long-term measurement of N_2 fixation. A major problem with this technique is calculation of the ratio of ethylene formed to nitrogen to be reduced. The theoretical conversion ratio of C_2H_2 reduction to N_2 fixed, calculated from electron ratio, is 3 to 1, but this theoretical ratio is not universally applicable to all N_2-fixation studies (Bergerson, 1980).

^{15}N Gas Incorporation – Nitrogen gas that is labeled with the stable isotope ^{15}N is placed in the atmosphere of a closed chamber in which the test plants are growing. The amount of N_2 fixed is calculated by the amount of ^{15}N incorporated into the plant (Burris and Miller, 1941). Nitrogen gas is a genuine substrate of nitrogenase, and hence the value obtained by this method is a realistic estimate of N_2 fixation. However, the use of this method is restricted to only short-term measurements because of the requirement for a closed chamber and the high cost of ^{15}N-labeled gas.

^{15}N Dilution – The principle of this method is that an N_2-fixing plant growing in a medium enriched by ^{15}N fertilizer contains less ^{15}N in the plant than does a nonfixing plant growing in the same medium (McAuliffe et al., 1958). This is because the nonfixing plant obtains all its N from the ^{15}N-enriched medium, whereas the fixing plant obtains a significant portion of its N from the atmosphere, which is 99.637% ^{14}N; the result is an overall lower ^{15}N enrichment in the plant tissue (McAuliffe et al., 1958). Major difficulties in applying this technique under field conditions include selecting an appropriate nonfixing control, providing uniform distribution of the ^{15}N label at the soil depths where fixing and nonfixing plant roots are growing, and ensuring that the level of ^{15}N-enriched fertilizer is not so high that it inhibits N_2 fixation. The main advantage of this technique is that it can be used with ease for the measurement of N_2 fixation in the field without disturbing the soil-plant system during the experiment.

Natural Abundance of ^{15}N – This method of calculating percent N derived from atmospheric N_2 is based on the same concept as that for the use of ^{15}N dilution and makes use of the differences between the abundance of ^{15}N in the soil and that of the atmosphere. Usually, the natural abundance of ^{15}N in the soil is slightly higher than that in the atmosphere, possibly as a result of isotopic discrimination during long-term N cycling between the soil and the atmosphere. Although ^{14}N is identical to ^{15}N in terms of chemical properties, there is a difference in their masses. In other words, with this method, the amount of naturally occurring ^{15}N in the soil that is in excess of that in the atmosphere is considered to be an ^{15}N tracer. Because the difference in ^{15}N between the soil and the atmosphere is usually very low, the measurement of N_2 fixation using this technique requires mass spectrometers with high precision, and even a slight change in ^{15}N value results in significant changes in N_2-fixation estimates. Nevertheless, a major advantage of this method is that the measurements can be made without addition of ^{15}N-labeled compounds and without disturbing the plant-soil system in the field. Thus fixing and nonfixing plants have equal access to profile variation in ^{15}N with depth.

N Difference Method – This method, which simply compares N yields of fixing and nonfixing plants, is often used in the fields to obtain rough estimates of N_2 fixed by legumes. The method requires an appropriate non-N_2-fixing control plant which must possess the same efficiency of use of soil or fertilizer N as the N_2-fixing plant to which it will be compared. This classical method has generally been used by agronomists in fields where the N_2-fixing plant and nonfixing plant are simultaneously grown.

N Balance Method – If all the inputs of N to a given field through precipitation, fertilizer, etc. (except N_2 fixation) are measured and all removal of N from that field is also measured (leaching, denitrification, and crop harvesting), the positive difference between input and output will be ascribed to N_2 fixation. Such N input and output measurements are possible only in a pot or in the field specially designed for this purpose, and much greater efforts are required to measure the changes in soil N because of a large N pool in the soil and large spatial variability in soil N content. This method will provide a more accurate estimate of N_2 fixation in the field where the experiment is conducted for several seasons or years.

Some Examples of N_2-Fixation Estimates – Some estimates of the amount of N_2 fixed by crops are shown in Table 1. The amount of N_2 fixed by a leguminous species varies not only with genotype, location, and soil fertility but also with the measurement techniques that are employed. In Table 1, the estimates were obtained by N difference, ^{15}N dilution, and natural ^{15}N abundance techniques that do not require the closed chamber and do not disturb the plant-soil system.

Because these techniques use a nonfixing plant as a reference, their estimates are generally fairly close if the measurement is done by comparing N_2-fixing and nonfixing varieties of the same plant species at the same location. However, the use of a nonfixing variety limits the precision of these techniques because they are based on the incorrect assumption that the roots of both plant varieties exploit the same soil volume. However, the greatest advantage of these methods is that they provide an integrated estimate over time under field conditions.

Role of Nitrogen Fixation

It is universally accepted that the beneficial effect of legumes is through addition of N_2 fixed in root nodules to the plant-soil system in sole cropping, in intercropping, or in rotation. In almost all the trials where benefits were obtained from growing legumes, the role of legume has been examined from the viewpoint of nitrogen economy. Traditionally, it has been said that the major effects of legume are through maintenance of adequate soil N and

Table 1. Some Examples of Estimates of N_2-Fixation by Grain Legumes

Crop	Estimation Method	N_2 Fixed (kg N ha^{-1})	Percent N Derived From N_2 Fixation (%)	Reference
Soybean	N difference	130	51	Bhangoo and Albritton (1978)
	^{15}N dilution	108	60	Deibert et al. (1980)
	Natural ^{15}N	49	48	Yoneyama et al. (personal communication)
Groundnut	N difference	113[a]	85	Yoneyama et al. (personal communication)
	^{15}N dilution	152	92	Giller et al. (1987)
	Natural ^{15}N	112[a]	85	Yoneyama et al. (personal communication)
Pigeon pea	N difference	69	52	Kumar Rao and Dart (1987)
	^{15}N dilution	69	88	Kumar Rao et al. (1987)
Chick-pea	N difference	26[a]	44	Giller et al. (1988)
	^{15}N dilution	36[a]	61	Giller et al. (1988)
Cowpea	N difference	53[a]	NA	Eaglesham et al. (1982)
	^{15}N dilution	77[a]	NA	Eaglesham et al. (1982)

a. Measurement was done on the same genotype at the same location and time.

NA = not available.

contribution of available N to an associated crop or the succeeding crop. However, it has sometimes been difficult to attribute the beneficial effects solely to increased availability of N to other crops (Ketcheson, 1980).

Transfer of Fixed N_2–Two important effects of fixed N_2 are its transfer to the associated crop and its transfer to the succeeding crop.

Evidence for the transfer of symbiotically fixed N_2 to an associated crop has not been directly obtained by feeding isotopically labeled N_2 gas to the legume. There have been reports (Van Kessel et al., 1985; Francis and Read, 1984) of direct hyphal linkage of mycorrhiza allowing transportation of nutrients between two root systems. It is possible that nitrogen fixed by a legume in intercropping is transferred through such a hyphal linkage to an associated nonlegume, but the nature and the quantity of this transfer system have not been substantiated under field conditions.

In a 3-year N balance study, Simpson (1976) estimated that 20% of total nitrogen in subterranean clover (*Trifolium subterraneum*), 6% of that in white clover (*Trifolium repens*), and 3% of that in lucerne (*Medicago sativa*) were transferred to the associated grass, cockfoot (*Dactylis glomerata*). However, in his experiment sole crops or intercrops were grown in the same plots, and hence the amount of N transferred to the grass may have consisted of concurrently fixed N or the N_2 fixed previously.

It is important to use an ^{15}N-labeled source in measuring the transfer of N, but data obtained using ^{15}N in India are not available. An estimate of the transfer of N by the ^{15}N dilution technique in intercrops or mixed cropping is based on the calculation of the enrichment of ^{15}N in the legume and the associated crop. The ^{15}N enrichment of Kleingrass (*Panicum coloratum*) grown with siratro (*Macroptilium atropurpurem*) was lower than that for Kleingrass grown in pure stand by 13% and 6%, which accounted for 14% and 5% of the total N in the Kleingrass for the low and high rates of N fertilization, respectively (Ismaili and Weaver, 1987). The maize intercropped with cowpea showed a significant (52%) dilution of ^{15}N in comparison with the sole-cropped maize (Eaglesham et al., 1981), and it was concluded that N excreted by the intercropped legume gave significant benefit to the associated maize.

Ledgard et al. (1985) used a new method in which subterranean clover was labeled with ^{15}N by foliar absorption, and the transfer of N from the subterranean clover to the associated ryegrass (*Lolium rigidum*) was measured. Over a 29-day period, 2.2% of the N from the subterranean clover was transferred to the ryegrass.

The above evidence obtained by using ^{15}N compounds, though not as direct as the estimate by the ^{15}N gas incorporation method, suggests that N from the legume is transferred to the associated nonlegume during the same growing season. However, the amount of N transferred does not seem to have been substantial except in the study reported by Eaglesham et al. (1981). The main pathway of N transfer may be as sloughed-off roots, N excreted from legume roots, and decomposition of nodules.

A second beneficial effect of fixed N_2 is its transfer to a succeeding crop. Cowpea and groundnut sole crops have been shown to benefit the succeeding maize crop in terms of increased grain and dry-matter yields equivalent to 60 kg N ha^{-1} supplied through fertilizer (Dakora et al., 1987). At a medium level of fertility management, rainy-season greengram or cowpea provided 30 kg N ha^{-1} for succeeding post-rainy maize (Shinde et al., 1984). The N requirement of maize following a sole crop pigeon pea was reduced by 38-49 kg N ha^{-1} compared with maize following either fallow, sole sorghum, or sorghum/pigeon pea (*Cajanus cajan*) intercrop (Kumar Rao et al., 1983). Similarly, a preceding crop of pigeon pea reduced the N requirement of a succeeding wheat crop by 30 kg N ha^{-1} (Narwal et al., 1983).

Beneficial effects of residual N on subsequent crops have been demonstrated not only for sole legume crops but also for intercropped legumes. Intercrops of sorghum with cowpea, groundnut, or greengram saved 18 to 55 kg N ha^{-1} for the target yield of 4.0 tonnes of the wheat that followed (Waghmare and Singh, 1984).

The magnitude of the residual N effect on a succeeding crop depends on the preceding cropping system, preceding legume species, and succeeding crop species and on the method of estimation. In most cases in the SAT, the contribution by legumes of residual N to the succeeding crop has been estimated to be 30 to 70 kg N ha^{-1}. However, these values have been obtained through N fertilizer equivalence methods and do not indicate the exact amounts of N derived from the preceding legumes.

The amount of N transfer from the preceding legume depends not only on the rate of decomposition of legume residue but also on the amount of legume N that is released and made available to a succeeding crop. Therefore, it is essential to know the source of N in the succeeding crop. For that purpose, the use of an ^{15}N-labeled legume material will be a good guide in that the legume N can be distinguished from the soil N during decomposition. As far as we know, no experiment with ^{15}N-labeled legumes has been conducted in India.

Vallis (1983) applied dried ^{15}N-labeled siratro to Rhodes grass (*Chloris gayana*) pasture in Queensland, Australia, and examined the recovery of the ^{15}N. The cumulative recovery of ^{15}N in Rhodes grass shoots after the first, second, and third years was 13.7%, 16.8%, and 14.5%, respectively, of the initial amount added.

In southern Australia, Ladd et al. (1981) incorporated unground ^{15}N-labeled *Medicago littoralis* material into the fields and allowed it to decompose for 8 months before sowing wheat. The wheat took up only 11%-17% of legume residual N, the amount of which corresponds to 5%-10% of total N in the wheat. In a subsequent study (Ladd et al., 1983), ground ^{15}N-labeled *Medicago littoralis* was used and allowed to decompose for 7 months in successive years. The first wheat crop took up only 28% of the legume N, corresponding to 6.1% of the total N in the wheat, and the second crop took up less than 5% of the N in the legume incorporated in the first year.

Thus, a major part of the N in a legume residue is not made available even to the succeeding crop. The rate of N released from legume residue is controlled by the rate of decomposition, which varies with chemical composition of the plant or root, environmental conditions, type of soil, soil organisms, and management practices.

All the available information on decomposition of ^{15}N-labeled legume residues indicates that much lower mineralization of N occurs than is estimated by biomass yield and N yield methods. The discrepancy in the estimates may be ascribed to a significant "priming" effect of legume residue incorporation on soil organic N mineralization and to the fact that a large part of the beneficial effect of legume residue on the succeeding crop is not directly related to N mineralization.

Rhizosphere pH Changes Induced by N_2 Fixation–It is known that nitrate-fed plants make the rhizosphere more alkaline, whereas plants using ammonium-N sources make the rhizosphere acidic due to establishment of an electrochemical equilibrium. When legumes fix atmospheric N_2, the cation absorption usually exceeds the anion absorption and, consequently, the rhizosphere becomes comparable with that of ammonium-fed plants. It has been calculated that a well-nodulated legume root induces a reduction in the average soil pH of about 0.14 units in

100 days (Nye and Kirk, 1987). Therefore, some nutrients will become more available in the rhizosphere of N_2-fixing legumes than in that of nitrate-fed plants.

The availability of phosphorus, for example, is enhanced in soil of lower pH. Soybean (*Glycine max*) fertilized with ammonium-N (and therefore comparable with N_2-fixing soybean) decreased the pH of the rhizosphere and stimulated P uptake (Riley and Barber, 1971). Increased capacity for solubilizing P by N_2-fixing legumes has been demonstrated by using sparingly soluble phosphate rock. The N_2-fixing alfalfa (*Medicago sativa*) plants used phosphate rock more efficiently than did the nitrate-fed plants (Aguilar and van Diest, 1981). The tropical legume *Pueraria javanica* mobilized even very insoluble phosphate rock because of the acidifying effect in its rhizosphere, and the quantity of acid produced by *Pueraria* was calculated to be 10 kmoles H+ ha^{-1}, which would require 500 kg ha^{-1} of calcitic limestone in order to neutralize the rhizosphere.

Under upland conditions, nonleguminous crops, whether fertilized with N or nonfertilized, generally acquire N as nitrate. On the other hand, N_2-fixing legumes influence chemical changes in the rhizosphere differently than the plants that are taking up nitrate-N. In the long run, the form in which the legumes acquire N will influence not only the soil in the rhizosphere but also the bulk soil through alteration of the pattern of absorption of other nutrients. Thus, it would be worthwhile to assess the effect of legumes on the rhizosphere pH and accompanying changes in the availability of other nutrients.

Organic Manures

Crop Response to Organic Manures

Organic matter has received considerable attention as a source of nutrients for plant growth. The classical experiments at Rothamsted, United Kingdom, indicated no superiority of FYM over NPK fertilizers in maintaining crop yields (Johnston and Mattingly, 1976). However, with the introduction of high-yielding crop varieties, evidence is accumulating from the long-term tests that FYM and other organic manures can give larger yields than can be obtained with equivalent fertilizer use (Johnston and Mattingly, 1976; Narayanswamy, 1968; Sahu, 1971).

Farmyard Manure or Compost – The response of crops to FYM application depends on several factors such as degree of humification, maturity of the compost, its C:N ratio, the time and method of its application, soil type, agroclimatic conditions, and moisture regime of soil during the growth of the crop.

Tables 2 and 3 summarize the results of several experiments conducted at different locations in India to study crop responses to FYM application. The results of 210 experiments with irrigated wheat and 71 experiments with rainfed wheat showed that FYM application at 12.6 tonnes ha^{-1} increased the yield of irrigated wheat by 80-300 kg ha^{-1} with an average response of 200 kg ha^{-1}. However, under rainfed conditions the response obtained to an application of 6.3 tonnes ha^{-1} FYM was lower (85 kg ha^{-1}) (Table 2). Similarly, data from several experiments with sugarcane, cotton, potato, and other vegetable crops have shown increased yields with FYM application though Dhingra et al. (1979) failed to obtain increased yields of irrigated wheat with application of 10 tonnes ha^{-1} FYM and 60 kg P_2O_5 ha^{-1}.

In trials conducted in India using different crop rotations (Table 3), incorporation of FYM at 10-15 tonnes ha^{-1} every year along with the recommended dose of NPK produced higher crop yields than did the NPK treatment alone. The highest average increase in yield over 12 years for the crops grown in a rotation was observed in acidic submontane soil at Palampur, followed by the red loam soil at Hyderabad and medium black soil at Jabalpur. At all the locations (except at Barrackpore), FYM application increased the yield of the first crop in the rotation over the non-FYM treatment, and generally positive yield effects were observed in succeeding crops in the rotation, irrespective of soil type (Table 3).

Undecomposed Crop Residues – Crop residues can be used directly for improving the soil productivity. Direct incorporation of crop residues in the soil, along with appropriate management practices, or use as a mulching material on the soil surface has proven to be beneficial in improving soil physical properties and, in some cases, has led to increased crop yields. However, when low-N materials, such as cereal straw, were plowed into soil, it was found that additional fertilizer N was needed to narrow the C:N ratio in order to avoid adverse effects on crop yields by immobilization of soil N (Bear, 1948; Gupta and Idnani, 1970; Gaur and Mathur, 1979; Ganry et al., 1978).

When ^{15}N was used in a lysimeter experiment on a sandy soil, it was found that straw incorporation depressed the grain yield by 32%. This effect was mainly due to immobilization of fertilizer N and was alleviated by application of additional N (Ganry et al., 1978). The average crop yield data for 2 consecutive years showed that sugarcane trash, rice straw + water hyacinth (1:1), and rice

Table 2. Summary of Experiments on Response of Different Crops to FYM/Compost Application in India

Number of Locations	Number of Experiments	Crop	FYM/Compost Applied	Response	
				Range	Average
			(t ha^{-1})	--------(kg ha^{-1})	-------
63	341	Rice	12.6	99-216	168
31	210	Wheat (irrigated)	12.6	82-295	202
14	71	Wheat (unirrigated)	6.3	74-140	85
19	258	Sugarcane (*Saccharum officinarum*)	25.1	3,700-11,700	8,000
10	71	Cotton (irrigated)	12.6	39-81	56
25	294	Cotton (unirrigated)	6.3	12-22	16
1	1	Sorghum	25	-	1,220
1	74	Sorghum (unirrigated)	5	-	1,340
1	48	Sorghum (irrigated)	5	-	1,280
1	74	Finger millet (unirrigated) (*Eleusine coracana*)	5	-	940
2	48	Finger millet (irrigated)	5	-	1,660
		Pearl millet (irrigated)	5	-	610
		Wheat (irrigated)	5	-	320
1	6	Sweet potato (unirrigated) (*Ipomoea batatas*)	11.2	-	2,760
1	3	Sweet potato (irrigated)	11.2	-	1,080
3	13	Potato (irrigated) (*Solanum tuberosum*)	22.4	-	1,490
1	7	Potato (unirrigated)	37	-	3,890
2	3	Potato (irrigated)	37	-	1,070
1	3	Tapioca (irrigated) (*Manihot utilissima*)	11.2	-	455
1	2	Onion (*Allium cepa*)	11.2	-	2,980
1	2	Onion	24.4	-	5,410
1	8	Chilies (dry) (*Capsicum annum*)	11.2	-	74
1	4	Chilies (dry) (*Capsicum annum*)	12.5	-	620
1	2	Okra (*Abelmoschus esculentus*)	11.2	-	235
	2	Okra	12.5	-	360
1	3	Tomato	11.2	-	175
		Tomato	22.4	-	870
1	4	Brinjal (*Solanum melongena*)	12.5	-	660
		Brinjal (*Solanum melongena*)	25.0	-	370
1	1	Fenugreek (*Trigonella foenum-graecum*)	5.6	-	-120
	1	Fenugreek (*Trigonella foenum-graecum*)	11.2	-	350
	1	Fenugreek (*Trigonella foenum-graecum*)	12.5	-	430
	1	Fenugreek (*Trigonella foenum-graecum*)	25.0	-	590

- = Not available.

Source: Derived from Garg et al. (1971); Krishnamoorthy and Ravikumar (1973).

Table 3. Summary of Long-Term Manurial Experiments on Response of Different Crops to FYM Application in India[a]

Location	Number of Crops	Crop	Soil Type	Average Response to FYM Application (kg ha^{-1})
Barrackpore	12	Rice	Alluvial	-10
	13	Wheat	Sandy loam	30
	13	Jute		-5
Ludhiana	13	Maize	Alluvial	680
	14	Wheat		120
	14	Cowpea (fodder)		35
New Delhi	3	Maize	Alluvial	330
	11	Wheat	Sandy loam	420
	10	Cowpea (fodder)		-130
Coimbatore	10	Finger millet	Medium black	505
	9	Cowpea	Clay loam	90
	7	Maize		510
Jabalpur	12	Soybean	Medium black	220
	12	Wheat	Clayey	440
	9	Maize (fodder)		890
Bangalore	7	Finger millet	Red loam	100
	4	Maize	Sandy loam	-110
	10	Cowpea		10
Ranchi	12	Soybean	Red loam	270
	10	Wheat	Silty clay loam	120
Hyderabad	13	Rice (rainy season)	Red loam Sandy clay loam	560
	13	Rice (post rainy season)		760
Bhubaneswar	12	Rice (rainy season)	Lateritic	430
	12	Rice (post rainy season)	Sandy	530
Palampur	12	Maize	Submontane	1,430
	13	Wheat	Silt loam	655
Pantnagar	13	Rice	Foot hill (Terai)	690
	13	Wheat	Silty clay loam	450
	8	Cowpea (fodder)		110

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[a] In all the experiments 10-15 t ha^{-1} FYM was applied every year to the first crop of the rotation.

Source: Derived from ICAR (1986).

straw applied at 2.5 and 5 tonnes ha^{-1} increased wheat yields even when the wastes were applied without mineral N addition (Table 4; Bhardwaj, 1985). Incorporation of straw at 18 tonnes ha^{-1}, 15 days prior to sowing, at a depth of 15 cm gave yields similar to those obtained by application of 200 kg N ha^{-1}. However, incorporation of straw at shallow depths (7.5 cm) reduced crop yields. Significantly higher increases in yields were obtained when one-third of the organic material was incorporated as neem cake along with the straw (Gaur and Mathur, 1979). In a sandy soil, incorporation of wheat straw at 18 tonnes ha^{-1} alone or with mineral N addition plus inoculation with straw-decomposing microorganisms resulted in increased yields of groundnut (Table 4) and also increased uptake of N and P by the groundnut crop (Wani and Shinde, 1980).

Crop residues left on the soil surface as a mulch also have some potential for erosion control, soil fertility maintenance, and increased microbial activity in the soil (McCalla et al., 1962; Agboola, 1982). Mulching adds considerable amounts of nutrient to the soil, and some mulches interact with fertilizer to reduce soil pH. Some straw mulches such as *Typha* and paddy straw may cause nutrient imbalance and toxicities because of the high amounts of Mn and Al they may release during decomposition. The beneficial effects of leguminous mulches appear to be due to their lower C:N ratio (Agboola, 1982). However, when crop residues are left on the soil surface, crop yields are occasionally reduced because of phytotoxic substances released from most crop plants though the phytotoxic effect decreases as the decomposition period is extended (Guenzi et al., 1967; Borner, 1960; Patrick and Koch, 1963). It has been observed that wheat straw contained the least toxic substances, causing only a 6% reduction in root growth of wheat seedlings, and that all the phytotoxic material disappeared from wheat and oat residues after 8 weeks of field exposure. At the end of 8 weeks, corn residues were still quite toxic while sorghum residues remained highly toxic and caused 37%-85% reduction in root growth of wheat test plants during a period of 16 weeks (Norstadt et al., 1967).

Green Manures – The practice of green manuring has been used to improve the soil productivity. However, it is now well established that green manures have a negligible effect on soil organic matter levels if continuous cropping is followed. Singh (1963) summarized the conclusions of several studies on the positive effects of green manures in the restoration of soil organic matter in tropical regions. He reported that, even after removal of the aboveground parts of sunn hemp (*Crotolaria juncea*) grown as a green manure crop, yields of the subsequent crop were still increased.

It has been observed that several accessions of *Sesbania* produced dry-matter yields ranging from 8 to 17 tonnes ha^{-1} and added 70-245 kg N ha^{-1} to the soil depending on the age of the plant at the time of incorporation (Singh, 1982; Ghai et al., 1985; CSSRI, 1985). Maximum N content of different *Sesbania* species was observed after 45 days of growth at which time the N content of the plant shoot on a dry-weight basis ranged from 1.06% for *S. speciosa* to 4.34% for *Sesbania sp.* (Ghai et al., 1985). It has therefore been suggested that incorporation of *S. aculeata* be carried out when the crop is 45 days old (Bhardwaj, 1982; CSSRI, 1985). Sunn hemp was found to be superior among the different green manuring crops and added 100 kg N ha^{-1} to soil and increased its available N content (Alikhan et al., 1963; Bansal et al., 1971). During 42 days of growth, soybeans produced 1,880 kg biomass containing 40 kg N ha^{-1}, and much of the N became available within 7-10 days following incorporation. This increased the grain yield of the succeeding maize by an average of 600 kg ha^{-1} over the control which had not received green manure (Pandey and Pendleton, 1986).

Nitrogen-fixing legumes bear nodules on roots. However, three genera, viz., *Sesbania*, *Aeschynomene*, and *Neptunia*, also form stem nodules containing *Rhizobia* and thus are called stem-nodulated legumes. So far, only *S. rostratra* and *S. punctata* have been reported to be stem nodulated (Dommergues et al., 1988), and the shoots have to be inoculated to ensure adequate infection of all the nodulation sites of the plant. Various methods of estimation (isotopic, balance, and difference) have shown that *S. rostratra* fixed 100-300 kg N ha^{-1} in 7 weeks (Rinaudo et al., 1983), indicating that it is one of the most effective N_2-fixing systems known to date (Dommergues et al., 1988). Several field trials carried out in Senegal indicated that, when *S. rostrata* was applied as green manure in rice fields, the succeeding crop yielded 100% more than the control plot, and the subsequent crop yielded 50% more (Rinaudo et al., 1983).

In addition to the contribution to soil N through biological N_2 fixation, a green manuring crop such as *Sesbania* reduces the leaching losses of mineral N because of its deep rooting system. It also mobilizes nutrients such as phosphorus, potassium, and other trace elements from subsoils; these nutrients are likely to be deficient in surface layers (CSSRI, 1985). Despite the advantages attributed to green manuring, it has not gained the acceptance it deserves for several reasons: (1) it gives no immediate income, (2) its effects in tropical soils are short lived, (3) it does not fit into the farmer's traditional mixed-cropping systems, and (4) it requires labor that the

Table 4. Effect of Direct Incorporation of Plant Residues on Crop Yields

Treatment	Crop	Crop Response	Remarks	Reference
Wheat straw at 13 t ha^{-1} incorporated at 15 cm depth + 200 kg N ha^{-1}	Maize	40	Straw yield was increased by 2,000 kg ha^{-1} over 200 kg N ha^{-1} alone treatment	Gaur and Mathur (1979)
Wheat straw at 18 t ha^{-1} incorporated at 7.5 cm depth + 200 kg N ha^{-1}	Maize	-560	Grain yield was reduced due to immobilization of N in top layer. However straw yield increased by 3,000 kg ha^{-1}	Gaur and Mathur (1979)
Wheat straw at 13.5 t ha^{-1} + neem cake at 4.5 t ha^{-1} + 200 kg N ha^{-1}	Maize	1,380	Straw yield was increased by 7,000 kg ha^{-1}	Gaur and Mathur (1979)
Sugarcane trash 5 t ha^{-1} x zero N	Wheat	125	Total N applied through sugarcane trash was 18 kg ha^{-1}	Bhardwaj (1985)
Sugarcane trash 5 t ha^{-1} 120 kg N ha^{-1}	Wheat	380	Total N applied through sugarcane trash was 18 kg ha^{-1}	Bhardwaj (1985)
Rice straw + water hyacinth (1:1) 5 t ha^{-1} x zero N	Wheat	175	Total N applied through rice straw + water hyacinth was 46.5 kg ha^{-1}	Bhardwaj (1985)
Rice straw + water hyacinth (1:1) 5 t ha^{-1} x 120 N	Wheat	690	Total N applied through rice straw + water hyacinth was 46.5 kg ha^{-1}	Bhardwaj (1985)
Rice straw 5 t ha^{-1} x zero N	Wheat	410	Total N added through rice straw was 31 kg ha^{-1}	Bhardwaj (1985)
Rice straw 5 t ha^{-1} x 100 N ha^{-1}	Wheat	310	Total N added through rice straw was 31 kg ha^{-1}	Bhardwaj (1985)
Rice straw 7.5 t ha^{-1}	Rice	760	Nitrogen was applied at 60 kg ha^{-1}	Mandal and Ghosh (1984)
Rice husk 7.5 t ha^{-1}	Rice	930	Nitrogen was applied at 60 kg ha^{-1}	Mandal and Ghosh (1984)
Wheat straw at 18 t ha^{-1}	Groundnut	440	Grain yield of succeeding wheat crop was also increased by 350 kg ha^{-1}	Wani and Shinde (1980)
Wheat straw at 18 t ha^{-1} with C:N ratio adjusted to 36:1 + inoculated with *Penicillium digitatum*	Groundnut	510	Grain yield of succeeding wheat crop was also increased by 400 kg ha^{-1}	Wani and Shinde (1980)
Eupatorium odarum at 20 t ha^{-1}	Wheat Maize	25 370	The soil was acidic clay loam	Bhardwaj (1986)
Maize crop residues incorporated	Maize	270	Average of 5 years experiment	Hegde et al. (1982)
Rice straw at 10 t ha^{-1}	Rice	245	Experiment was conducted on heavy clay soil for four seasons. Straw yield and also N uptake was increased due to application.	Subbaiah et al. (1983)

farmer considers unnecessary. Suggestions for overcoming these problems include growing fodder or grain legumes in a multiple-cropping sequence (Singh, 1975), intercropping shade-tolerant legumes with different food crops, or interplanting legumes with grasses (Agboola, 1982).

Effect of Organic Manures on Soil Properties

Organic manure affects soil productivity through its improved effects on physical, chemical, and biological soil properties though the extent of these effects is generally difficult to assess. It is still more difficult to quantify the effects of individual properties on crop productivity because most of these properties are interrelated with each other and have a cumulative effect on yields.

Physical Properties-A wide range of soil physical properties such as structure, pore space percentage, volume expansion, maximum water-holding capacity, and aeration are directly or indirectly influenced by soil organic matter content.

The effects of organic matter content on soil structure vary for soils of different texture and mineralogical compositions. Favorable effects in terms of reduced bulk density and increased percentage of water-stable aggregates have been observed for FYM applications in India (Table 5). Khaleel et al. (1981) reviewed the results of 42 field experiments dealing with the effects of manures and composts on soil properties. They found highly significant correlations between increased organic carbon content (induced by manure application) and reduced bulk density and between increased organic carbon content and increased field capacity. Increased organic matter content due to continued application of FYM improved the percentage of water-stable aggregates and the permeability of alluvial soils of northern India (Biswas et al., 1964) as well as other soil types (e.g., see ICAR, 1986). Better structural stability was also observed with increases in soil organic matter content due to addition of water hyacinth (Ghani et al., 1967), sugarcane trash (Sandhu and Bhumbla, 1967), compost (Lal and Kang, 1982), and wheat straw (Gaur et al., 1972).

Table 5. Effect of FYM Application on Soil Bulk Density and Soil Aggregate Stability at Different Locations After 7-11 Years of Manuring and Cropping

	Soil Bulk Density			Percent Water-Stable Aggregates >0.25 mm		
Location	Control	NPK	NPK + FYM	Control	NPK	NPK + FYM
	--------(g cm^{-3})--------			--------(%)--------		
Barrackpore	1.46	1.44	1.40	19.8	24.1	40.4
New Delhi	1.47	1.45	1.42	14.3	18.7	28.4
Coimbatore	1.40	1.36	1.31	61.3	67.9	65.2
Jabalpur	1.22	1.21	1.18	84.6	86.0	90.1
Hyderabad	1.53	1.68	1.34	70.0	73.0	84.6
Bhubaneswar	1.65	1.63	1.56	NA	NA	NA

Source: Nambiar and Ghosh (1984).

After 44 years of experimentation in the long-term, old permanent manurial experiment (OPM) at Coimbatore, there was no appreciable difference in the physical properties due to cattle manure application at 12.5 tonnes ha^{-1} year^{-1} (Krishnamoorthy and Ravikumar, 1973). However, in a new permanent manurial experiment (NPM) started in 1925 at Coimbatore, which received 2.3 tonnes cattle manure ha^{-1} year^{-1} as basal dressing, favorable increases in pore space percentage, volume expansion, and water-holding capacity were observed after growing 77 crops that received cattle manure and NPK treatments. The increased yields in cattle manure treatments were associated with the improved soil structure (Krishnamoorthy and Ravikumar, 1973). Similarly, incorporation of organic residues, FYM, or pig manure at 25 tonnes ha^{-1} (Shanmugam and Ravikumar, 1980) and also at 10 tonnes ha^{-1} improved physical properties such as hydraulic conductivity, infiltration rate, stability index, and aggregate stability in red sandy loam soils (Ravikumar et al., 1975). Conversely, negligible improvements in structure have resulted from addition of even large quantities of FYM to sandy soils of Egypt (Abdou and Metwally, 1967) and to clayey Vertisols in central India (Venkoba Rao et al., 1967; Lal and Kang, 1982).

Organic matter improves soil aggregation mainly by stimulating earthworm activity and increasing microbial production of a variety of linear organic polymers, such as humic substances of low polysaccharides and polyuronides which bind the particles together into micro- and macroaggregates.

Favorable effects of organic matter content on water retention and availability have been reported for many Indian soils (Biswas and Ali, 1967, 1969; Somani and Saxena, 1976; and Murali et al., 1979). Increased organic matter content in soils generally results in improved water use efficiency through increased water retention in the root zone, improved root proliferation, and decreased losses due to water runoff. These factors, in turn, result in improved nutrition and better crop growth with the same inputs. In lysimeter studies, green manuring in sandy soils decreased leaching of several major nutrients, particularly N (Jurgens-Gschwind and Jung, 1979).

Chemical Properties – Soil organic matter and added organic materials not only act as a source of nutrients but also influence availability of nutrients. The influence of soil organic matter on availability of plant nutrients has been reviewed (Flaig et al., 1978; Flaig, 1982; Stevenson, 1982).

The results of long-term manurial experiments conducted at different locations in India are summarized in Table 6; they indicate an appreciable increase in soil organic carbon content due to continued application of FYM for several years. Addition of cattle manure resulted in a considerable increase in N content (0.029%) in soils of the new manurial experiment, whereas only a marginal increase in N content (0.003%) was observed in the old manurial experiment over the initial soil N levels. Increased cation exchange capacity of the soil was also observed with basal dressing of cattle manure compared with the unmanured controls (Krishnamoorthy and Ravikumar, 1973). In the long-term manurial experiments, the highest N buildup was observed with application of FYM and the optimal NPK dose (ICAR, 1986). An appreciable increase in organic carbon and nitrogen content in the soil was found after the harvest of a groundnut crop in which wheat straw had been incorporated (Wani and Shinde, 1980). Addition of unhumified dung in soil depressed N mineralization initially, but after 105 days, N mineralization increased (Bhandari et al., 1972). Dhar (1965) and Dhar and Arora (1968) noted that organic

Table 6. Organic Carbon Content in Soils With and Without Organic Manure From Various Experiments

Location	Organic Carbon		Remarks	Reference
	Control	With Organic Matter		
	(%)			
Coimbatore OPM	0.12	0.16	During 1953/54 i.e., after 44 years	Krishnamoorthy and Ravikumar (1973)
Coimbatore NPM eastern series	0.25	0.34	After 26 years	Krishnamoorthy and Ravikumar (1973)
Coimbatore NPM western series	0.30	0.49	After 26 years	Krishnamoorthy and Ravikumar (1973)
Bangalore	0.45	0.48	Red loam soil after 9 cropping cycles	ICAR (1986)
Hyderabad	0.82	1.25	Red loam soil	ICAR (1986)
Ranchi	0.38	0.45	Red loam soil	ICAR (1986)
Bhubaneswar	0.59	0.76	Laterite soil after 14 cropping cycles	ICAR (1986)
Palampur	0.83	1.20	Submontane soil after 14 cropping cycles	ICAR (1986)
Pantnagar	0.90	1.44	Foothill soil after 14 cropping cycles	ICAR (1986)
Barrackpore	0.45	0.52	Alluvial soil after 14 cropping cycles	ICAR (1986)
Ludhiana	0.27	0.37	Alluvial soil after 14 cropping cycles	ICAR (1986)
New Delhi	0.52	0.56	Alluvial soil after 10 cropping cycles	ICAR (1986)
Coimbatore	0.37	0.46	Medium black soil after 8 cropping cycles	ICAR (1986)
Jabalpur	0.85	1.25	Medium black soil after 13 cropping cycles	ICAR (1986)

matter is the main source of soil N; it helps in N_2 fixation and also increases the amino acid content. Application of FYM along with NPK also resulted in marginal buildup of phosphorus and maintained the initial level in the soil over treatment with NPK alone (ICAR, 1986).

Microbiological Properties – In general, the level of microorganisms in the soil is positively correlated with the level of organic matter (McCalla, 1959; Russell, 1973). Immediately after incorporation into the soil, plant materials are subjected to the transformation and decomposition processes of the heterotropic microflora, and as shown in Table 7, the population of bacteria, fungi, and actinomycetes will be increased with application of plant residues and FYM (Krishnamoorthy and Ravikumar, 1973; Gaur et al., 1971; Shantaram et al., 1975; Sidhu and Beri, 1986). Similarly, application of FYM to soil was shown to increase the population of cellulose-decomposing *Vibrio* in neutral soils (Jensen, 1931). All forms of organic materials help the N_2-fixing heterotrophs in the soil (Gaur et al., 1968, 1971), and if sufficient time is allowed for their activity, the N content of the soil is increased (Desai, 1933). Desai also observed that FYM prepared from straw fixed N_2 in soil and benefited the plants to a great extent. Application of FYM to sandy soils or Alfisols has been shown to stimulate nitrogenase activity associated with pearl millet and sorghum plants (Wani et al., 1984). Similarly, application of wheat straw at 7 tonnes ha^{-1} prior to sowing increased nitrogenase activity in the maize rhizosphere (Sidhu and Beri, 1986).

Organic amendments generally have an inhibitory effect on the activity of soil-borne plant pathogens responsible for causing root diseases (Ledingham, 1970; James and Bruel, 1962; Goswamy and Swarup, 1971; Gouda and Setty, 1973; and Sitaramaiah and Singh, 1978). The role of plant residues in this respect may be one of the factors that contribute to the beneficial influence of the plant materials on the crop to which they are applied. *Fusarium solani, F. phaseoli* were found to be controlled by adding organic amendments with high C:N ratios, such as mature barley or wheat straw, corn stover, or pine shavings. *Fusarium* root rot of bean was managed by adding barley straw (James and Bruel, 1962), and root rot and pea wilt caused by *F. solani* were controlled by adding millet straw. The population of parasitic nematodes was reduced considerably by the incorporation of wheat straw and other organic amendments (Gaur and Prasad, 1970). However, the addition of plant residue does not always inhibit disease development, and addition of green barley (with higher content of N) was shown to increase the severity of disease (Ledingham, 1970).

Future Research Needs

It is evident that biological N_2 fixation can help sustain soil N fertility and that organic manures can be

Table 7. Effect of Organic Manures on Microbial Population in the Soil

Treatment	Bacteria	Fungi	Actinomycetes	*Azotobacter*	*Rhizobium*	*Nitrosomonas*	*Nitrobacter*	Remarks	References
Control	$43x10^5$	$51x10^2$	-	$36x10^2$	$55x10^2$	$131x10^3$	$70x10^3$	Samples were taken up to 15 cm depth	a
Rice straw at 8 t ha^{-1}	$68x10^5$	$76x10^2$	-	$50x10^2$	$74x10^2$	$256x10^3$	$125x10^3$	Samples were taken up to 15 cm depth	a
Control	$3x10^5$	$76x10^2$	$3.5x10^5$	$2.1x10^2$	-	-	-	Samples up to 15 cm depth were collected after 40 years of experimentation in old permanent manurial experiment at Coimbatore started in 1909.	b
FYM at 12.5 t ha^{-1} $year^{-1}$	$3.0x10^5$	$141x10^2$	$5.8x10^5$	$7.1x10^2$	-	-	-		
Control	$1.2x10^6$	$2x10^3$	-	-	-	-	-	Samples were collected after 35 years of addition of FYM at 12.5 t ha^{-1} $year^{-1}$ in new permanent manurial experiment.	b
FYM at 12.5 t ha^{-1}	$3.2x10^6$	$6x10^3$							

a. Sidhu and Beri (1986).
b. Krishnamoorthy and Ravikumar (1973).

successfully recycled to improve soil productivity. Though awareness of their beneficial effects is evident, gaps remain in understanding the mechanisms by which these two biological resources contribute to soil fertility. The following areas are some that need to be considered in future research.

Biological N_2 Fixation

It is important to work out a strategy for the role of N_2 fixation in relation to the use of chemical fertilizer. In doing so, a prerequisite will be to measure or estimate N gain by plants and soils via N_2 fixation.

The quantity and the pathways by which mineralized legume N is made available to the associated or succeeding crop have not been fully elucidated. It is essential to conduct experiments using ^{15}N-labeled legumes to study the process of decomposition of legume N in the soil and its uptake by plants.

The value of legumes in the plant-soil system has been recognized, but it has usually been discussed from the viewpoint of N economy. The role of legumes in improvement of soil structure and accumulation of soil organic matter is also important and should be investigated.

Organic Manures

Most of the information available on the effects of organic manures on crop yields and soil properties is from one or two crop seasons. However, a practical approach would be to conduct such experiments for longer durations at the same site under different agroclimatic conditions.

The effect of application of fresh organic materials in immobilizing available soil nutrients is mainly derived from the negative effects of plant residues on crop yields. Use of labeled material would provide precise information on immobilization and remineralization of the nutrients.

Mutually complementary or synergistic effects of organic manures and chemical fertilizers need to be studied, and the abundantly available biomass from naturally growing plants such as water hyacinth, *Parthenium*, *Lantana*, *Eupatorium*, etc., needs to be profitably used in agriculture with appropriate management.

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Fertilizer Use on Soils of the Semiarid Tropics – Economic and Social Factors

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Abstract

Although soils in the semiarid tropics (SAT) are generally responsive to N and P, farmers apply significant amounts of fertilizer only to cash crops. On-farm surveys were conducted in regions where Vertisols and Alfisols predominate to determine why fertilizer use was low and to see if its use rate was improved by training farmers in appropriate fertilizer management. Generally farmers used less than the recommended amounts of fertilizer and did not apply a urea topdressing because of an anticipated lack of yield response. High cost and fear of risk were the major limitations to fertilizer use in these villages. Farmers involved in training and demonstrations showed significantly higher rates of fertilizer use. Generally, fertilizer use in Vertisols was higher than that with Alfisols because of the more favorable soil moisture conditions in the clay of the Vertisols.

Introduction

The semiarid tropics (SAT) region of India, an area covering 956,750 km^2, has varied soil types. Vertisols and associated soils, which range in depth from shallow to very deep, predominate in this region, followed by Alfisols and related soils and Entisols. Vertisols have a clay content of 30%-70%, which allows them to hold about 30 cm of water per meter of soil profile and therefore be productive. Alfisols and related soils, which tend to be shallow to medium in depth, have a 10%-20% clay content and hold about 15 to 20 cm of water per meter profile depth. Entisols, generally loamy sands or sandy loams, can hold up to 20 cm of water per meter profile.

By and large, soils of the SAT region are deficient in N and P. Other limiting nutrients include zinc, iron, and occasionally potassium and sulfur. Economic responses have been obtained from fertilizer use on these soils (Randhawa and Singh, 1983; Kanwar and Rego, 1983; Singh and Das, 1984; Singh and Venkateswarlu, 1985; Singh and Das, 1986; Venkateswarlu, 1987). Yet, in spite of convincingly remunerative responses obtained at experimental stations, farmers seldom apply fertilizers to crops grown under dryland conditions. A survey conducted by Jha and Sarin (1984) in 114 nonirrigated districts of the semiarid tropics of India revealed that the average fertilizer use ($N + P_2O_5 + K_2O$) is only 18.5 kg ha^{-1} in these districts as against the all-India average of 46.4 kg ha^{-1} during the same year (1984/85). Most of the fertilizer use in dryland areas is confined to cash crops like cotton, groundnut, chilies, etc. Coarse grains, pulses, and oilseed crops, which constitute the predominant cropping systems in dryland situations, receive either no fertilizer or negligible amounts. Although this has been a major concern in boosting the productivity of dryland crops, no systematic study has been conducted to find out the reason(s) why the dryland farmers are not enthusiastic about applying fertilizers to dryland crops. It has only been assumed that the reasons for not using fertilizer lie in (1) uncertainty of return from investment in fertilizer use and (2) the poor resource base of dryland farmers with little risk-bearing capacity.

Socioeconomic Survey

With a view to finding out socioeconomic constraints to fertilizer use in drylands, a survey was conducted covering six villages having two representative soil types, viz., Alfisols and related soils and Vertisols and related soils. The survey was conducted during September 1988 through a prescribed questionnaire designed to gather information on current fertilizer use in dry areas and to evaluate the constraints to fertilizer use in the context of their present socioeconomic framework.

For Alfisols, two villages, Kawadipalli and Anazpur, were selected for the study. These villages are located about 25 km from Hyderabad. Kawadipalli village was represented by 52 farm families. This village has been adopted by the Central Research Institute for Dryland Agriculture (CRIDA) under Krishi Vigyan Kendra (KVK) since 1987/88, under which the farmers are given skill-oriented training in dryland agriculture. Crop demonstrations with an improved package of practices are also being done in this village. The farmers of the adjacent Anazpur village had no such exposure to dryland technology. This village is represented by 46 farm families for the present study.

For studying the socioeconomic factors in use of fertilizers for dryland crops grown in Vertisols and related soils, four villages located about 110 km from Hyderabad were selected. Fifty-five farmers were interviewed from Chevella and Pothulaboguda villages. These two villages have been adopted by CRIDA under the Model Watershed Development Program of the Indian Council of Agricultural Research (ICAR). The neighboring village of Vatpalli, representing 51 farming families, had not been exposed to watershed technology. Further, a tribal hamlet from Dakbangla tanda and Vatpalli tanda was also covered. Twenty-nine tribal farmers were interviewed for this study.

Fertilizer Use

Alfisols and Related Soils

The Setting–Of the total 98 farmers included in the survey in two villages (Kawadipalli and Anazpur), about 60% had landholdings of less than 2 ha; the average holding was 1.05 ha per household. Another 27% of the farmers had an average holding of 2.72 ha (Table 1). The majority of the farming families belonged to the category of marginal farmers.

Table 1. Landholding Pattern in a Typical SAT Alfisol Region

Size (ha)	Number of Farmers	Average Holding Size (ha)
<2	59	1.05
2-4	27	2.72
>4	12	6.82
Total	98	

The share of dryland agriculture in the total landholdings varied from 68% to 76% (Table 2). No definite trend was noticed between the landholding size and the area under dryland agriculture. Sorghum and castor are the predominant dryland crops in these villages. A small area is also put to intercropping systems with pigeon pea as the principal component crop (Table 3).

Table 2. Dryland Area Under Different Landholdings

Size (ha)	Dryland	Irrigated	Others
		(%)	
<2	72.5	21.5	6.0
2-4	76.0	19.5	4.5
>4	68.0	19.5	12.5

Fertilizer Use Patterns–The study has revealed that castor and sorghum received 24.0 and 23.0 kg ha^{-1} fertilizers (N + P), respectively (Table 4). However, fertilizer use under the sorghum + pigeon pea intercropping system was lower (15.6 kg ha^{-1}). The amount of farmyard manure (FYM) used was quite meager. Interestingly, the ratio of

Table 3. Major Cropping Systems of Dryland Farmers

Holding Size (ha)	Sorghum - Castor	Sorghum + Pearl Millet - Castor	Castor - Castor	Sorghum + Pearl Millet - Sorghum + Pigeon Pea
		(%)		
<2	93	15	-	-
2-4	62	67	19	12
>4	47	73	17	43

Note: Individual farmers may employ more than one cropping system on their landholdings.

Table 4. Average Fertilizer Use Pattern for Different Dryland Crops

Crops	FYM	N	P	N + P
	(t ha^{-1})	-----	(kg ha^{-1})	-----
Castor	0.23	14.3	9.7	24.0
Sorghum + pigeon pea	0.04	9.5	6.1	15.6
Sole sorghum	0.25	13.7	9.3	23.0

N:P used by the farmers varied from 1.47 to 1.55. However, the fertilizer use was confined to basal dressing only. On an average, 53% of the farmers did not apply topdressing for various reasons. Of this group, 89% did not apply urea as topdressing because of uncertainty in obtaining a favorable response from the applied fertilizer (Table 5). Other constraints to topdressing were lack of adequate rains at the time of topdressing (70%), the belief that topdressing may not contribute to increases in yield (38%), and difficulty of topdressing in the standing crops (31%).

Table 5. Reasons for Not Topdressing With Fertilizer

Constraints	Farmers
	(%)
No guarantee to response	89
Lack of adequate rains	70
No improvement in yield	38
Difficulty in applying	31

Note: Individual farmers cited more than one reason for not using fertilizer.

Fertilizer use was found to be the highest (24.6 kg ha^{-1}) among the farmers having landholdings of more than 4 ha (Table 6). A similar use pattern (23.3 kg ha^{-1}) was observed for holdings of less than 2 ha. Interestingly, little fertilizer (9.7 kg ha^{-1}) was used by the farmers having landholdings of 2-4 ha.

Table 6. Average Fertilizer Use Under Different Landholdings

Size	FYM	N	P	N + P
(ha)	(t ha^{-1})	--------	(kg ha^{-1})	--------
<2	0.20	14.2	9.1	23.3
2-4	0.15	5.8	3.9	9.7
>4	0.08	14.6	10.0	24.6

Besides using 24.6 kg ha^{-1} of fertilizer, 55% of those with larger holdings (>4 ha) apply FYM for grain crops (mostly sorghum) every year (Table 7). By contrast, only 29% and 33% of marginal and small farmers used FYM every year; 10% to 25% of the farmers also use FYM in alternate years. Grain crops received more FYM than cash crops like castor.

Table 7. Frequency of FYM Application to Dryland Crops by Farmers

Farm Size	Grain Crop	Commercial Crop
(ha)	----------- (% farmers)	-----------
	Every Year	
<2	29	16
2-4	33	11
>4	55	-
	Alternate Years	
<2	17	6
2-4	25	7
>4	10	-

Constraints – It can be seen that the rate of fertilizer applied is lower in all cases than the recommended dose for sorghum (40 kg N ha^{-1} and 30 kg P ha^{-1}) and castor (50 kg N ha^{-1} and 20 kg P ha^{-1}). Of the farmers, 50% believed that crops might not respond to higher levels of fertilizer than they used (Table 8). Some others (49%) believed that FYM is better than chemical fertilizer for their soils, and 42% of the farmers believed that dryland

Table 8. Reasons for Not Applying Fertilizer at Recommended Levels

Constraints	Farmers
	(%)
Crops don't respond	50
FYM is better	49
Fertilizers burn the crops	42
Soils are poor to respond	20
Tank silt is preferred	12
Damage soil structure	11

Note: Individual farmers cited more than one reason for not applying fertilizer at recommended levels.

crops may be damaged by higher levels of fertilizer application. Fertilizer use was inadequate for other reasons: (1) some farmers preferred tank silt over fertilizers, (2) some believed that soil structure may be damaged by fertilizer use, and (3) some believed their soils are too poor to respond to fertilizer application.

High cost and lack of finances coupled with fear of risk were the major constraints to fertilizer use in these villages (Table 9). Lack of knowledge and conviction concerning judicious fertilizer use and incidence of pests are other minor constraints. Lack of availability of fertilizers in the villages, however, did not emerge as a constraint.

Table 9. Constraints to Fertilizer Use

Type of Constraint	Responding Farmers Decreasing Priority →				
	---------- (%) ----------				
Costly	32	36	14	5	-
Lack of finance	28	11	21	11	2
Heavy risk	13	31	26	7	1
High pest incidence due to fertilizer use	7	3	9	16	5
Lack of conviction	5	2	6	4	-
Lack of availability of credit	2	8	4	3	3
Lack of knowledge	1	8	6	4	1
High interest on borrowed money	-	1	10	4	1
Lack of improved seed	-	-	3	3	6
Lack of training	-	3	3	4	6
Lack of suitable implements	-	-	-	-	-
Not profitable	-	-	-	-	-

Note: Farmers were asked to leave blank any constraint that was not applicable and to rank each constraint that was applicable on a scale of 1-5. The percentage of farmers given in a particular rank was established on the basis of the total number of selected farmers in the study.

Farmers thought that provision of a subsidy and loans could boost fertilizer use in drylands (Table 10). This is in agreement with the observation that fertilizer use is mostly constrained by lack of finances (Table 9). Again, non-availability of fertilizers at the farm gate did not pose a major problem in fertilizer use. It appears that, once finances are available, farmers would be willing to obtain fertilizers even from longer distances.

Table 10. Conditions Under Which the Farmers Would be Willing to Use Fertilizers in Dryland Crops

Conditions	Farmers (%)
With subsidy + loan	53
With subsidy + loan + self-financing	26
With subsidy	15
Availability in the village + the other above factors	3
With subsidy + self-financing	2

KVK Program – The impact of the KVK program on fertilizer use in the two villages was studied by separating their responses. The KVK farmers who had received training in dryland agriculture and participated in crop demonstrations used higher fertilizer doses than did the farmers who had not been exposed to the KVK program (Table 11). The KVK-trained farmers used 123%, 381%, and 113% more fertilizer for castor, sorghum + pigeon pea, and sole sorghum, respectively, than did the farmers in the non-KVK village.

Table 11. Fertilizer Use Pattern in Different Crops in KVK and Non-KVK Villages

Crops	KVK Village N	P	N + P	Non-KVK Village N	P	N + P
	- - -(kg ha^{-1}) - - -			- - -(kg ha^{-1}) - -		
Castor	20.1	13.2	33.3	8.6	6.3	14.9
Sorghum + pigeon pea	15.7	10.3	26.0	3.4	2.0	5.4
Sole sorghum	17.9	13.5	31.4	9.5	5.2	14.7

Training apparently had some effect on the perceptions concerning fertilizer use. More farmers in the non-KVK village believed that fertilizer may not give profitable return and instead may damage the crop (Table 12). Perhaps this is the reason that farmers in the non-KVK village used less fertilizer for the crops. Many of them believe that FYM is a better source of plant nutrients than are fertilizers. The positive attitude of the farmers in the KVK village, which led to higher use of fertilizer, might have been due to the training and demonstration program conducted by CRIDA in Kawadipalli village.

Table 12. Response of Farmers Not Applying Fertilizer at Recommended Levels

Constraints	Farmers KVK	Farmers Non-KVK
	--------(%)------	
FYM is better	45	53
Crops do not respond	43	57
Fertilizer burns the crops	35	50
Soils are poor to respond	20	20
Tank silt is preferred	12	13
Damage soil structure	10	13

Note: Individual farmers cited more than one reason for not applying fertilizer at recommended intervals.

Vertisols and Related Soils

Three categories of farmers were selected to cover the fertilizer practices on the Vertisols and related soils: (1) farmers who belonged to the watershed program being run by CRIDA; (2) farmers of the neighboring village, who did not have exposure to the watershed program; and (3) tribal farmers not exposed to the watershed program.

The Setting – In all three categories, the majority of the farmers (65.5% to 75.9%) had landholdings of less than 2 ha. This category was more predominant in the tribal village (Table 13). Average landholdings in the watershed villages (Chevella and Pethulaboguda) varied between 0.84 ha and 7.17 ha. The average for the nonwatershed village (Vatapalli) was 1.35 ha to 6.53 ha. The average landholding in the tribal village was 1.33 to 4.56 ha. It is evident that about one-third of the farmers belonged to the marginal and small-farmer category.

Table 13. Landholding Pattern in a Typical SAT Vertisol Region

Size (ha)	Number of Farmers	Constituents (%)	Average Holding Size (ha)
		Watershed Villages	
<2	36	65.5	0.84
2-4	9	16.4	2.92
>4	10	18.1	7.17
Total	55		
		Nonwatershed Village	
<2	34	66.7	1.35
2-4	8	15.7	3.26
>4	9	17.6	6.53
Total	51		
		Tribal Village	
<2	22	75.9	1.33
2-4	5	17.2	2.67
>4	2	6.9	4.56
Total	29		

Dryland farming is the major occupation in these villages (Table 14). Dryland areas varied from 87.4% to 100% under different categories of farmers. The extent of irrigated area was only 0% to 12.1%. No definite trend was noticed between landholding size and the area under irrigation.

Table 14. Dryland Area Under Different Landholdings

Size (ha)	Dryland	Irrigated	Others
	--------------	-(%)-	-------------
	Watershed Villages		
<2	100.0	0	0
2-4	98.8	1.2	0
>4	91.1	0	8.9
	Nonwatershed Village		
<2	98.7	0	1.3
2-4	87.4	2.8	9.8
>4	90.2	0	9.8
	Tribal Village		
<2	98.6	1.4	0
2-4	87.9	12.1	0
>4	100.0	0	0

The predominant cropping systems in the drylands are greengram – Rabi sorghum/chick-pea, blackgram – Rabi sorghum/chick-pea, sorghum + pigeon pea, and sunflower (Table 15).

Sunflower, although newly introduced, has been accepted more by the tribal farmers than by other types of farmers. Greengram followed by Rabi sorghum/chick-pea is the most popular cropping system in the area.

Fertilizer Use Patterns – FYM and fertilizer use (N and P) varied with crops. Farmers gave preference to FYM application to chilies, followed by greengram. Sorghum-based cropping systems also attracted FYM

Table 15. Major Cropping Systems in Drylands

Holding Size	Greengram-Rabi Sorghum/ Chick-Pea	Blackgram-Rabi Sorghum/ Chick-Pea	Sorghum + Pigeon Pea	Sunflower	Chilies
	(%)	(%)	(%)	(%)	(%)
		Watershed Farmers			
<2	53	3	50	11	8
2-4	100	22	78	11	22
>4	70	40	100	30	30
		Nonwatershed Farmers			
<2	85	26	59	15	-
2-4	63	13	75	38	25
>4	78	33	100	89	22
		Tribal Farmers			
<2	41	-	36	95	5
2-4	40	-	80	80	-
>4	100	-	100	100	-

Note: Individual farmers practiced more than one cropping system.

Table 16. Average Fertilizer Use Pattern in Different Dryland Crops

Crops	FYM	N	P	N + P
	(t ha^{-1})	-------	(kg ha^{-1})	-------
		Watershed Villages		
Greengram	6.30	12.0	20.2	32.2
Blackgram	3.60	16.3	18.7	35.0
Sorghum + pigeon pea	2.51	10.6	16.2	26.8
Sunflower + pigeon pea	-	23.7	26.8	50.5
Chilies	7.17	37.3	38.8	76.2
Sorghum (Rabi)	-	5.9	6.1	11.8
		Nonwatershed Village		
Greengram	2.76	7.5	13.6	21.1
Blackgram	1.68	7.5	16.6	24.1
Sorghum + pigeon pea	1.20	11.4	18.4	29.8
Sunflower + pigeon pea	1.70	14.0	25.6	39.6
Chilies	4.71	26.0	17.0	43.0
Sorghum (Rabi)	0.73	4.1	9.0	13.1
		Tribal Village		
Greengram	1.46	9.0	23.1	32.1
Sorghum + pigeon pea	5.01	37.0	36.9	74.7
Sunflower	3.82	23.7	38.7	62.4
Sole sorghum	-	46.4	39.7	85.6
Sorghum (Rabi)	-	8.9	22.7	31.6

application by the farmers (Table 16). By and large, all the crops are fertilized with nitrogen and phosphorus. Kharif crops received more fertilizers than did Rabi (post-monsoon) crops. Fertilizer application varied between 11.8 and 85.6 kg ha^{-1}. However, what is disturbing is the ratio of nitrogen and phosphorus used in these villages. Phosphorus use often is greater than use of nitrogen. Evidently, it is due to the basal application of fertilizer only at sowing. Most of the farmers do not resort to topdressing with nitrogen. The reasons for not topdressing are given in Table 17. Most of the farmers in the watershed villages believed that they may not get adequate rains for full use of topdressed fertilizer. Another strong point for not topdressing was the belief that the topdressed fertilizer may not give remunerative response. The farmers in the nonwatershed village had mixed reaction to topdressing. The majority of tribal farmers did not believe that topdressing will improve the yield. Difficulty in applying fertilizer to the standing crop was another reason cited. No definite trend was noticed in the fertilizer consumption under different landholding sizes except in the tribal village, where fertilizer consumption decreased with the increase in landholdings (Table 18). Most of the farmers in all three groups preferred applying FYM to a cash crop, such as chilies. However, the greengram crop is also manured with FYM. Application of FYM every year is the common practice (Table 19).

Constraints – The reasons for not applying fertilizer at recommended doses were studied. Lack of finance appears to be the major constraint with the farmers in the watershed program (Table 20). They prefer FYM over chemical fertilizer. A large percentage (31%) of the farmers in the watershed village believed that

Table 17. Reasons for Not Applying Fertilizer as Topdressing

	Constraints			
Size	Lack of Adequate Rains	Difficulty in Applying	No Guarantee of Response	No Improvement in Yield
(ha)	(%)			
	Watershed Farmers			
<2	72	6	89	-
2-4	75	25	25	25
>4	100	-	100	-
	Nonwatershed Farmers			
<2	45	21	39	12
2-4	40	40	100	40
>4	67	33	83	17
	Tribal Farmers			
<2	-	50	50	50
2-4	-	-	-	-
>4	-	-	100	100

Note: Individual farmers cited more than one reason for not applying fertilizer.

Table 18. Average Fertilizer Use Under Different Landholdings

Size	FYM	N	P	N + P
(ha)	(t ha^{-1})	(kg ha^{-1})		
	Watershed Villages			
<2	2.71	9.8	15.0	24.8
2-4	3.16	9.1	17.9	27.0
>4	0.74	14.2	12.9	27.1
	Nonwatershed Village			
<2	1.91	9.7	22.0	31.7
2-4	1.69	6.6	11.6	18.2
>4	1.16	8.3	12.6	20.9
	Tribal Village			
<2	4.42	30.7	37.4	68.1
2-4	2.96	25.3	31.8	57.1
>4	3.03	9.8	15.2	25.0

Table 19. Frequency of FYM Application to Dryland Crops by Farmers

Farm Size	Grain Crop	Commercial Crop
(ha)	(% farmers)	
	Watershed Villages, Every Year	
<2	52	52
2-4	44	33
>4	33	44
	Watershed Villages, Alternate Years	
<2	4	19
2-4	-	44
>4	11	44
	Nonwatershed Village, Every Year	
<2	21	35
2-4	25	63
>4	11	22
	Nonwatershed Village, Alternate Years	
<2	18	32
2-4	25	25
>4	22	56
	Tribal Village, Every Year	
<2	40	55
2-4	60	20
>4	50	100
	Tribal Village, Alternate Years	
<2	25	20
2-4	20	20
>4	50	50

fertilizer application, particularly by topdressing, may burn the crop. Lack of finance was yet another major constraint with the farmers of the nonwatershed village. Interestingly, finance did not appear to be a constraint with the tribal villagers. This may be due to the fact that they get official subsidy for purchasing fertilizers. Some of the tribal villagers also believed that fertilizer application may not give response and instead may damage the crop. They thought it better to rely more on FYM.

Table 20. Reasons for Not Applying Fertilizer at Recommended Levels

Constraints	Watershed Farmers	Nonwatershed Farmers	Tribal Farmers
	-------------	(%)	-------------
FYM is better	45	55	34
Fertilizer may burn the crops	31	49	28
Crops do not respond	16	29	21
Tank silt is preferred	4	4	7
Damage soil structure	4	22	-
Soils are poor to respond	11	2	-
Moisture stress in Rabi season	-	14	-
Lack of finance	49	43	-

Note: Figures indicate percentage of farmers reported for different constraints. Individual farmers cited more than one reason for not applying fertilizers.

The constraints to fertilizer use are shown in Tables 21a, 21b, 21c for watershed, nonwatershed, and tribal villages, respectively. The high cost of fertilizers and the lack of adequate finance to support fertilizer use emerged as the major constraints in the watershed villages. Uncertainty in getting response was the other constraint in these villages. Similar constraints were reported by the farmers in the nonwatershed village. These include high cost of fertilizer, lack of finance, and uncertainty in response. Although lack of finance was never a constraint to fertilizer use in the tribal village, some farmers believed that it is costly and that fertilizer use may increase risk to the crops. In all the villages, it appeared that the farmers had adequate knowledge about the impact of fertilizer use in dryland crop production.

Availability of fertilizers in the village itself, coupled with facility for subsidy and loan, would help to increase fertilizer use under all the situations (Table 22). Self-financing and subsidy did not find much favor in these villages.

Table 21a. Constraints to Fertilizer Use – Watershed Villages

Type of Constraints	Responding Farmers							
	Decreasing Severity →							
	------------			(%)				------------
High cost	44	22	2	-	-	-	-	-
Heavy risk	9	40	18	-	-	-	-	-
Lack of conviction	-	-	-	4	-	-	-	-
Lack of knowledge	2	5	4	9	-	-	-	-
Lack of availability	2	2	-	2	-	-	-	-
Lack of finance	33	11	35	-	-	-	-	-
High interest on borrowed money	-	2	4	13	-	-	-	-
Nonavailability of credit	2	4	9	7	9	-	-	-
High pest incidence	-	4	2	7	-	2	-	-
Lack of improved seed	2	-	2	-	2	-	-	-
Lack of guidance/ training	-	-	4	7	2	-	-	-
Lack of implements for application	-	4	7	4	7	4	-	-
Lack of profit	-	-	-	-	4	-	-	-

Table 21b. Constraints to Fertilizer Use – Nonwatershed Village

Type of Constraints	Responding Farmers							
	Decreasing Severity →							
	------------			(%)				------------
High cost	49	20	16	2	-	-	-	-
Heavy risk	6	41	12	2	4	-	-	-
Lack of conviction	-	-	2	8	2	2	-	-
Lack of knowledge	2	6	6	12	4	-	-	-
Lack of availability	-	2	8	2	-	-	-	-
Lack of finance	39	16	14	8	2	-	-	-
High interest on borrowed money	-	2	4	2	2	2	-	-
Nonavailability of credit	2	6	10	2	4	4	-	-
High pest incidence	-	-	2	2	2	-	-	-
Lack of improved seed	2	-	-	6	6	6	-	-
Lack of guidance/ training	-	-	10	8	8	10	8	-
Lack of implements for application	-	2	4	8	4	6	12	4
Lack of profit	-	2	-	2	-	-	-	-

Table 21c. Constraints to Fertilizer Use–Tribal Village

Type of Constraints	Responding Farmers Decreasing Severity →							
	(%)							
High cost	38	7	7	-	-	-	-	-
Heavy risk	14	28	-	-	3	-	-	-
Lack of conviction	-	-	3	-	-	-	-	-
Lack of knowledge	3	-	-	7	-	-	-	-
Lack of availability	-	-	10	-	3	-	-	-
Lack of finance	-	-	-	-	-	-	-	-
High interest on borrowed money	-	3	10	-	-	-	-	-
Nonavailability of credit	-	3	-	-	-	-	-	-
High pest incidence	7	-	-	-	-	-	3	-
Lack of improved seed	-	3	3	3	-	-	-	3
Lack of guidance/ training	-	-	7	-	3	-	-	3
Lack of implements for application	-	-	-	-	-	-	-	-
Lack of profit	-	-	-	-	-	-	-	-

Note: Farmers were asked to leave blank any constraint that was not appropriate and to rank each constraint that was important on a scale of decreasing severity. The percentage of farmers given in a particular priority rank was established based on the total number of selected farmers in the study.

Table 22. Conditions Under Which the Farmers Would Like to Use Fertilizers in Dryland Crops

Conditions	Watershed Farmers	Nonwatershed Farmers	Tribal Farmers
	(%)		
With subsidy + loan + self-financing	33	33	38
With subsidy + loan	20	41	38
With subsidy	4	6	7
With subsidy + self-financing	-	2	-
Availability in the village + other above factors	43	18	17

Conclusion

These studies have clearly brought out that fertilizer is used for dryland crops grown in Alfisols and Vertisols. However, the amount applied and the ratio of nitrogen and phosphorus used are the major issues. Topdressing is not in vogue for various reasons. The high cost of fertilizer and the lack of finance are the major constraints under both the soil types. Availability of the fertilizer with subsidies and loans would help boost fertilizer use in the Vertisol villages. Provision of subsidies and loans could also increase fertilizer use in Alfisols. Although the responses of the farmers under both the soil conditions were similar, the fertilizer use per unit area was higher for Vertisols than for Alfisols because of the better moisture regime obtainable in Vertisols. Involvement of the farmers in the training and demonstrations provided in the KVK and watershed villages helped considerably to increase fertilizer use.

Application of FYM is a general feature in both Alfisols and Vertisols. Farmers rely more on FYM than on chemical fertilizers although the quantity used is meager. Commercial crops like chilies receive FYM dressing every year.

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Simulation of N Dynamics in Cropping Systems of the Semiarid Tropics

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Abstract

The CERES sorghum model and risk analysis procedures were used to quantify variability in sorghum grain yield and response to N fertilizer over time in various areas of the Indian SAT. The CERES sorghum model simulates crop growth, development, and water and nitrogen balance. It considers other factors such as pests, diseases, and nutrients other than N not to be limiting growth. The model's performance was evaluated on the basis of IFDC/ICRISAT experiments conducted over a 5-year period. The 25-year simulation studies indicated that the availability of soil moisture in drier environments and N leaching in wetter areas were key factors in low N efficiency.

Introduction

The semiarid tropical area of India is characterized by an erratic rainfall and impoverished soils. In this region, much of the rain occurs in high-intensity storms, which can result in substantial runoff and severe soil erosion. Because of the uncertainties and risk of both short- and long-term droughts, farmers in the semiarid tropics (SAT) have been reluctant to adopt the use of high-yielding varieties, fertilizers, and other inputs characteristic of the green revolution in some areas (Krantz et al., 1978). It has been estimated (Tandon, 1977) that only about 15% of the area cropped to wheat or sorghum in the SAT receives fertilizer.

Since the early 1970s, considerable fertility research in the Indian SAT has indicated positive and significant responses to fertilizer N (Katyal, 1989). The results obtained from these studies and others suggest that the low or almost complete lack of fertilizer application to rainfed crops of the SAT is a much more conservative policy than is warranted (Kampen and Burford, 1980). The very small resource base from which SAT farmers operate and other socioeconomic factors also hinder the widespread adoption of fertilizer use on rainfed crops in the SAT.

Earlier work by Spratt and Chowdhury (1978) has indicated that, even in fairly dry years, economic responses can be obtained with applications up to 40 kg N ha^{-1}. When nitrogen fertilizer is used in the SAT, its efficiency of use is highly variable. Craswell and Godwin (1984), in a survey of experiments on nitrogen use on sorghum in the SAT, found efficiencies of use ranging from 2 to 24 kg additional grain per hectare per kg N applied. Low efficiencies of N use can occur in the SAT for reasons other than periodic drought. Because of the nature of rainfall events, periodic inundation of the soil can occur, which can lead to the development of conditions conducive to nitrogen losses via leaching or denitrification. Nitrogen can also be lost from the soil-crop system by ammonia volatilization or rendered temporarily unavailable to the crop by immobilization. In the many different climatic and edaphic environments of the SAT, these processes will vary greatly in importance. Given the many different transformations and the large impact of climate on fertilizer use efficiency, it is generally difficult to identify universally optimum fertilizer strategies. Climatically driven simulation models describing the major transformations of nitrogen in soil, the processes of crop growth and development, and the balance of water in the soil can provide valuable insights into fertilizer behavior. Coupled with long-term climatic data, simulation models of this type can be used to quantify variability in response to fertilizer and the magnitude of loss processes. This paper describes the use of the CERES models and risk analysis procedures as an aid to identifying appropriate fertilizer strategies in various areas of the Indian SAT. The CERES sorghum model is used as an example.

Description of CERES Sorghum Model

The CERES models are a family of simulation models describing crop growth and development, water balance, and nitrogen balance. Currently there are models for wheat (Ritchie et al., 1988), maize (Jones and Kiniry, 1986), sorghum (Alagarswamy et al., 1989), and millet and rice (Singh, Godwin, and Ritchie, 1988; Singh et al., 1988). Each of these models has components to describe the processes of soil water balance, nitrogen balance, and crop growth and development. The models operate with a daily time step and use daily weather data as inputs. A detailed documentation of the models can be found in the references cited above and will not be repeated here. To provide an understanding of the level at which processes are modeled in the sorghum model, a general description follows.

The models incorporate a soil water balance component, which includes calculations of surface runoff, evaporation, through-drainage, and plant water extraction. The soil water balance model operates on a layer by layer basis with the layer depths and storage characteristics as input parameters. It includes two field-determined limits of plant-available water, a lower limit and a drained upper limit (Ritchie, 1985). Water in the profile above the drained upper limit moisture content drains to lower layers and, in so doing, leaches nitrate.

The leaching process is modeled as a function of the volume of this drainage water that moves through a layer. The nitrate and water moving out of one layer are added to the layer below, and the cascading system continues until a sufficiently dry layer or the bottom of the profile is reached. The reverse process of upward movement of nitrate with loss of water by evaporation and the movement associated with unsaturated flow are also modeled.

Plant water extraction is calculated as a function of root length density, water availability, and potential transpiration. The root growth submodel includes procedures that simulate the distribution of a daily increment of new root growth between layers on the basis of water and N availability. Root distribution is modeled as a water- and N-sensitive process, and therefore processes that are dependent on root distribution, such as water extraction and nitrogen uptake, will reflect this sensitivity. In environments such as the SAT, where timing and placement of fertilizer applications may be critical, simulation of root distribution in this manner enables the model to have sensitivity to fertilizer management.

Light interception and photosynthesis are modeled as a function of leaf area index and incoming solar radiation. Nitrogen deficiency in the plant reduces crop photosynthesis by (1) reducing the rate of leaf expansion and (2) reducing the amount of photosynthesis per unit of leaf area. Plant N status is also used to modify the tiller survival rate in tillering environments and stem growth and leaf senescence. A root and shoot pool of labile nitrogen is used to simulate nitrogen remobilization from vegetative and root tissue to grain. All transfers of N to the grain pass through this labile nitrogen pool.

The models include components that simulate plant development and thus provide estimates of the timing of important events in the life cycle of the sorghum or millet crop. These procedures are also used to determine the duration of each distinct phase of growth. Differences between cultivars in the length of the growing season and yield components are accounted for by including some genetic-specific constants in the model. The timing of the onset of water or N stress will thus have differing ramifications for different cultivars in the same environment. The capacity of the model to describe these important differences enables modeling studies to identify appropriate genetic characters for particular environments. The model calculates growth rates of leaves, stems, ears, roots, and grain during phases defined by the crop's development.

The nitrogen submodel incorporates a component to describe the mineralization and/or immobilization of nitrogen associated with the decay of crop residues or green manures and the slow turnover of the soil humic fraction. The organic matter turnover rates are modified by indices describing the effects of soil moisture, soil temperature, residue composition, and N availability in the model. The balance between mineralization and immobilization of nitrogen associated with this decay is a function of the C:N ratio.

Urea hydrolysis rates are simulated by first determining a maximum rate of urea hydrolysis for the particular soil on the basis of its pH and organic carbon content. This maximum rate is then scaled downward as a function of the prevailing moisture and temperature conditions. Nitrification of ammonium is modeled as a function of substrate concentration, water availability, soil temperature, and a lag phase factor that is dependent upon recent soil history. Denitrification of nitrate is modeled as a function of water availability (a surrogate for water-filled porosity at high water availability), soil temperature, and the availability of the water-soluble carbon in soil. The method is a modification of that described by Rolston et al. (1980).

The processes of urea hydrolysis, ammonification, nitrification, and denitrification are modeled as first-order processes.

Crop nitrogen uptake rate is calculated in two steps. The first of these involves determining the crop demand for nitrogen. This is determined on the basis of the nitrogen concentration in the existing crop biomass plus a component related to the N required for new growth. The second step is to estimate potential N uptake as a function of root length density, N availability, soil water availability, and a scalar value of maximum uptake per unit length of crop root. The actual uptake rate predicted on each day is the lesser of N supply (potential uptake) and N demand. The model has the capacity to differentiate between nitrate and ammonium uptake. Because organic matter decomposition, crop N uptake and growth, and soil N transformations occur simultaneously, each process will affect soil N availability and will thus have feedback implications for the rates of the other processes.

Model Input Requirements

The minimum data set required for simulating nitrogen dynamics in a sorghum cropping system has been described in detail elsewhere (IBSNAT, 1986; Godwin and Jones, 1988). Briefly, the following inputs are required:

1. Weather data consisting of daily values of rainfall, maximum and minimum temperature, and solar radiation.
2. Soils data defining limits of soil water extraction, organic carbon, pH and bulk density, and mineral nitrogen availability.
3. Crop residue information describing the amount, its depth of incorporation, and C:N ratio.
4. Management information defining the planting date, population, cultivar, dates, rates, placement depths and sources of N fertilizer used, and dates and amount of irrigation water, if any added.
5. Genetic coefficients for the particular variety.

Evaluation of the CERES Sorghum Model

The earliest of the CERES models, the CERES wheat model, has been the subject of extensive testing (Otter-Nacke et al., 1986) in very diverse environments. The data sets used for testing this model ranged from extremely dry low-yielding environments in Syria and Australia to the high-yielding environments of the United Kingdom and the Netherlands. The maize model has been similarly evaluated with many data sets from the United States and from humid tropical regions in Venezuela, Thailand, the Philippines, and Indonesia. In most circumstances the models performed well.

The CERES sorghum, rice, and millet models were completed only recently and thus to date have been the subject of only limited testing. Some details of the testing of the sorghum model are provided below.

Data were assembled from field experiments conducted at ICRISAT as part of the IFDC/ICRISAT collaborative project studying N fertilizer use efficiency in SAT soils. The experiments involved various comparisons of fertilizer rates, sources, and placement strategies on Alfisols and Vertisols of varying depths. The experiments simulated were conducted over a 5-year period. The weather observed over this period spanned the range from seasons that were considerably drier than average to those that were abnormally wet. The observed data have been reported by Moraghan, Rego, and Buresh (1984) and Moraghan et al. (1984) and by Katyal et al. (1987). Additional data used for testing the model were obtained from irrigation and nitrogen experiments conducted at Kununurra in northern Australia (Wright, 1985a,b) and from dryland sorghum experiments at Katherine also in northern Australia (Myers, 1980). Each of the data sets reported had a range of nitrogen rates and often a range of other treatments, among them irrigation timing, fertilizer application timing, and cultivar. In each data set, pests, diseases, and nutrients other than nitrogen were considered not to be limiting growth. The observed grain yield in these experiments ranged from less than 1 tonne ha^{-1} to over 8 tonnes ha^{-1}.

The performance of the model in predicting grain yield, total biomass, N content of the aboveground biomass, and grain N uptake from these experiments is indicated in Figures 1-4. The performance of the model in

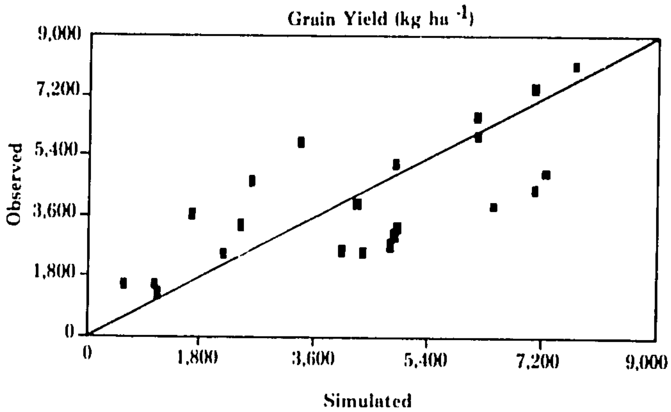

Figure 1. Comparison of Predictions of the CERES Sorghum Model With Observed Grain Yield.

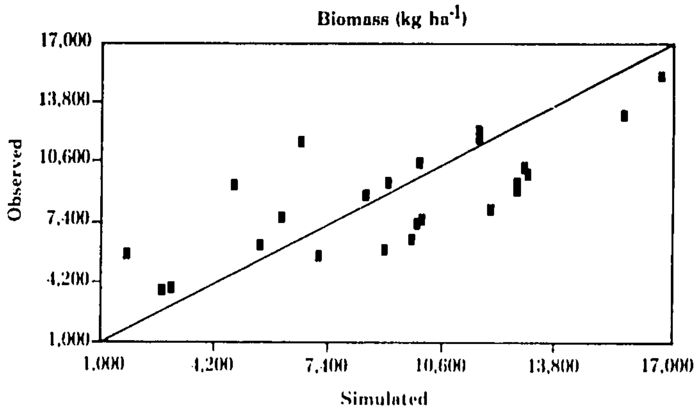

Figure 2. Comparison of Predictions of the CERES Sorghum Model With Observed Aboveground Biomass at Maturity.

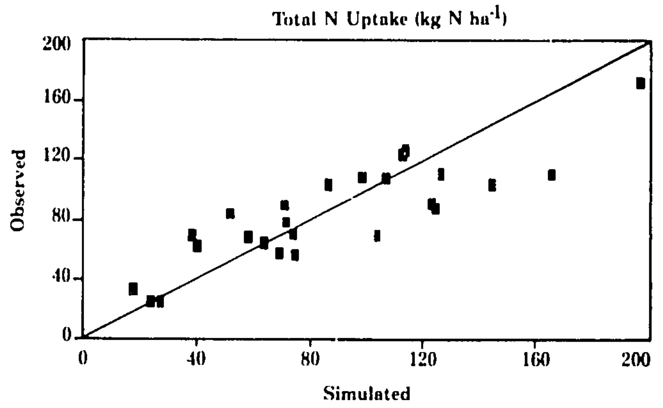

Figure 3. Comparison of Predictions of the CERES Sorghum Model With Observed Nitrogen Uptake Into the Aboveground Biomass at Maturity.

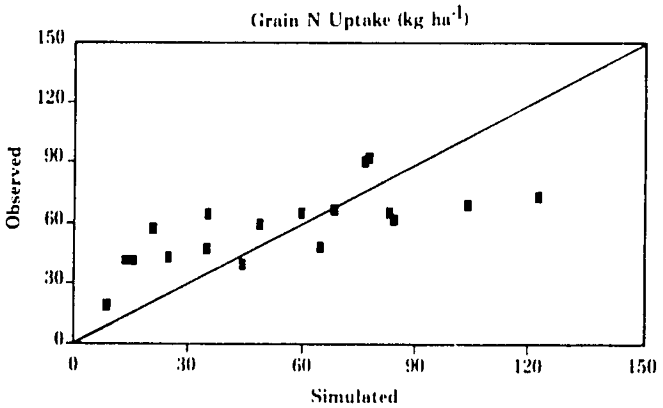

Figure 4. Comparison of Predictions of the CERES Sorghum Model With Observed Grain Nitrogen Uptake at Maturity.

simulating grain yield response to applied nitrogen for several of the data sets is also shown (Figures 5-7). This preliminary testing of the model against the range of data sets indicates that the model generally gives reasonable predictions of grain yield, biomass, N uptake by the aboveground plant, and the partitioning of this nitrogen into grain.

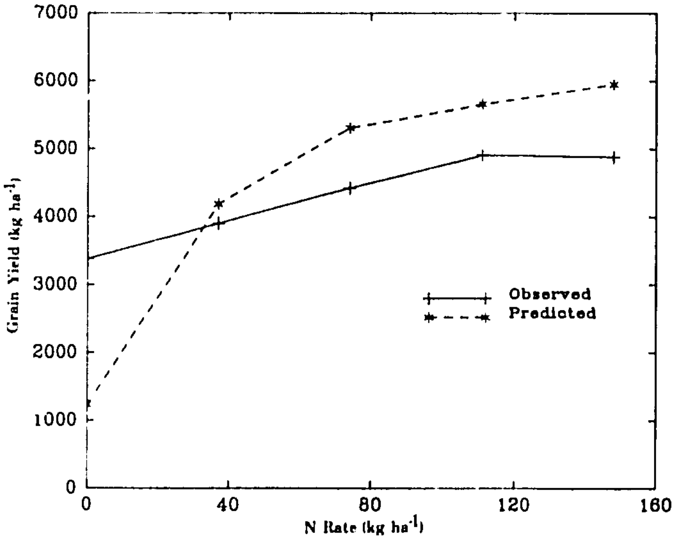

Figure 5. Comparison of Observed and Predicted Grain Yield Response to Applied Nitrogen at ICRISAT on a Deep Vertisol in 1980.

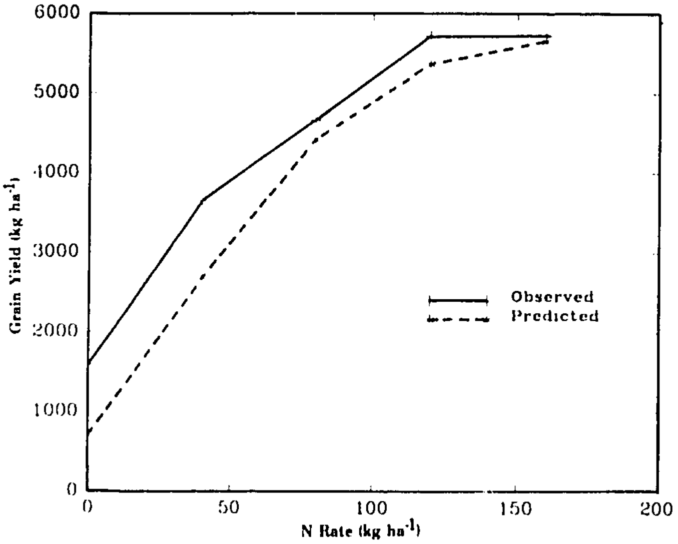

Figure 6. Comparison of Observed and Predicted Grain Yield Response to Applied Nitrogen at ICRISAT on a Deep Alfisol in 1981.

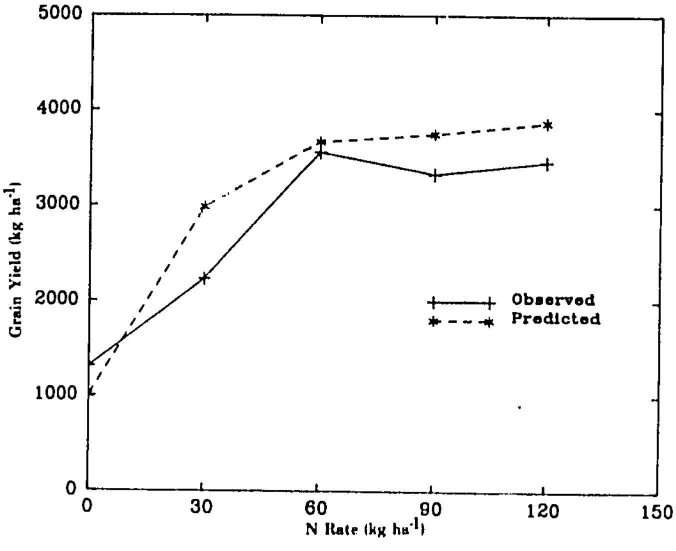

Figure 7. **Comparison of Observed and Predicted Grain Yield Response to Applied Nitrogen at ICRISAT on a Shallow Vertisol In 1984.**

Using the Model to Evaluate Fertilizer Strategies

Losses of N, fertilizer recovery, grain yield, and the processes affecting these vary greatly from year to year in any location. Thus, to develop optimal fertilization strategies in any location, it would be desirable to have fertilizer experiments conducted over many years. Fertilizer experiments are rarely conducted for more than two seasons, and thus long-term data providing insights into the nature of temporal variability are usually not available. Where long-term weather records exist, the model can be run to provide a more complete picture of fertilizer response variations over time. An alternative to the use of observed weather data is to use stochastic generation of weather data. Richardson (1981), Nicks (1974), and Stern et al. (1982) describe practical methods for this stochastic generation process. Coupling such generators to simulation models can produce a very flexible and powerful tool for rapidly examining crop production strategies.

When the outputs generated by the models are assembled, the problem of interpretation arises. Means can readily be calculated from the temporal data, but good decisionmaking will require more information than simply a knowledge of the average or most likely response (Dent and Blackie, 1979). It is desirable to know the risk associated with a particular strategy as well as the mean outcome. Agricultural economists have devoted much time and effort to developing procedures for selecting strategies under conditions of uncertainty and providing due recognition to farmers' attitudes to risk. These procedures, known as risk analysis, have only rarely been adopted by agronomists and soil scientists. These procedures have been described by Anderson (1974) and have been used in fertilizer practice evaluation by Godwin and Vlek (1985). The International Benchmark Sites Network for Agrotechnology Transfer (IBSNAT) project has developed a software package termed the Decision Support System for Agrotechnology Transfer (DSSAT), which incorporates these various tools (ATNews 2, 1986).

Initial Conditions

The CERES sorghum model, coupled with a version of the Richardson (1981) weather generator, was used to simulate N dynamics in three contrasting locations in India. The characteristics of the three locations and the average amount of rainfall over the growing season are indicated in Table 1.

Table 1. **Characteristics of the Locations Used in the Simulation Study**

Location	Latitude	Annual Rainfall	Growing Season Rainfall[a]	Growing Season Length[a]
		----- (mm) -----		(days)
Indore	22	1,186	541-1,071	84-92
Anantapur	22	560	71-206	76-83
Hyderabad	17	793	220-640	81-91

a. Range over 25-year period of simulation.

At each location, 25 years of daily weather data were stochastically generated. The study examined 11 different fertilizer strategies:

1. No fertilizer applied.

2-6. 30, 60, 90, 120, or 150 kg N ha^{-1} applied as a basal application of urea at planting.

7-11. 30, 60, 90, 120, or 150 kg N ha^{-1} applied in two applications, 50% as a basal application at planting and 50% as a topdressing 25 days after planting.

For the purposes of the study, all fertilizers were incorporated to a depth of 5 cm. Genetic coefficients appropriate to the variety CSH-1 were used in the study, and the nominal planting date was June 18 in each year. The simulated date of emergence would depend largely on simulated soil water availability in the surface layer following planting. At each location, four soil profiles typifying the two major soil orders found in the Indian SAT were used. The soils differed in water-holding capacity, depth, and mineral N availability (Table 2). For each location, 1,100 simulations (25 years x 11 strategies x 4 soil types) were run.

Table 2. Characteristics of the Soils Used In the Simulation Study

Soil	Depth	Extractable Soil Water	Mineral Nitrogen
	------ (cm) ------		(kg N ha^{-1})
Shallow Alfisol	53	5.3	55
Deep Alfisol	155	9.5	125
Shallow Vertisol	44	5.2	35
Deep Vertisol	172	22.0	108

Interpretation of Outputs

The simulated response to fertilizer over the 25-year period at Hyderabad (Figure 8) indicates the very large variation in response that occurs from year to year. Consistent with the principles of risk analysis, an alternative method of examining these response variations is to construct cumulative probability density functions (CPDFs) from the simulated yields. This can readily be done by ranking the yields associated with each of the fertilizer rates into ascending order and assigning a 4% probability (1 year in 25) to each outcome (Figure 9). This is not a true CPDF but rather a linear segmented estimation of the CPDF.

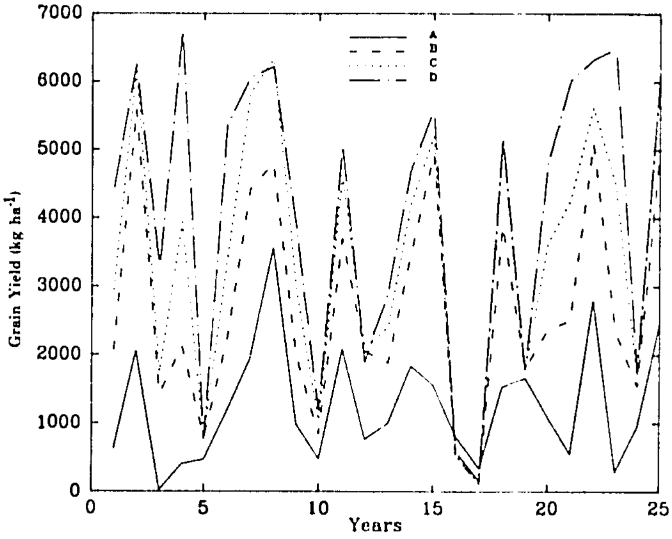

Figure 8. Variation in Simulated Yield and Response to Fertilizer Over a 25-Year Period on a Shallow Alfisol at Hyderabad (A = 0 kg N ha^{-1}, B = 30 kg N ha^{-1}, C = 60 kg N ha^{-1}, D = 150 kg N ha^{-1}).

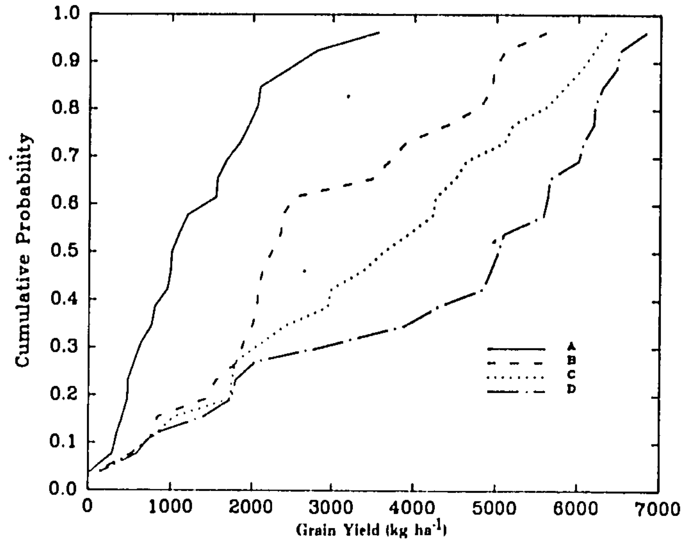

Figure 9. Cumulative Probability Density Function for Simulated Grain Yield Response to Four Fertilizer Strategies at Hyderabad on the Shallow Alfisol Soil (A = 0 kg N ha^{-1}, B = 30 kg N ha^{-1}, C = 60 kg N ha^{-1}, D = 150 kg N ha^{-1}).

The plotted CPDFs convey a wealth of information:

1. The range of response from any individual treatment can readily be gleaned (e.g., from 0 to 3,500 kg ha^{-1} for strategy A in Figure 9).
2. The frequency with which yields associated with a particular strategy are superior to those associated with an alternative strategy is readily discernible.
3. Some insights into the nature of the response patterns are provided. In Figure 9 the CPDFs for strategies B, C, and D lie close to each other in the low-yielding range. This configuration indicates that in low-yielding years there is little or no response to fertilizer beyond 30 kg N ha^{-1}, which in this location would appear to occur in about 25% of the years (lines B, C, and D overlap in the region below 0.25 on the vertical axis). In high-yielding years, the CPDFs are widely separated, indicating a large response. Thus, in this location the largest responses to fertilizer are most apparent in the highest yielding years (the most typical case). The frequency with which the response is apparent is also readily attainable from the plot.
4. The best strategy is easily discernible from the figure as the one most displaced to the right (D). This strategy has a higher frequency of more favorable outcomes than the others.

Problems in interpretation can occur when the CPDFs cross. The interpretation and description of methods used to identify the most efficient strategies under these circumstances are beyond the scope of this paper and will not be elaborated further.

Comparison of Fertilizer Strategies at the Three Locations

When fertilizer strategies are compared on a shallow Alfisol, very distinct differences between response patterns at the three locations are evident. For the dry location, Anantapur, the CPDFs are difficult to distinguish, indicating that a response to fertilizer seldom occurs (Figure 10). The ceiling yield in this environment is about 3,000 kg ha^{-1}. Yield in 80% of the years will be less than 1,500 kg ha^{-1}, indicating that the high yields are only seldom achieved. A median yield of about 750 kg ha^{-1} was achieved at this site. Response to fertilizer occurred in only 20% of the years, and these were the high-yielding years.

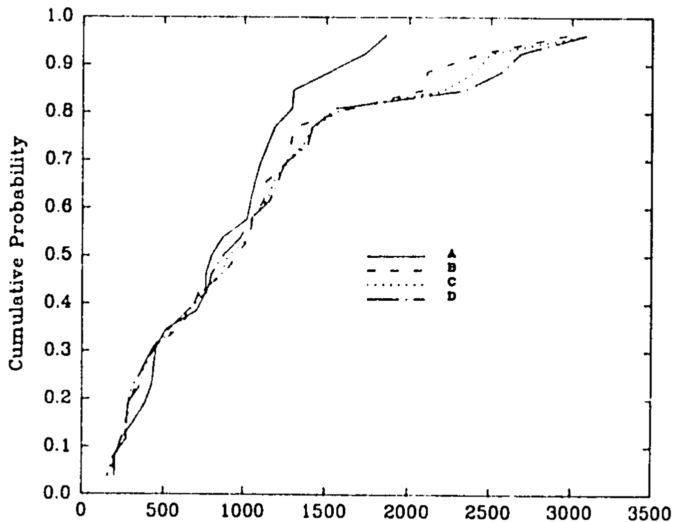

Figure 10. **Cumulative Probability Density Function for Simulated Grain Yield Response to Four Fertilizer Strategies at Anantapur on the Shallow Alfisol Soil (A = 0 kg N ha^{-1}, B = 30 kg N ha^{-1}, C = 60 kg N ha^{-1}, D = 150 kg N ha^{-1}).**

At Hyderabad (Figure 9), yields ranged from less than 1 tonne ha^{-1} to over 7 tonnes ha^{-1}. As indicated previously, no response to fertilizer beyond 30 kg N ha^{-1} occurs in 30% of the seasons. A clear response to 30 kg ha^{-1} occurs in all years. At Indore there is a 30% chance of total crop failure if crops are not fertilized, presumably because of extreme nitrogen stress (Figure 11). The ceiling yield in this environment is also about 7 tonnes ha^{-1}. The fact that the CPDFs are always widely separated indicates a clear response to fertilizer over the whole range of rates studied.

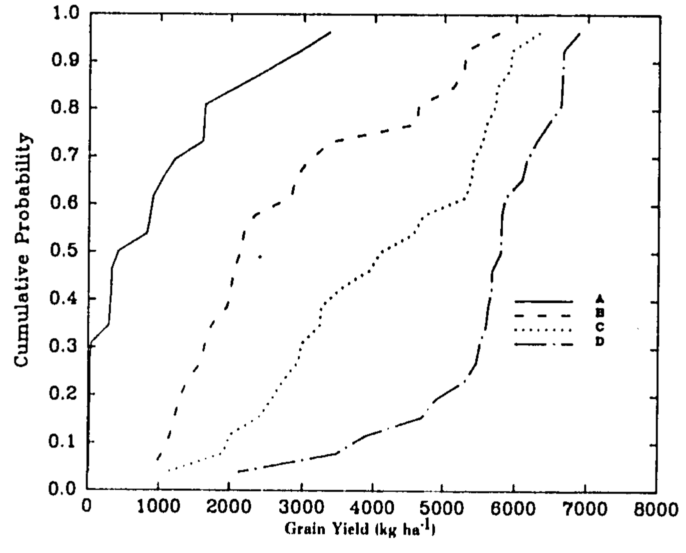

Figure 11. **Cumulative Probability Density Function for Simulated Grain Yield Response to Four Fertilizer Strategies at Indore on the Shallow Alfisol Soil (A = 0 kg N ha^{-1}, B = 30 kg N ha^{-1}, C = 60 kg N ha^{-1}, D = 150 kg N ha).**

The CPDFs for apparent recovery of fertilizer N (not depicted) show a somewhat different pattern. At Anantapur recoveries were low in general, and the median recovery for all rates of N was approximately 20%. Apparent recovery exceeded 60% in only a few years. At Indore there was a very wide range in apparent recoveries. In some years the recovery was zero, presumably when losses were very high, and in some years recovery was greater than 100% when moisture conditions throughout the season were optimal and fertilizer provided an additional priming effect on mineralization and/or plant uptake. The median recovery across N rates was about 50%. At Hyderabad, the CPDFs for apparent recovery exhibited a much narrower range. The median recovery here was 60%. This pattern is to be expected, in that losses occur less frequently than at Indore and the extreme moisture shortage occurs less frequently than at Anantapur.

Similar patterns of response and recovery were apparent on the shallow Vertisol at the three sites although recoveries tended to be higher and yields slightly higher because of the slower drainage rate of the Vertisol. The differences in the leaching losses at the three sites (Figure 12) are very marked. Because leaching losses are

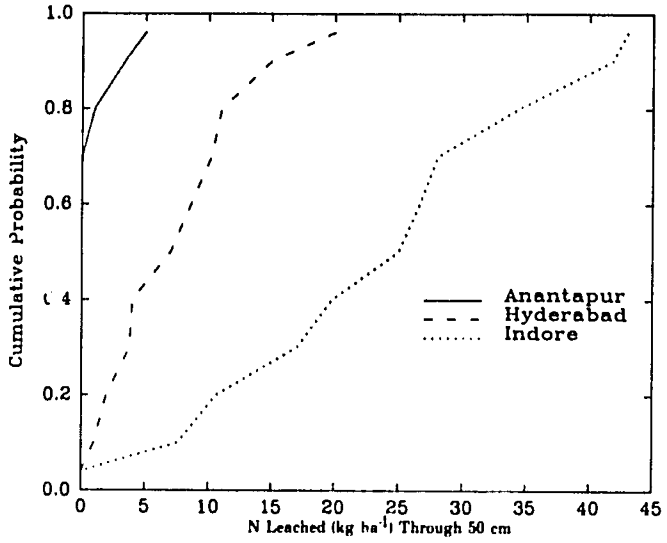

Figure 12. Cumulative Probability Density Function for Simulated N Leaching at Anantapur, Hyderabad, and Indore.

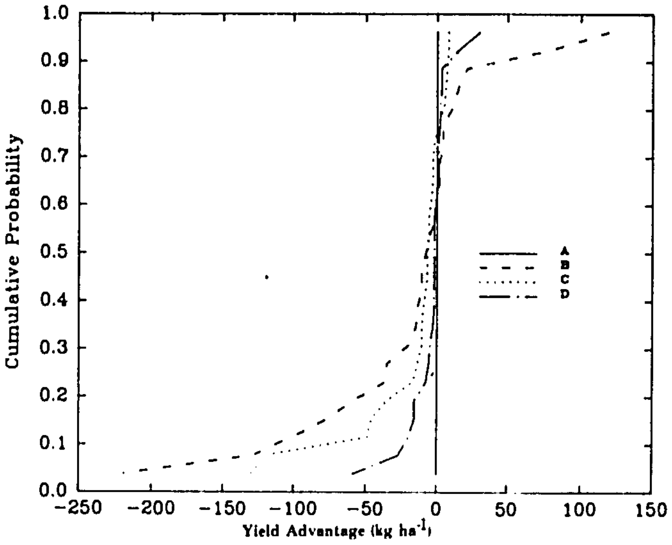

Figure 13. Cumulative Probability Density Function for Simulated Yield Advantage of Splitting Fertilizer Applications Over Basal Application at Anantapur on the Shallow Vertisol Soil (A = 0 kg N ha^{-1}, B = 30 kg N ha^{-1}, C = 60 kg N ha^{-1}, D = 150 kg N ha^{-1}).

small at the dry site, little advantage to splitting fertilizer applications would be expected. Conversely, a large response to splitting would be expected at Indore where losses are larger. The simulation study indicated this to be the case (Figures 13 and 14).

In some years there is a disadvantage to splitting fertilizer applications, and in some years there is an advantage. Figures 13 and 14 indicate how often and by what magnitude the advantages outweigh the disadvantage. One further advantage to splitting not exploited in this study is that it enables farmers to "hedge" on seasonal outcomes. If seasonal outlook and crop condition are poor when the time comes for applying a topdressing, the rate can be adjusted downward or fertilizer not applied at all. This can lead to considerable improvement in both fertilizer use efficiency and the economics of fertilizer application.

In this study, large differences in CPDFs for yield response were found between deep and shallow soils. Differences between Alfisols and Vertisols were less apparent.

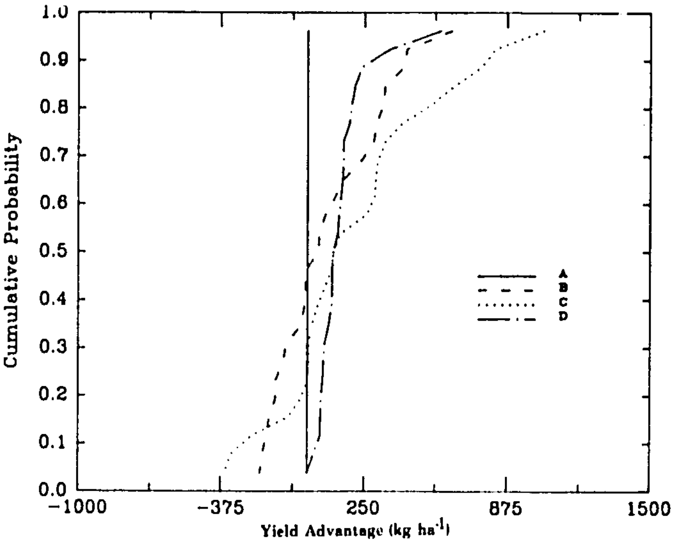

Figure 14. Cumulative Probability Density Function for Simulated Yield Advantage of Splitting Fertilizer Applications Over Basal Application at Indore on the Shallow Vertisol Soil (A = 0 kg N ha^{-1}, B = 30 kg N ha^{-1}, C = 60 kg N ha^{-1}, D = 150 kg N ha^{-1}).

Conclusions

The simulation studies indicated that, in the wetter environments, fertilizer use efficiency is often limited by losses of N associated with leaching. In dry environments, fertilizer efficiency is usually limited by the availability of moisture in the soil profile. The simulation studies indicated that, where losses were high, there was a yield advantage to splitting fertilizer applications; in the intermediate or Hyderabad-type environment, however, there was an equal probability that splitting would result in a disadvantage because of N stress early in the season.

It is important to remember that the model can only account for variations in the factors defined in the model's description, and this assumes that other potentially important factors such as other nutrients, pests, and diseases are nonlimiting. The present version of the model is unable to account for volatile losses of ammonia from the soil surface, ammonium fixation and movement, or direct losses of nitrogen from plants to the atmosphere. Where these losses are substantial, the model will be inaccurate. Because the soil water and N components of the model operate in a one-dimensional manner, placement patterns such as side banding and point placement can only be simulated by assuming uniform incorporation into a layer. From the preliminary validation studies cited above, it appears that the model is able to explain most of the observed variation in yield and N uptake where these conditions of loss and placement do not apply. Work is currently underway at IFDC to develop routines for simulating ammonia volatilization, which can be incorporated into future versions of the model. A phosphorus submodel is also being constructed, which should allow studies of the nitrogen/phosphorus/water interactions that commonly occur in the SAT.

The model, particularly when coupled with long-term weather data or generated climatic data, is a valuable tool for providing insights into the behavior of many aspects of a cropping system. Running the model with long-term weather data allows a quantification of the temporal variability in yield and response to fertilizer. In the SAT environments, the frequency with which periods of moisture shortage lead to poor fertilizer use can be determined. When losses of N from the system occur, the frequency and nature of these losses, which lead also to poor fertilizer efficiency, can be identified and their relative significance evaluated. Simulation experiments can be conducted to determine the effects of varying fertilizer rates, timing, placement depths, sources, planting times, etc., and in this way a fertilizer strategy to maximize efficiency under the uncertainties of climatic variability can be readily obtained.

Acknowledgments

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Fertilizer and Soil Fertility Research Needs in the Nineties With Special Reference to Semiarid Tropical India

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Abstract

Almost 80% of fertilizer use in India is concentrated in irrigated agriculture, and rainfed crops do not get the nutrients required for maximum production. Research by the Indian Council of Agricultural Research (ICAR) has concentrated on determining the nutrient requirements within the various agroclimatic regions of India. The research shows that integrated use of organic matter with fertilizer and the inclusion of legumes in crop rotation are important factors in minimizing costs and sustaining production. Fertilizer use in the semiarid tropics (SAT) must be correlated to rainfall and soil moisture status to obtain maximum benefit. In this region, green manures, crop residue, and livestock excreta are important components of continued crop production. Research has shown that potential exists for "biofertilizers" such as free-living and symbiotic N_2-fixing bacteria, VAM fungi, *Azolla*, and bluegreen algae to improve crop yields. In order to optimize fertilizer efficiency within a specific agroecological zone, soil testing must be used to determine economically optimal fertilizer rates for each crop. Issues concerning sustainability in crop production are discussed.

Introduction

The Indian semiarid tropics (SAT) area is spread over 10 States, namely, Tamil Nadu, Karnataka, Andhra Pradesh, Maharashtra, Madhya Pradesh, Uttar Pradesh, Punjab, Haryana, Gujarat, and Rajasthan, and covers nearly two-thirds of the country's arable area. The districts in these States are classified on the basis of normal annual rainfall, and 192 districts receiving between 500 mm and 1,500 mm rainfall are identified as semiarid. These are further divided into irrigated and unirrigated districts depending on whether more or less than 25% of the area is irrigated. On this basis, 114 districts fall under unirrigated districts and 78 districts under irrigated districts (Bapna et al., 1979).

Intercrop and Interregional Disparities in Fertilizer Use

A study by the National Council of Applied Economic Research (NCAER) has brought out several disparities in the use of fertilizers (NCAER, 1974). About 80% of fertilizer use is concentrated on four major crops, namely, rice, wheat, sugarcane, and cotton. The coarse grains, millets, pulses, and oilseeds, which are predominantly grown under rainfed situations, and most of the fruit trees do not get the required fertilization.

The skewed nature of fertilizer distribution and use in different regions is another inequality which needs correction. It is estimated that the five States of Punjab, Haryana, Uttar Pradesh, Tamil Nadu, and Andhra Pradesh, which have more than 40% of the irrigated area under food crops, account for 57% of the total fertilizer consumption in the country. Another five SAT States, namely, Gujarat, Rajasthan, Madhya Pradesh, Maharashtra, and Karnataka, with less than 20% of irrigated area under food crops, account for only 27% of total fertilizer use in the country.

An analysis of fertilizer consumption in 1985/86 in 350 districts in 16 states indicates that the level of fertilizer consumption is less than 50 kg ha^{-1} in 211 districts, between 50-100 kg ha^{-1} in 89 districts, and more than 100 kg ha^{-1} in 50 districts only. Our future efforts in fertilizer promotion should be aimed at narrowing these interregional and interdistrict disparities in fertilizer use. The State Department of Agriculture, the fertilizer industry, and the Cooperative Marketing Federations can offer considerable help in alleviating these disparities.

At the present levels of inherent fertility, these Indian soils can sustain a food-grain production of about 85 million tonnes, and additional food-grain production has to come from use of organic manures and chemical fertilizers. Although India ranks as the fourth largest producer and consumer of fertilizer nutrients in the world, the average consumption of 50 kg ha^{-1} is still very low.

Research Support for Improved Nutrient Management

Irrigated Agriculture

Various All India Coordinated Research Projects of the Indian Council of Agricultural Research (ICAR) and the agricultural universities have carried out extensive investigations on the nutrient requirements and management in various agroclimatic regions of the country. Some of the important cropping systems under irrigated agriculture where nutrient management has been investigated in detail are rice-rice, rice-wheat, sorghum-wheat, maize-wheat, jute-rice-wheat, sugarcane, and cereal-based cropping system with legume component. For these systems, the integrated use of organic manures and fertilizers reduces fertilizer requirements for the crop. In the rice-wheat system, the addition of 12 tonnes ha^{-1} of farmyard manure (FYM) could contribute about 40 kg N ha^{-1} and 13 kg P ha^{-1} during Kharif. A catch crop of sunn hemp, *Daincha*, or cowpea before rice could supply about 40-60 kg N ha^{-1}. In legume-based cereal cropping systems, it is advantageous to apply phosphate to the legume and realize the carryover effect for the benefit of the succeeding crop. Recent emphasis on increasing nitrogen fertilizer use efficiency has centered on testing of better forms of N carriers such as sulfur-coated urea, neem cake-coated urea, and urea supergranules. The beneficial effect of these carriers over prilled urea has been demonstrated under specific soil conditions and water management practices.

Rainfed Agriculture

The rainfed lands in the Indian SAT offer great scope for promoting the significant contribution of fertilizer use to total agricultural production. It is estimated that, even after the realization of the full irrigation potential in the country, about 50% of our arable land will be under rainfed agriculture. The rainfed lands are represented by Vertisols, Alfisols, Inceptisols, and Entisols. The work carried out at the research centers of the All India Coordinated Research Project for Dryland Agriculture (AICRPDA), the Central Research Institute for Dryland Agriculture (CRIDA), and the International Crops Research Institute for the Semi-Arid Tropics (ICRISAT) has provided valuable results for adoption by farmers in the area of soil fertility and fertilizer management. It is now well recognized that dryland soils are not only thirsty but also hungry for nutrients. Randhawa and Singh (1983) have discussed in detail the fertilizer management in different soil types under rainfed agriculture.

A large number of trials (Table 1) on cultivators' fields have shown that balanced fertilization provides not only higher yields but also profitable response to fertilizer on rainfed crops.

Table 1. Summary of Fertilizer Experiments on Cultivators' Fields With High-Yielding Crop Varieties Without Irrigation Over the 1969-80 Period in India

Crop	Number of Trials	Rate N	Rate P_2O_5	Rate K_2O	Mean Yield Control[a]	Mean Yield N	Mean Yield NP	Mean Yield NPK
		(kg ha^{-1})			(t ha^{-1})			
Rice (K)	380	120	60	40	2.42	3.60	4.22	4.59
Wheat (R)	627	90	60	60	0.76	1.27	1.55	1.69
Sorghum (K)	367	90	60	60	1.10	1.66	1.98	2.17
Pearl millet (K)	207	90	60	60	0.50	0.77	1.05	1.15
Chick-pea (R)	1,325	20	40	20	0.75	1.02	1.19	1.33
Pigeon pea (K)	53	20	40	20	0.30	0.59	0.93	0.98
Groundnut (K)	771	20	60	40	0.79	1.10	1.37	1.45
Cotton	55	120	60	40	0.34	0.49	0.65	0.72

a. No fertilizer applied.

Note: K = Kharif (monsoon season).
R = Rabi (post-monsoon season).

Source: Randhawa and Tandon (1982).

Table 2. Effect of Method of Fertilizer Application to Safflower on Grain Yield, Nutrient Removal, and Fertilizer N and P Recovery

Methods	Grain Yield	Nutrient Removal N	Nutrient Removal P	Nutrient Removal K	Calculated N and P Recovery N	Calculated N and P Recovery P
	(kg ha^{-1})	(kg ha^{-1})			(%)	
Control	410	13.1	2.1	31.6	-	-
Kera (15 cm by the side of seed row)	750	20.9	2.3	29.7	19.4	1.5
Pora (10 cm below seed)	1,170	32.6	4.4	67.0	48.7	17.4
Pora (16 cm below seed)	1,250	35.2	4.5	68.4	55.3	17.8

Source: Das et al. (1984).

Nitrogen has to be applied in splits depending on the stage of crop growth, rainfall distribution, and aberrant weather situations. Deep placement (10-15 cm below seed) of N has been found beneficial in post-rainy-season crops. Das et al. (1984) recorded higher yield and N recovery by safflower with deep placement of nitrogen (Table 2). In intercropping systems with pearl millet as the principal crop and greengram or fodder cowpea as a companion crop, Singh (1984) found indirect evidence of transfer of 20 kg N from legume to cereal (Table 3). Proper method of N application leads to better N recovery by the plant. In sorghum-safflower sequence cropping in black soil at ICRISAT, Kanwar and Rego (1983) found that N recovered by sorghum varied from 29% to 56% depending on method of application, namely, surface or split band application (Table 4). There was no residual effect of N applied to sorghum. Safflower could recover 1.1 to 3.1 kg ha^{-1} of N applied to sorghum.

Table 3. Grain Yield of Crops Grown in Different Intercropping Systems as Influenced by Two Levels of Fertility at Hissar

Cropping Systems	Fertility N + P_2O_5	Grain Yield Principal Crop	Grain Yield Companion Crop
	(kg ha^{-1})	(kg ha^{-1})	
Pure pearl millet	40 + 20	1,560	-
	20 + 0	1,350	-
Pearl millet + greengram	40 + 40	870	330
	20 + 20	790	320
Pearl millet + cowpea (fodder)	40 + 40	1,240	6,860
	20 + 20	1,330	6,770

Source: Singh (1984).

Table 4. Effect of Method of Application on the Recovery of 74 kg Labeled Urea-N ha^{-1} Applied to Rainy-Season Sorghum on a Vertisol in 1981

Application Method	N Recovered Soil	N Recovered Plant	N Recovered Total	N Lost or Unaccounted for
	(%)			(%)
Split band	38.6	55.6	94.2	5.8
Surface	41.8	30.5	72.3	27.7
Incorporation	45.2	28.9	74.1	25.9
S.E. ±	2.7	1.6	2.1	

Source: Kanwar and Rego (1983).

In post-monsoon rainfed crops, it is essential to relate efficient use of nitrogen fertilizer with available water capacity of the soil profile. Prihar and Sandhu (1987) have demonstrated the adjustment of fertilizer nitrogen in relation to rainfall and available water supply. They have indicated that, for the Hoshiarpur region of Punjab, the optimum N levels for 30, 40, and 60 cm of available water supply would be 50, 85, and 120 kg N ha^{-1}, respectively.

Green Manuring

For dryland situations, three methods of green manuring/green leaf manuring have been brought out as feasible:

1. Planting greengram with the early monsoon showers, picking up the pods of the first flush, ploughing in the residues, and then sowing the late monsoon or early post-monsoon crop as demonstrated in the deep black soil of Andhra Pradesh and the red soil tracts of Karnataka.

2. Interspace green manuring–Cowpea is planted in the interspace of long-duration castor bean crop grown with spacing of 90 cm in shallow red soils of Andhra Pradesh and turned under after 45 days. The benefit to castor due to the legume effect was 30 kg N ha^{-1}.
3. Greenleaf manuring in alley cropping–*Leucaena leucocephala* is now recommended as the tree component of the alley cropping system. When loppings of *L. leucocephala* were applied as green manure, 9.45 tonnes ha^{-1} green matter was turned into the soil, which added 75 kg N ha^{-1} and significantly increased the Rabi sorghum yield.

Use of Organic Sources as Manures

In the context of nutrient management on cropping system basis, the judicious use of available organic sources of manure such as FYM, compost, biogas slurry, sewage sludge, and green manures provides ample scope for increasing the soil productivity of marginal drylands and partially meeting the nutrient needs of crops. It is estimated that the total potential of nutrients ($N+P_2O_5+K_2O$) from livestock excreta in the country is around 11.05 million tonnes (Gaur and Sadasivam, 1981). Bhardwaj and Gaur (1985) estimated the availability of 185 million tonnes of crop residues from nine principal crops of India with nutrient content of 3.32 million tonnes. Considerable amounts of these crop residues are used as cattle feed and as fuel. With increased production of food grain, however, there is scope for recycling of crop residues for mulch and manuring. Research efforts to isolate efficient strains of microorganisms for quick decomposition of crop residues and to improve methods for production of nutrient-enriched organic manures will go a long way in better recycling of organic wastes for land improvement.

There is much scope for ley cropping in marginal shallow soils under dryland conditions. Reddy et al. (1984) have shown that, on shallow red soils at Hyderabad, sorghum grain yields were significantly higher in the system where *Stylosanthes hamata* was grown consecutively for 2 years as compared with the traditional castor-sorghum rotation (Table 5).

The role of green manuring in a rice-based cropping system in a noncompetitive season has been established at Punjab Agricultural University (Table 6). Beri and Meelu (1981) reported a substitution of 60 kg N ha^{-1} by turning under *Sesbania aculeata* at the time of transplanting and topdressing with N at 40-50 days after transplanting.

Table 5. Influence of *Stylosanthes hamata* on Yield and Ancillary Characteristics of Sorghum

Treatments	Plant Height	Grain Yield	Fodder Yield
	(cm)	(kg ha^{-1})	
Castor-sorghum	105.0	950	1,840
Stylo-sorghum	125.5	1,300	2,450
SEM ±	15.0	30	145
C.D. 0.05	15.1	130	440

SEM = Standard error of mean.

Source: Reddy et al. (1984).

Table 6. Nitrogen Economy in Rice-Wheat System With Green Manuring

	Rice		Residual Effect on Wheat	
N	Fallow	Green Manured	Fallow	Green Manured
(kg ha^{-1})	(t ha^{-1})		(t ha^{-1})	
0	2.37	3.85	1.67	2.37
40	4.0	4.91	1.71	2.78
80	4.63	5.27	1.88	3.18
120	4.98	5.37	2.27	3.35
Mean	4.01	4.85	1.88	2.90

Source: Beri and Meelu (1981).

Biofertilizers

The research work carried out under the Coordinated Project on Biological Nitrogen Fixation of ICAR, at the agricultural universities, and at ICRISAT has identified efficient strains of microorganisms for enhancing nitrogen fixation in legumes (pulses and oilseeds) and rice. The constraints in the large-scale propagation of *Azolla* and algae, particularly the edaphic factors, need to be identified in different agroclimatic regions so that appropriate management measures may be devised for their establishment in rice culture. Research efforts need to be stepped up in microbial genetic engineering to develop more competitive and efficient microbial strains and better storage methods, carrier materials, and inoculation methods. There is need for greater emphasis on vesicular arbuscular mycorrhizae (VAM) fungi research for more efficient exploitation of soil P and also on *Frankia* species for enhancing nitrogen for tree crops in agroforestry.

A detailed analysis of experiments at ICRISAT concerning the role of nonsymbiotic N-fixing bacteria (*Azotobacter* and *Azospirillum*) in production of coarse grains has not indicated consistent positive results. There is scope for identification of more competitive strains of these bacteria suited to different edaphic conditions in the SAT environment.

Secondary and Micronutrients

The progressive emergence of deficiencies of secondary and micronutrients under exploitive agriculture needs to be recognized, diagnosed, delineated, and corrected. Tandon and Kanwar (1984) have pointed out that for sorghum production in Vertisols, amelioration of zinc and iron deficiency deserves attention. Manganese deficiency also has been noted in Maharashtra and Madhya Pradesh. Crop nutrient surveys carried out under the Coordinated Project on Dryland Agriculture have identified extensive deficiency of phosphorus and moderate deficiency of zinc for various crops in parts of Gujarat, Maharashtra, and Karnataka. The role of gypsum as a supplier of calcium and sulfur for groundnut has been established by the work under this project, and gypsum is recommended for groundnut grown on Alfisols in Andhra Pradesh. Recently, deficiency of sulfur and response to its application have been established (Tandon, 1986). Under the Coordinated Project's long-term fertilizer experiments, yield loss without sulfur was much more pronounced in soybean in medium black soils at Jabalpur, on Kharif rice in laterite soil at Bhubaneswar, in alluvium at Barrackpore, and in Tarai soils at Pantnagar.

In areas where there are endemic nutrient stresses involving deficiency or toxicity of certain elements or imbalance in the nutrient uptake, and thus an unfavorable ionic ratio in the plant tissue, these maladies can also be corrected by a genetic approach, i.e., by developing cultivars that can tolerate such situations. Nutrient management in crop and herbage production systems will also have to monitor the possible toxic effects of certain trace elements in the long run on plant, animal, and human health. The elements that need greater attention in this type of study by scientists from multidisciplinary areas are selenium, molybdenum, and boron. Selenium toxicity in cattle fed with wheat straw and forage that contain high concentrations of selenium has been reported in some parts of Punjab and Haryana. Forage grown on alkaline soils where the water table is high can contain high levels of molybdenum causing toxicity effects in cattle. Boron toxicity in rice is also found in salt-affected soils.

Soil Testing and Balanced Fertilization

The nutrient status of soils varies from field to field. Hence fertilizer use based on soil testing assumes great importance. The 340 soil testing laboratories and 101 mobile soil testing vans in the country have a great service to render to the farmers. An overall summary of the fertility mapping of Indian soils (IARI, 1980) indicates that 95%, 98%, and 65% of the area fall in the low to medium category with respect to availability of N, P, and K, respectively (Table 7). A monitoring system for soil fertility trends at benchmark sites representing different levels of agricultural production and management should be initiated in the country by the soil testing laboratories.

Table 7. Summary of the Fertility Status of Indian Soils

Item	Available Nutrients		
	N	P_2O_5	K_2O
Samples analyzed (million)	9.2	8.2	4.5
Districts covered	364	363	360
Low fertility (%)	62.7	46.8	21.1
Medium fertility (%)	32.4	51.0	44.2
High fertility (%)	4.9	2.2	34.7

Source: IARI (1980).

The Coordinated Project on soil test/crop response correlation has developed fertilizer recommendations based on soil tests for targeted yields of major food crops. An analysis of 55 followup trials conducted on six crops indicated that the response ratio obtained for soil test-based fertilizer recommendations was 16.5 as against 8.0 for regional/state recommendations (Velayutham et al., 1985). The soil testing laboratories need to conduct a large number of followup trials as simple experiments to refine the soil test calibration obtained from experimental stations.

Because of the increase in the share of complex and mixed fertilizers, the consumption ratio of N:P_2O_5 in the country has decreased from 9:2.2 in 1951/52 to 6.8:2.4 in 1985/86. This is a welcome trend that needs to be improved and sustained. Simultaneously, regional disparities in the consumption ratio need to be corrected. For example, the N:P_2O_5 consumption ratio is wider in Haryana and Uttar Pradesh than in Punjab.

A qualitative presentation of research strategies in India directed toward efficient nutrient management is given in Table 8 (Randhawa and Tandon, 1982).

Table 8. A Qualitative Presentation of the Research Strategies Used in India Towards Efficient Fertilizer Use

Research Strategy	N	P	K	Zn
Soil testing	*	**	**	*
Suitable nutrient carrier	*	**		*
Methods of application	**	**	*	*
Timing/split application	**		*	
Accounting for residual effects		**		**
Proper phasing within a cropping system		**		*
Water management practices	**			
Complementary use of legumes	**	*		
Complementary use of FYM	*	*	*	*
Root dip in nutrient solutions		*		*
Nitrification inhibitors	**			
Slow release/coated fertilizers	**			
Reduction in losses from soil	**			
Biofertilizers	**	*		

Note: Number of asterisks indicate relative emphasis among nutrients.

Source: Randhawa and Tandon (1982).

Nutrient Management for Sustainable Agriculture

The projected food-grain production target in the year 2000 for a population of about 1 billion is 225-245 million tonnes; in 2050, when the population is expected to stabilize at around 1.5 billion, we will have to produce 380-400 million tonnes. To meet these food production targets, the fertilizer nutrient requirements are estimated at 20 and 40 million tonnes, respectively. Our advice on nutrient management must be based on detailed understanding of the soil fertility considerations in irrigated and unirrigated environments. Some of the requirements for the rainfed SAT areas are as follows:

1. Detailed characterizations of different dryland environments. These should include nutrient capacity as indicated by electroultra filtration (EUF) measurements, mineralogy of clay fraction, nutrient fixation characteristics, and soil moisture-holding capacity.
2. Soil test service for rational fertilizer recommendations. Determination of critical limits, presowing status of mineral N as an index of N requirement, P dynamics and availability in Vertisols; soil fertility summaries based on intensive and extensive soil test service; and modified general fertilizer recommendations.
3. More detailed quantification of biological N fixation. Nitrogen transfer in intercropping and sequence cropping systems, characterization of pool of organic N and its mineralization rate, better management of crop residues, and minimum tillage.
4. Nutrient dynamics and management in alternate land use systems such as agroforestry, silvipastoral, and agrihorticultural systems. Allelopathic effects and inoculation with rhizobial and mycorrhizal cultures.
5. Nutrient management in relation to soil conservation and rainwater management in Kharif and stored profile moisture in Rabi season on a watershed basis. Alleviating soil physical constraints to enhance nutrient use efficiency and efficient on-farm water management practices to minimize salinity hazards.
6. Diagnosis and amelioration of emerging macro, micro, and secondary nutrient deficiencies.
7. Development, through land use simulation models, of management techniques to arrest land degradation and impoverishment.
8. Establishment of a benchmark sites network on well-defined soil units for agrotechnology transfer and monitoring of the sustainability of production. Maintenance of a soil health and nutrient balance sheet at two to three levels of production management to foretell emerging soil fertility problems.
9. Development of better forms of nitrogenous fertilizers and enhancing the use of indigenous sources such as phosphate rock, gypsum, and phosphogypsum. Devising improved implements for simultaneous application of seeds and fertilizers suited to different soil types.

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Summary and Discussion

Session I – Setting the Stage

Chairman: J. L. Monteith

Rapporteur: T. J. Rego

World Fertilizer Market Review and Outlook

by J. H. Allgood and L. L. Hammond

Dr. Hammond reviewed the fertilizer market situation, pointing out the striking contrasts between the 1970s and 1980s. Nitrogen, phosphate, and potash production capacity increased by 90%, 84%, and 24%, respectively, during the 1970s with much of the new capacity being located in the Developing Market Economies and Centrally Planned Economies. In contrast, the 1980s has been a decade of instability. It is expected that during this period N, P, and K capacity will increase by only 22%, 33%, and 17%, respectively, and the majority of this new capacity during the 1980s will be located in Developing Market and Centrally Planned Economies. The world fertilizer supply-demand outlook seems to indicate adequate supplies of P and K and likely deficit of N by 1991. Of course, these predictions in supply-demand may change due to government policies and cropping season.

In the discussion, it was noted that doubt has been raised regarding the calculation of compound growth rate, which may distort the real situation. The author agreed.

A decline in fertilizer consumption in the United States was questioned. The decline has been attributed to a shift in grain production and market policy.

The paradox of the situation in the U.S.S.R. was noted in that this country is the biggest producer and consumer of fertilizer although it is the biggest importer of food also. The author replied that there may be other factors that limit food production.

It was noted that at a recent World Economists' Meeting, three different models predicted not much change in fertilizer production and consumption, suggesting that the market will be relatively stable in the near future.

Fertilizer Production and Consumption Trends – India

by B. C. Biswas

Dr. Biswas pointed out that commercial fertilizer production started in 1906 in India. However, initial growth in production was slow, and it is only in the last 35 years that growth has been very rapid. The demand for fertilizer was created due to (1) the introduction of high-yielding varieties, (2) an increase in irrigated area, and (3) an increase in consumption of fertilizer per unit area. During 1986/87, near self-sufficiency in fertilizer production was achieved in India (90%). The present rate of fertilizer production is around 7.1 million tonnes annually, and present consumption is 9.0 million tonnes of nutrients. By the year 2000, the production capacity may go up to 15 million tonnes, and the consumption level may be 17-18 million tonnes.

It was noted in the discussion that factors such as high temperature and low humidity may be limiting grain yield in an arid environment like West Rajasthan and may be the reason for low response to applied fertilizers under such situations.

Even though N fertilizer production capacity remained at a quite satisfactory level, the P capacity factor declined because of the limited supply of feedstock.

In general, the ratio of grain to nutrient is about 10:1, and this situation may continue until 2000 A.D. Therefore "fertilizer use efficiency" is the key factor in achieving higher production of food.

Soil Fertility and Fertilizer Management in Semiarid Tropical India – A Historical Perspective

by I. P. Abrol

Dr. Abrol reviewed soil fertility concerns from as far back as 1500 B.C. to the present day and highlighted many aspects of soil fertility in relation to crop production. Indian farmers were using organic manures in ancient times. Modern scientific study of soil fertility started in 1892 by the appointment of J. W. Leather as Imperial Chemist. As per the recommendations of the Royal Agricultural Commission, permanent manurial trials were started at Pusa, Kanpur, and at Coimbatore. Dr. Abrol also summarized the significant factors in the rapid rise in fertilizer consumption during the post-independence period, i.e., the 1960s, 1970s, and 1980s.

In the 1960s, need for fertilizer by the individual crops was given emphasis, and little concern was shown to organics, long-term aspects of fertility, and rainfed agriculture. A few coordinated projects were started.

In the 1970s, major emphasis shifted to meeting the nutrient needs of the cropping system instead of single crops, with increased emphasis on balanced nutrition and interaction of nutrients.

In the 1980s, concern was on rainfed agriculture and the farming systems approach. The interaction with water and residue management was also considered an important aspect of dryland agriculture. In irrigated agriculture, the role of legumes and the use of farmyard manure (FYM), in cropping systems were again emphasized.

In the 1990s, the emphasis will be on (1) sustainability and (2) whole farm approach, i.e., soil-plant-animal interaction.

During discussion, the role of biofertilizers was questioned. The author answered that they will serve only as a supplement to chemical fertilizers and will not be the sole source of crop nutrition.

The importance of long-term studies of soil organic matter was again emphasized. In this connection, the author mentioned that the interaction with agroforestry will supply the fuel, and the availability of FYM as a source of plant nutrients will increase.

There was also a question of pollution by nitrates in India. It was suggested that this only occurs in isolated cases such as grape vineyards or eroded soils and surface water collection areas and is not a serious problem elsewhere. It was noted that less than 10% of the farmers today apply the recommended dose of fertilizers. Therefore, pollution may not be a serious problem in the near future except possibly for certain areas such as vineyards.

The role of legumes either in crop rotation or intercropping was again emphasized. Specific fertilizer recommendations rather than general recommendations should be considered for efficient use of fertilizers.

There was discussion of fertilizer subsidy and price controls for fertilizers and food grains. The role of economists in this regard was emphasized in that government policy has a major role to play in price control. It was also stated that international prices of fertilizers do not seem to follow any pattern.

Doubts were raised about the availability of P fertilizers, which in turn may limit N use efficiency. In this regard, the government has changed its view, and a few P fertilizer production units will be set up. ICAR is reviewing its coordinated projects, and new broad-viewed networking with emphasis on interactions may be the future line of work in fertility management.

Session II – SAT Environments and Soil Fertility Management
Chairman: I. P. Abrol
Rapporteur: K. L. Sahrawat

Soil Fertility Problems in the Semiarid Tropics of Africa
by P.L.G. Vlek and A. U. Mokwunye

Dr. Vlek largely covered aspects of soil fertility management in Africa. Soils in Africa are generally chemically fragile and need judicious use of fertilizers and crop residues in order to maintain their fertility in the absence of the traditional shifting cultivation system that maintained soil fertility in the past. In Africa, P is the most important nutrient limiting crop productivity, but because of the low phosphate adsorption capacity of these soils, only small amounts of P (30-40 kg P_2O_5 ha^{-1}) are necessary to satisfy the crop P requirements. Significant national deposits of phosphate rocks in West Africa offer advantages for use as P sources either directly or after partial acidulation. Deficiencies of S, Mg, K, and Zn are also observed in many ecosystems in the region. Response to N in West Africa is dependent on rainfall, and split application is generally better.

A question was raised regarding applicability of the experience gained in West Africa in N management to similar problems in the arid regions of Jodhpur particularly with regard to the amount of N to be added at planting. It was suggested that N application would depend on crop response and rainfall and the crop's need for N. About 20 kg N ha^{-1} may be applied at planting or as soon as possible after planting based on the experience in West Africa. A question was raised about the sustainability of the sorghum and millet system in the Sahel region. It was stated that the system could be sustained if a part of the straw is recycled along with P application. N could be obtained by alley cropping. However, with 3% annual growth in population, it is not easy to sustain the system because fallowing of soils is completely eliminated. In this regard, an example is the Rajasthan arid zone, where the system is sustainable with a synergistic combination of agriculture and animals, an approach which may not be feasible in West Africa.

A question was raised about the possible diversification of crops in the SAT since the crops grown are needed for grain as well as fodder supply. There was good discussion about the holding size and fertilizer use and management. It was thought that, though small farms are more efficient than the larger ones, diversification is possible only with larger holdings of 2-5 ha.

The following point was driven home clearly: If the small farmer's resource base can be ameliorated, then he can effectively adopt improved technology because such technology is scale neutral but not resource neutral. It was felt that the cash constraint has been one of the most important limitations for fertilizer use. The area to be treated with phosphate fertilizer within Africa is very large.

Elements of Climate – Their Relevance to Crop Productivity and Fertilizer Use Planning in the Semiarid Tropics
by S. M. Virmani, A.K.S. Huda, R. P. Singh, T. J. Rego, and K. V. Subba Rao

Dr. Virmani emphasized the need for adjusting fertilizer use in relation to rainfall in that the interaction between water and fertilizer N is crucial for increasing crop productivity. Several examples illustrated how water conservation could promote fertilizer use for increasing crop productivity. Results were presented to show that the variability in rainfall and crop productivity of sorghum and chick-pea were of the same order (30%) during the last 11 years at the ICRISAT Center. For top yields, fertilizers contributed to about 50% of that yield increase in climatically good years.

In discussing Dr. Virmani's presentation, it was felt that soil and water conservation combined with crop production activity is likely to succeed in increasing crop productivity and implementation of the improved technology. It was also felt that about 40 kg N ha^{-1} could always be applied profitably at the ICRISAT Center and surroundings of Hyderabad if water is conserved.

It was emphasized that whatever technology we use should not only be productive and sustainable but also in harmony with the environment. There is also a great need for a policy for improving the soil resources to encourage conservation and maintain sustainable crop production.

It was hinted that the Government of India was aware of these problems and a policy decision in the right direction is contemplated.

Session III – Fertilizer Use and Management in the SAT
Chairman: N. S. Randhawa
Rapporteur: Piara Singh

Nitrogen Availability in SAT Soils: Environmental Effects on Soil Processes
by J. R. Burford and K. L. Sahrawat

Dr. Burford stated that, in the past, the fertilizer needs of crops in India have been assessed by conducting numerous fertilizer response experiments, and that most recommendations have been made using empirical approaches. There has been little attempt to understand the soil processes that could be used to help explain responses to fertilizer applications, especially in the tropical rainfed environment. Recent advances in crop modeling have led to the suggestion that models based on physical environmental factors may be extended to include descriptions of nutrient behavior. Therefore, stratifying the environment (both agroclimate and soil) and using the modeling approach could lead to better management of fertilizers under variable environments. Dr. Burford stressed the need to assess the effect of the harsh SAT environment on both supply (from soil and fertilizer) and losses of nutrients in order to quantify nutrient availability and plant response. He also emphasized the need to have appropriate methodologies for quantifying various nutrient transformation processes in the soil to provide information needed for models that include nutrient terms.

Questions were raised regarding the role of climatic factors (such as rainfall and temperature) in enhancing the availability of nutrients in the soil. To this, Dr. Burford replied that such information on the interactions of soil and climate is scanty for the rainfed tropical environments, and more information needs to be generated. Questions were also raised regarding the prediction of nitrate nitrogen profiles, provided the information on root growth, soil moisture movement, and nitrogen mineralization is available. Dr. Godwin added that this is what is being done in modeling of nutrient uptake from the soils, and it is possible to model individual processes to some degree. Because soil tillage can influence water management in soil, and thus leaching of nutrients, land management practices must be considered in assessing soil nutrient availability.

Nitrogen Fertilizers – Their Use and Management in the Indian Semiarid Tropics
by J. C. Katyal

Dr. Katyal stated at the outset that nitrogen is the deficient element in almost all of India and urea is the dominant fertilizer being used. IFDC/ICRISAT collaborative experiments have shown that about 7%-10% of nitrogen is lost from Vertisols and Alfisols, and the remaining N is either taken up by the crop or stays in the soil. From shallow soils, losses as great as 25% to 30% can occur. Dr. Katyal discussed nitrogen efficiency in relation to timing of fertilizer application, placement of fertilizer, kinds of fertilizer, and rainfall and concluded that placement of fertilizer gives best results in the post-rainy season. He also concluded that the fertilizers containing nitrate are not the best choice for shallow soils; however, these products could be used on deep soils. He suggested that denitrification is a major cause of nitrogen loss from soils and needs to be investigated.

Questions and comments were raised concerning the use of climatic information and weather forecasting to increase the efficiency of fertilizer use. Dr. Katyal agreed to this and considered it to be a useful activity in the future. Questions were also raised regarding the fate of "locked-up" N at the end of the season, to which Dr. Katyal replied that further investigation is needed in that the residual recovery was only 4%-5% over a period of 4 years.

Management of Fertilizer Nutrients Other Than Nitrogen in the Semiarid Tropics of India
by H.L.S. Tandon and T. J. Rego

Dr. Tandon reviewed the available information on the management of fertilizer nutrients other than nitrogen in SAT India. He mentioned that crop responses to fertilizer nutrients are high under dryland conditions. P and Zn are of major importance for the nonirrigated SAT, but significant yield responses to K and S have also been obtained in reddish brown laterite soils of the Bangalore area. Dr. Tandon also mentioned that iron chlorosis is increasingly being mentioned as a problem in the SAT. He made suggestions for further research on the nutrients he reviewed. He also emphasized that crops often need more than one fertilizer nutrient and thus maximum yield response can only be achieved in the presence of a balanced approach to crop nutrition.

Questions were asked in relation to the interaction of climate with nutrient use efficiency and the need to study root growth, nutrient availability, and other physiological information needed to explain plant responses to fertilizers. It was also emphasized that, while describing the nutrient status of soils in various states of India, we need to have a look at the relative contribution of different states to the total grain production of the country. Therefore we need not expand our soil fertility surveys for micronutrients to all states at this stage.

Significance of Biological Nitrogen Fixation and Organic Manures in Soil Fertility Management

by K. K. Lee and S. P. Wani

Dr. Lee reviewed the work done on nitrogen fixation and the use of organic manures in relation to soil fertility management. He discussed the work done at ICRISAT and by the research workers in other environments and stressed the need to quantify the contribution of legumes to N availability for cereals. He also emphasized the need to have long-term manuring experiments in order to study the influence of manures on both the physical and chemical properties of soils and on crop response.

Questions were raised regarding the role of nitrogen fixation research in N management of crops under dryland conditions. It was also stated that, although the contribution of legumes in a crop sequence is well known and well documented, a legume may not fit well in the cropping systems acceptable to the farmer.

Fertilizer Use on Soils of the Semiarid Tropics – Economic and Social Factors

by R. P. Singh, S. K. Das, and Y.V.R. Reddy

Dr. Singh pointed out that fertilizers are used in the dryland crops grown on both Alfisols and Vertisols. However, the amounts applied and the ratio of N and P used vary greatly depending on climate, crop, and soil type. Farmers usually tend to apply fertilizers as a basal dose, and topdressing is not common. The high cost of fertilizers and lack of finance are major problems for farmers, and it is thought that subsidies on fertilizer and farm credit schemes would help boost fertilizer use in rainfed areas. Because better moisture regimes are found in Vertisols, fertilizer use is higher in these soils than with Alfisols. Training of farmers and providing demonstrations as done in KVK and watershed villages would help increase fertilizer use. It was found that application of FYM rather than chemical fertilizers is a general feature in Alfisols and Vertisols although the quantities used are meager.

Queries were made regarding the basal versus the split application of fertilizers because it is believed that split applications of fertilizers have often given better results. Water resource development in rainfed areas was emphasized because fertilizer use is linked with water availability. Dr. Randhawa stressed that all technologies generated on fertilizer use and water resource development need to be integrated with the cropping system used by the farmer before they will be adopted for general use.

Session IV – Modeling Soil Nutrients and Research Needs
Chairman: J. S. Kanwar
Rapporteur: S. P. Wani

Simulation of N Dynamics in Cropping Systems of the Semiarid Tropics

by D. C. Godwin, U. Singh, G. Alagarswamy, and J. T. Ritchie

Dr. Godwin noted that N use efficiency varies from 10%-90% with an average of 50%. Several factors such as weather, plant genotype, and soil properties affect the efficiency of N use by the crop.

The CERES models for wheat, maize, barley, sorghum, and millet consider:

- Water balance
- N source
- Phenology
- Photoperiod
- Vegetative phase
- Grain fill period

The N component of the model considers mineralization, immobilization, denitrification, leaching, N uptake, organic matter addition, and degradation as governed by various environmental and other factors. Dr. Godwin also covered the application of the simulation models. Questions were asked about the applicability of models for arid areas where rainfall is not predictable and about how the effects of moisture and temperature are integrated over the period. It was mentioned that the wheat model has been exhaustively tested in dry and wet areas and has performed well. However, the millet model is new and has not yet been tested widely. Mineralization is calculated on a day-to-day basis and not integrated over the period.

The possibility of using satellite data with simulation models for estimating yields over large areas was raised. Dr. Godwin responded that models could be used for small areas only, and he mentioned the danger in overselling the model as well as the requirement for correct information on N supply, pests, and diseases.

Fertilizer and Soil Fertility Research Needs in the Nineties With Special Reference to Semiarid Tropical India

by N. S. Randhawa and M. Velayutham

Dr. Randhawa mentioned that fertilizer use trends in India vary greatly depending on region and crop. Presently, 80% of fertilizer use is concentrated on rice, sugarcane, and cotton, and only a very small proportion of fertilizer is used on dry lands.

Dr. Randhawa discussed irrigated agriculture and quoted the example of Punjab where on 0.6 million ha average wheat yields exceed 4 t ha^{-1}. He also mentioned that large quantities of crop residues are available under such intensive agriculture schemes.

He discussed rainfed agriculture with respect to fertilizer response, irrigation, method of fertilizer placement, organic manuring, biofertilizers, etc. As was shown by the example of finger millet production in Karnataka, farmers are interested in new varieties and the associated technologies if the results are good. Also, micronutrients must be considered in intensive agriculture.

Dr. Randhawa discussed the future issues for research, especially the following:

1. Characterization of rainfed areas.
2. Biological N_2 fixation – more detailed quantification is needed, and its role in intercropping must be defined.
3. Organic manuring – the building of an organic N pool in the soil must be understood.
4. Nutrient and rainwater management in the SAT.
5. Diagnosis and amelioration for macro- and micronutrient deficiencies.
6. Establishment of benchmark sites and network studies.

During discussion, questions were raised about the role of government in increasing the use of fertilizer in dryland agriculture. It was also noted that future work must be divided into important and secondary areas of research.

The simulation models were recognized as having an important role to play in improving crop productivity by increasing fertilizer use and its efficiency. It is expected that the workshop on modeling will identify the needs for running a coordinated research program to bridge the gaps in the available knowledge.

Fertilizers have an important role to play in improving crop productivity in dryland agriculture. However, much more research needs to be done on green manuring, organic manuring, exact quantification of biological N_2 fixation, etc. There is a need for network and benchmark study programs in the SAT.

Closing Session
Chairman: L. L. Hammond
Rapporteur: C. B. Christianson

This final session presented an opportunity for delegates to summarize points that had arisen in the previous discussions.

It was noted that the colloquium had provided a number of definitions to the term sustainable agriculture in the SAT and highlighted the need for good land and water management before adoption by the farmer of improved technology. It was noted that fertilizers have had a critical role in the past in helping India meet the food requirements of her people. Though food production capacity is presently sufficient to meet the needs of the population, India's production capacity is not growing as quickly as is the number of people that must be fed. As a result, a food deficit could soon develop in India.

In order to maintain production capacity, it is essential to continue research with the goal of optimizing fertilizer use efficiency. In this respect, both national and international centers have a significant role to play in India.

It was again emphasized that questions of sustainability of production must be addressed when developing crop management strategies. Production programs that achieve immediate yield increases at the expense of long-term production capacity must be avoided.

This colloquium was provided as a forum for scientists to interact and to identify priorities for future research. The goals of the workshop had been stated as follows:

- Collate up-to-date knowledge of fertilizer use in the SAT.
- Identify principal impediments to on-farm use of fertilizer.
- Investigate aspects of fertilizer use efficiency in the SAT.
- Set goals for future research.

The consensus of the group in attendance was that these goals had been met.

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