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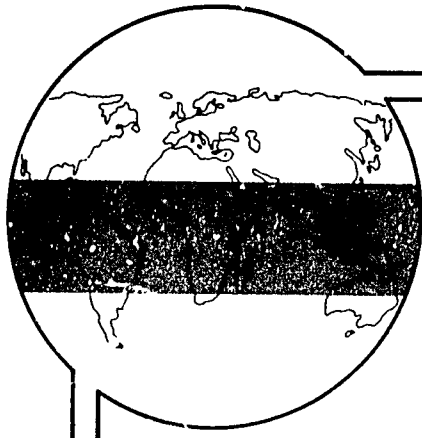
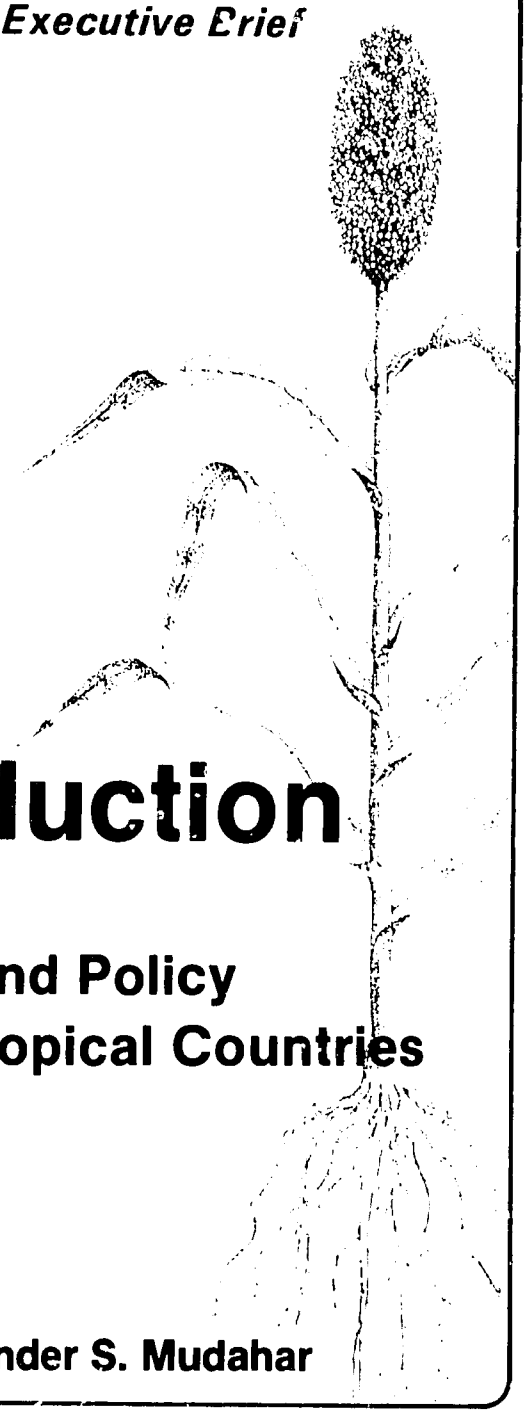


Executive Brief



Fertilizer Sulfur and Food Production

Research and Policy Implications for Tropical Countries

by J. S. Kanwar and Mohinder S. Mudahar

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Abstract

This study deals with the economic importance of sulfur in the fertilizer industry, food production, and the agricultural sector in the tropical countries of Asia, Africa, and Latin America. The executive brief provides the highlights, and complete details are available in the companion volume as Technical Bulletin No. 28. The study provides guidelines for future directions in fertilizer sulfur research and public policy. Even though the primary focus is on the tropical countries, the study is expected to be useful for fertilizer researchers, extension agents, manufacturers, distributors, planners, and policymakers around the world.

The main objectives are these: to analyze sulfur deficiency as a constraint to food production by examining the nature, causes, magnitude, and location of sulfur deficiency and crop response to applied fertilizer sulfur; to estimate aggregate fertilizer sulfur requirements, supplies, and implied gaps between the two in selected tropical countries and regions from 1960 to 2000; to examine past performance, the current economic situation, and future outlook with respect to sulfur demand, supply, prices, resources, and trade; to evaluate alternative fertilizer sulfur strategies in the context of indigenous sulfur resources; and to analyze implications for fertilizer sulfur research and public policy.

Sulfur is one of the major plant nutrients. It rivals nitrogen in protein synthesis and phosphorus in uptake by crops. Yet its importance in tropical agriculture has still not been fully recognized. Sulfur deficiency, inherent or induced, is widespread and growing, adversely affecting input productivity, crop production, and human nutrition. Serious sulfur deficiency problems have been identified in 46 tropical countries, including 10 in Asia, 21 in Africa, and 15 in Latin America. Intensification of agriculture, use of improved crop varieties, an increasing use of sulfur-free fertilizers, phosphating, liming, and leaching, especially in coarse-textured soils, are further aggravating the sulfur problem.

The world sulfur requirements in the year 2000 are estimated to be approximately 50 million mt of sulfur as crop nutrient and 65 million mt of sulfur for the fertilizer industry. The projected fertilizer sulfur gaps are estimated to be large and widening. Unless something is done to bridge these gaps, national and international efforts to accelerate food production will be seriously handicapped. This is a real challenge and also a great opportunity. The research and policy programs directed at removing sulfur as a constraint to agricultural production are expected to yield large economic payoffs.

In order to deal with increasing sulfur gaps, there is a need to identify, develop, evaluate, and transfer economically efficient fertilizer technology and strategies appropriate for tropical countries. Since most of the tropical countries are net importers of sulfur, alternative sulfur supply strategies must emphasize the use of indigenous sources such as gypsum, phosphogypsum, and pyrites. Even though a large share of sulfur is used in the fertilizer industry, mainly to manufacture phosphate fertilizers, most of it is discarded as byproduct phosphogypsum. Use of phosphogypsum and fortification of popular fertilizers with sulfur deserve high priority.

Sulfur-containing fertilizers are rarely priced for their sulfur content. As long as the sulfur is considered merely a bonus, the fertilizer industry will have no economic incentive to manufacture the sulfur-containing fertilizers as main products. A priority should be given to locally available sulfur resources, crop residue management, and monitoring of irrigation water, fertilizer use, and fertilizer policies. More field studies than greenhouse studies are necessary for the investigation of sulfur problems and the development of sulfur supply strategies. Appropriate information with respect to sulfur supply, use, response, uptake, prices, and economics is needed in order to develop sulfur use recommendations, regulations, research strategies, and public policy.

The national governments must take a lead in promoting balanced nutrient use and efficient public policies that encourage the production, imports, distribution, and use of sulfur-containing fertilizers. The international organizations should play a crucial role as a catalyst in initiating, facilitating, and funding interdisciplinary fertilizer sulfur research and development programs. Such a novel approach can result in formulating and implementing appropriate national sulfur strategies to alleviate malnutrition and hunger in the world.

Key Words: Fertilizer sulfur, food production, tropical countries, research strategies, public policy

Foreword

Fertilizer is a vital component of strategies for expanding food production. The rapid growth in population and the widening food deficits in tropical countries of Asia, Africa, and Latin America call attention to those aspects of fertilization that have been neglected but are expected to yield large economic payoffs in the future. Fertilizer sulfur falls into this category.

In the past, fertilizer sulfur received little attention from researchers and policymakers since sulfur deficiency was not considered a serious problem. Sulfur deficiency was not a problem because of low crop yields, extensive cropping, and incidental supply of sulfur through rain, irrigation water, manures, and sulfur-containing fertilizers.

However, the situation has changed in the last three decades. Modern agriculture, based on high crop yields, intensive cropping, improved crop varieties and greater use of sulfur-free fertilizers, and environmental regulations restricting sulfur emissions are creating large gaps between sulfur supply and sulfur requirements. Sulfur deficiencies are widespread and growing. Consequently, the full potential of a modern agricultural system in tropical countries is not being realized.

This research effort is the result of recognition of the seriousness of the sulfur problem and its adverse impact on food production as well as IFDC's dedication to the development and transfer of economically efficient fertilizer technology and know-how to tropical countries. This is a comprehensive analysis of the technical and economic linkages between fertilizer sulfur and food production, and it provides guidelines for future directions in fertilizer sulfur research and public policy.

The project was jointly undertaken by Dr. J. S. Kanwar, Director of Research, ICRISAT, and Dr. Mohinder S. Mudahar, Economist, IFDC. Dr. Kanwar, an eminent soil scientist, spent his 1982/83 sabbatical year at IFDC and participated in this research endeavor. This study now paves the way and provides needed impetus for national and international research and financial organizations to initiate and finance major fertilizer sulfur research and development programs.

The study is published in two volumes. The highlights are contained in this technical bulletin, and the complete details are published as Technical Bulletin No. 28. It is hoped that this study will be of major significance to fertilizer researchers, extension agents, manufacturers, distributors, planners, and policymakers in their efforts to improve fertilizer use efficiency and alleviate world hunger.

Donald L. McCune
Managing Director
International Fertilizer
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Symbols, Acronyms, and Abbreviations

Fertilizers and Chemicals

Al ..... Aluminum
AS ..... Ammonium sulfate
Ca ..... Calcium
DAP ..... Diammonium phosphate
FYM ..... Farmyard manure
K_2O ..... Potassium, expressed as potassium oxide
Mg ..... Magnesium
N ..... Nitrogen
P ..... Phosphorus
P_2O_5 ..... Phosphate, expressed as phosphorus pentoxide
S ..... Sulfur
SO_4 ..... Sulfate
SSP ..... Single superphosphate
TSP ..... Triple superphosphate
Zn ..... Zinc

Units of Measurement

cm ..... centimeter
ha ..... hectare
kg ..... kilogram
mt ..... metric ton
ppm ..... parts per million

Miscellaneous

$ ..... U.S. dollar
f.o.b. ..... free on board

Organizations

FAO ..... Food and Agriculture Organization of the United Nations
IARI ..... Indian Agricultural Research Institute
ICRISAT ..... International Crops Research Institute for the Semi-Arid Tropics
IFDC ..... International Fertilizer Development Center
ODA ..... Overseas Development Administration
UNIDO ..... United Nations Industrial Development Organization

Sulfur—A Neglected Fertilizer Nutrient

Sulfur (S) is one of the major plant nutrients. It rivals phosphorus (P) in its uptake by plants and nitrogen (N) in protein synthesis, and it is indispensable for certain essential amino acids. Yet its significance as a fertilizer nutrient has not been recognized, particularly in tropical agriculture.

There are two primary reasons why sulfur has not received adequate attention: (1) low-yield subsistence agriculture has been based on exploiting the natural reserves of soil sulfur, and (2) sulfur is supplied to agroecosystems from the atmosphere through rain, dust, and by gaseous absorption as well as by irrigation water, manures, and fertilizers like ammonium sulfate (AS) and single superphosphate (SSP), which added more sulfur than nitrogen or phosphorus to the soil so that the need for sulfur fertilizers was not felt in many countries.

However, the situation has changed in the last three decades. The replacement of AS and SSP with urea and triple superphosphate (TSP), respectively, which contain very little sulfur, and the focus of modern agriculture on high-yielding crop varieties, greater use of fertilizers, and intensive cropping are creating a large gap in the soil system between the sulfur supply and sulfur requirements. Thus, the potential of the modern agricultural system is not being fully realized. This study is the result of growing awareness of this problem and of continuing efforts by the International Fertilizer Development Center (IFDC) to identify fertilizer technology, soil fertility, and public policy constraints to agricultural production in the developing tropical countries.

Objectives of the Study

The primary objective of this study is to analyze the economic importance of sulfur in the fertilizer industry, food production, and the agricultural sector in the tropical countries. More specifically, the objectives of the study are as follows:

1. To provide a perspective on food and nutrition problems in tropical countries.
2. To examine the role of fertilizer sulfur in strategies for increasing food production.
3. To discuss the crucial role of sulfur in plant nutrition and its effect on human and animal nutrition.
4. To examine the sulfur status of tropical soils and its relation to crop production.
5. To analyze sulfur deficiency, with particular reference to nature, causes, magnitude, location, and crops affected, as well as to evaluate the diagnostic techniques.
6. To evaluate crop response to fertilizer sulfur in the tropics.
7. To estimate aggregate fertilizer sulfur requirements, supplies, and implied sulfur gaps in selected countries from 1960 to 2000.
8. To examine sulfur demand, supply, prices, resources, and trade in terms of past performance, the current economic situation, and future outlook.
9. To evaluate alternative fertilizer sulfur sources and supply strategies, particularly in the context of indigenous sulfur resources.
10. To examine the implications for fertilizer sulfur research and public policy, particularly in tropical countries.

Tropics and Food Production—The Target Area of Study

The central theme of the study is the relationship between fertilizer sulfur and food production in the developing countries of the tropics. The greatest problem of these regions is food (both quality and quantity), and the most serious threat to humanity is hunger and malnutrition caused by the widening gap between the demand for food and its production in the tropics.

The study was restricted to the tropics (humid, subhumid, and semiarid tropics), which is a region covering about 4.96 billion ha of land. Approximately 95% of it lies in Asia, Africa, and Latin America, and it includes areas like India, Indonesia, Bangladesh, Nigeria, Brazil, and Mexico which have some of the world's largest populations. Many experts believe that the future of humanity lies in the tropics.

The common man's concept of the tropics is limited to humid and subhumid tropics; yet the semiarid tropics is also an important agricultural region of the tropics. Moreover, most of the evidence for sulfur deficiency that has been reported in literature in the last 30 years is from this region. The harsh environments and large area of sandy or coarse-textured soils (nearly 452 million ha)

make this region an important component of the target area of the study because these soils are inherently low in organic matter and are highly susceptible to leaching of sulfate-S (SO_4-S). Sorghum, millet, groundnut, pulses, soybeans, oilseed, and cotton are the most common crops of the semiarid tropics, and they all have high sulfur requirements.

Sulfur in Plant Nutrition

The role of sulfur as a necessary nutrient for plant growth is undisputed; less clear, however, is the way in which sulfur performs its valuable functions and how it interacts in the soil, the living matter, and with other nutrients. Although considerable empirical information is available, more precise information is needed on these interactions. This is particularly important for tropical countries that consider phosphate and lime the key factors of sound fertilizer practice but fail to appreciate their effect in causing leaching losses of SO_4-S.

The disproportionately higher use of nitrogen and phosphate (P_2O_5) in comparison with sulfur, which is evident from the examples of fertilizer consumption in India and Brazil (Table 1), may adversely affect the availability of sulfur to plants. The widening ratios of N:S in fertilizers will lower efficiency of nitrogen utilization because of sulfur deficiency; the widening ratio of P:S will worsen the situation by aggravating sulfur deficiency through loss of sulfur in leaching.

Sulfur also differs from nitrogen in that, unlike nitrogen, it is not transferred from old leaves to growing parts or young leaves; nor can it be fixed as nitrogen can be fixed biologically from the atmosphere. There is a need for collection of sulfur-uptake data for different crops and especially their high-yielding varieties in different tropical regions to develop better understanding of the S-fertilizer problems for crop production.

Table 1.
Changes in Estimated N:S and P_2O_5:S Ratios in Total Fertilizer Consumption in India and Brazil Over Time

	N:S Ratios		P_2O_5:S Ratios	
Year	India	Brazil	India	Brazil
1960/61	0.9	0.9	0.2	1.1
1970/71	3.8	1.1	0.9	1.5
1980/81	14.1	1.8	4.3	4.1

Sulfur in Food Production and Human Nutrition

A survey of available evidence indicates that sulfur deficiency in soil adversely affects not only crop yields but also the nutritional quality of the crop. The data, although scanty, cannot be overlooked because of the serious nutritional consequences of sulfur deficiency.

Some examples of crops and areas in which sulfur deficiency in the soil has affected nutritional quality are as follows: **Asia**—rice in Sulawesi province of Indonesia; wheat, oilseeds (groundnuts, rape and mustard, soybeans), pulses and potatoes in India; **Latin America**—soybeans, maize, beans, rice, and pasture legumes in Brazil; and **Africa**—millets in Uganda. These examples are warning signals of potentially serious problems for human nutrition.

Sulfur deficiencies in tropical countries cause a reduction in the amount of methionine, cysteine, and cystine types of sulfur-containing essential amino acids in groundnuts, pulses, and cereals that will be disastrous for cereal-consuming countries. The gravity of the problem is intensified by the decline in production of these food commodities and the deterioration in their quality because of sulfur deficiency. The shortage of oil seeds and pulses, the widening protein gap, and increasing malnutrition are well-recognized problems of the developing countries in the tropics, and sulfur deficiency is worsening the situation.

There is much evidence that sulfur fertilization improves the quality of pasture legumes and grasses in all the tropical countries and, thus, directly affects animal health. Consequently, sulfur deficiency affects the quality of food for both human beings and other animals in the tropical countries. The magnitude of the problem cannot be quantified accurately because of inadequate research data. However, using as a base the average sulfur removal by crops and the present growth rate for the production of each crop, we have estimated the total sulfur removal and hence the likely gap between sulfur supply and requirements by the year 2000.

The general decline in the percentage share of the total sulfur uptake required for the likely production of pulses, oilseeds, and groundnuts in India and Nigeria during 1960, 1980, and 2000 indicates the potential impact of sulfur deficiency in the nutrition of the people who depend on these foods as sources of sulfur-bearing amino acids (Table 2). The phenomenal rise in production and exportation of soybeans from Brazil is over-

straining the sulfur reserves of the soil and creating a greater need for their replenishment. The slow growth or even a decline in production of pulses and groundnuts is also an indication that less sulfur is available in the food system in many tropical countries.

Table 2.
Estimated Proportion of Sulfur Uptake by Pulses and Oilseeds in India and Nigeria from 1960 to 2000

	Percentage of Estimated Total S Uptake by 15 Crops/Crop Groups[a]					
	India			Nigeria		
	1960	1980	2000	1960	1980	2000
Pulses	14.58	8.26	4.86	-	-	-
Oilseeds[b]	4.76	4.57	3.11	0.50	1.33	1.36
Groundnuts	5.29	4.64	3.40	11.68	5.12	3.45

a. Crops and crop groups included in this analysis of the estimated sulfur requirements are wheat, rice, maize, sorghum, millet, pulses, root crops, oil seeds, cotton, groundnuts, sugarcane, tobacco, coffee, soybeans, and oil palm.
b. Other than soybeans and groundnuts.

Sulfur Status in the Tropics—Additions

The supply of sulfur depends on (1) the sulfur-supplying capacity of the soil and (2) the addition of sulfur from external sources such as atmosphere, irrigation water, manures, and crop residues, as well as the addition from chemical sources, i.e., sulfur-containing fertilizers and other chemicals.

Sulfur-Supplying Capacity of Tropical Soils

There is scanty information about the amounts, forms, and distribution of sulfur, its availability to crops, and the rate of its disappearance from the agricultural system. However, available information suggests that, in general, tropical soils of Asia, Africa, and Latin America have low total reserves of sulfur because of low quantities of organic matter and its rapid mineralization as well as leaching losses.

There are some soils with high total sulfur and organic sulfur but limited available sulfur. The volcanic ash soils, the Andepts, may have a high organic matter content and a large amount of organic sulfur, but they are poor in available sulfur because of higher adsorption and immobilization of sulfur. Hence, they respond to sulfur application.

There is another large group of soils that have low sulfur-adsorption capacity in the surface soil but higher sulfur-adsorption capacity in the subsoil; they show a high amount of total sulfur reserves. Yet even in these soils the shallow-rooted crops generally suffer from sulfur deficiency. Deep-rooted crops like cotton may also initially experience a setback because of the low supply of available sulfur; after initial nutrient stress, however, many deep-rooted crops may be able to partly exploit the adsorbed sulfur.

Another group of soils is coarse-textured soils, with low reserves of sulfur, low sulfur-adsorption capacity, and high susceptibility to leaching losses. In such soils, besides determining the amounts of sulfur fertilizers to be used, the main problem is to reduce the loss of applied sulfur. These soils are very responsive to sulfur application.

Notwithstanding the limitations of the methods used for determining available sulfur and the inadequacy of research results from many countries, it is evident that a significant percentage of the soils in tropical regions are deficient in available sulfur. In some cases sulfur deficiency closely follows phosphorus deficiency.

As a result of leaching and lack of replenishment of the nutrients lost, soils of the tropical region, especially the coarse-textured soils and highly weathered soils such as Ultisols, Oxisols, Alfisols, and Inceptisols, are either inherently deficient in sulfur or are likely to become more deficient after clearing of the land, burning of the vegetation, and continuous cropping. Sulfur trends in virgin and continuously cropped lands of Brazil indicate that induced sulfur deficiency will soon become a limiting factor for crop production (Figure 1). Clearly any future strategy for increasing food production in new tropical areas must include sulfur fertilizers in the research and development programs.

Furthermore, there is evidence that sulfur deficiency in tropical soils is also aggravated by liming, phosphating, and an imbalanced use of NPK fertilizers that exclude sulfur. Thus, to avoid compounding the adverse effects of the "green revolution," which is synonymous with the use of high-yielding varieties of cereals and large amounts of nitrogenous fertilizers, the use of sulfur-supplying fertilizers becomes necessary for such situations.

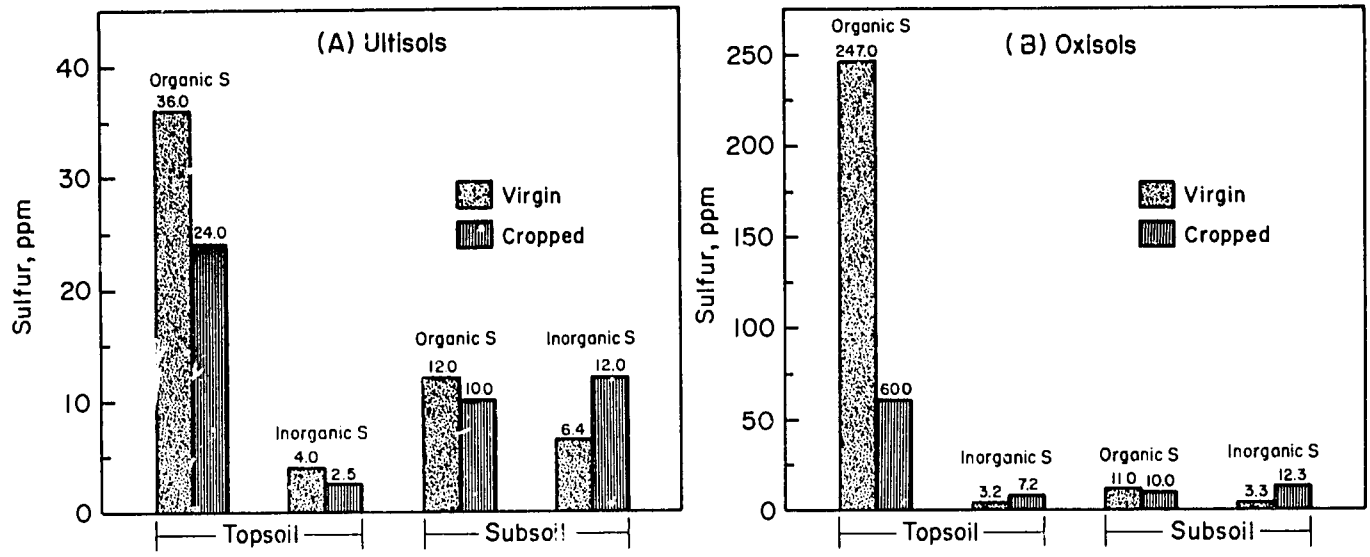


Figure 1. Effect of 20-30 Years of Cropping on Forms and Amounts of S in Two Soils of Brazil.

Contribution of Sulfur From External Sources

Contribution of Atmosphere

Studies from Nigeria and Kenya show that approximately 2-3 kg S/ha is added annually from the atmosphere to the soil and the amount increases with the rainfall. Such information is not available from the other tropical countries; however, on the basis of evidence from rural areas of tropical regions of Australia, central Kenya, and northern Nigeria, one could not expect the sulfur contribution from the atmosphere to be any higher than these estimates indicate. Nevertheless, there is need for collection of such data in developing tropical countries.

Contribution by Irrigation Water

The SO_4 in irrigation water could become an important source of sulfur to crops in irrigated areas. However, there is little research on irrigation as a source of sulfur in most of the tropical countries, particularly in the semiarid tropics where irrigation is becoming an important part of the strategy for increasing crop production.

Irrigation water of satisfactory quality with respect to the salinity and with a sufficient amount of SO_4-S could partially meet the sulfur needs of the crops. However, in spite of many normal waters with high SO_4-S content in India and elsewhere, sulfur deficiencies have still been observed.

There is also evidence of sulfur deficiency manifesting itself in areas irrigated with waters of low SO_4 content. Thus, the role of irrigation water in contributing sulfur to soil cannot be correctly assessed without more in-depth studies. Some of the conflicting results being obtained from different areas could be attributed to the sulfur content of water and the nature of soil.

Contribution by Crop Residues, Manures, and Fertilizers

In the developing countries of the tropics, crop residues are either removed or burned. Thus, the addition of sulfur through crop residues is very small. Likewise the average use of fertilizers and manures is so low that the contribution from this source is too small to be of major consequence. However, this can become an important source of sulfur with the modern system of agriculture and high rate of fertilizer application.

Thus, with the traditional system of farming and subsistence agriculture, the estimated annual additions of sulfur through all the external sources in tropical agriculture for all practical purposes will be no more than 4-5 kg/ha.

Sulfur Status in the Tropics—Removals

The removal of sulfur depends on sulfur needs of the crops and cropping systems, sulfur losses through drainage and immobilization, efficiency of applied sources of sulfur, and interactions of sulfur with other nutrients.

Crop removal appears to be the major source of depletion of sulfur, and drainage or leaching losses seem to be second. Volatilization loss in submerged soils could be another source of sulfur depletion. However, the nature and magnitude of sulfur depletion depend on crop, soil, and other factors. The adsorption of sulfur also reduces the amount of sulfur available to the crop. The average sulfur removal for producing 1 mt of food grain for important crop groups is as follows: cereals (wheat and rice)—3-4 kg; sorghum and millet—5-8 kg; pulses and legumes—8 kg; and oilseeds—12 kg.

Estimates of average levels of sulfur additions from fertilizer sources and sulfur uptake requirements per hectare of cropped area in India, Indonesia, Nigeria, and Brazil are given in Table 3. These estimates indicate that in the transitional stage, as agriculture changed from subsistence to modern farming systems, the sulfur requirements per hectare increased and sulfur additions generally decreased. This is a matter of great concern. Similar trends exist in most of the other developing countries. In Brazil, for example, the aggregate sulfur addition through fertilizers seems to match sulfur uptake by crops; yet when one considers the high sulfate-fixing nature of the soil, the higher ratio of P to S (4.5:1), and higher leaching, one cannot be complacent about the sulfur availability. Furthermore, it is possible that not all soils and crops receive sulfur. Moreover, in order to account for low use efficiency, replenishment of sulfur through fertilizers should be much higher than sulfur uptake by the crop.

There are no good estimates of SO_4 loss in leaching or drainage water. However, the experience in Kenya shows that the annual loss of sulfur under very high rainfall is 2.21 kg/ha, whereas in Nigeria it is 0.3 kg/ha. Thus, for most situations the sulfur loss under subsistence farming may not be more than 0.6 kg/ha.

Table 3.
Nutrient Consumption, Sulfur Uptake, and Sulfur Supply in Selected Tropical Countries During 1970 and 1980

Year	Country	Nutrient Consumption[a]				Total Cropped Area[b]	S Uptake Requirements		Sulfur Consumption	
		N	P_2O_5	K_2O	Total		'000 mt	kg/ha	'000 mt	kg/ha
		(kg/ha)				('000 ha)				
1980	Brazil	14.6	32.1	21.1	67.8	43,700	349	8.0	482	11.0
	India	20.8	6.5	3.7	30.9	148,271	784	5.3	250	1.7
	Indonesia	44.4	14.2	4.5	63.0	15,448	130	8.4	48	3.1
	Nigeria	3.0	1.8	0.8	5.7	16,064	66	4.1	17	1.1
1970	Brazil	8.2	11.1	9.0	28.3	32,052	205	6.4	252	7.9
	India	9.0	2.8	1.4	13.2	141,678	651	4.6	346	2.4
	Indonesia	11.1	1.6	0.4	13.1	14,293	87	6.1	c	c
	Nigeria	0.1	0.1		0.3	15,849	66	4.2	c	c

a. Per hectare of arable land and permanent crops.
b. Total of the 3-year averages centered on the years shown. The total cropped area includes area under root crops, pulses, oilseeds, wheat, rice, maize, millet, sorghum, sugarcane, soybeans, groundnuts, oil palm, cotton, coffee, and tobacco.
c. Not available.

Sulfur Balance Sheet and Likely Scenarios

On the basis of average sulfur addition and removal estimates, we have developed a sulfur balance sheet and likely scenarios for subsistence and modern agricultural systems in the tropics. These results are reported in Table 4. The balance sheet clearly indicates the serious sulfur problems emerging in the tropics and the need for realistic sulfur supply strategies.

Subsistence Agriculture

Under subsistence agriculture the additions and removals of sulfur may leave a slight deficit (0.6 kg/ha), which can be supplied by the soil provided it is not inherently deficient in sulfur (Scenario 1). Otherwise the crop production will be seriously reduced by sulfur deficiency. The sulfur deficit could increase to 1.6 kg/ha if the fertilizer used is sulfur free.

Even for a farmer trying to produce 1.5 times more food grain/ha, under subsistence agriculture the sulfur supply deficit will increase from 0.6 to 1.4 kg/ha (Scenario 2). The sulfur deficit will become 2.4 kg/ha if the fertilizer applied in the system does not contain any sulfur. This puts a great strain on the sulfur reserves in the soil or depresses the crop yields.

Modern Agriculture

Modern agriculture is assumed to be based on high-yielding crop varieties, intensive cropping, and high inputs of fertilizers and irrigation. In spite of all the additions of sulfur incidentally being provided by fertilizers, manure, and irrigation water as calculated for situations closely matching the actual situation in India (N:S ratio of 15:1), the sulfur deficit is estimated to be

Table 4.
Sulfur Additions, Removals, Balance and Replacement Requirements Under Subsistence and Modern Agriculture: Likely Alternative Scenarios

Sources	Subsistence Agriculture 1	Subsistence Agriculture 2	Modern Agriculture 1	Modern Agriculture 2	Modern Agriculture 3	Assumptions
	(kg/ha of S)					
Additions						
1. Atmospheric additions (rain-dust-gaseous)	3.0	3.0	3.0	3.0	3.0	3 kg/ha/annum (means for Nigeria and Kenya are 2.35 and 5.21 kg/ha)
2. Irrigation water						
Rainfed crop	-	-	-	-	-	
Irrigated, 30 cm water	-	2.0	-	-	-	Water[a] containing 2 ppm SO_4-S
Irrigated, 90 cm water	-	-	6.0	6.0	-	Water containing 2 ppm SO_4-S
Irrigated, 90 cm water	-	-	-	-	30.0	Water containing 10 ppm SO_4-S
3. Fertilizers ($N + P_2O_5 + K_2O$)						
15 kg nutrients	1.0	1.0	-	-	-	India's mean in 1970 = 13.2 kg/ha
120 kg nutrients	-	-	8.0	-	-	Approximately equal to mean of Punjab (India) and 2 times that of Brazil and Indonesia
240 kg nutrients	-	-	-	16.0	16.0	Approximately equal to mean of Ludhiana district in Punjab, India
4. Pesticides and chemicals	-	-	-	-	-	Negligible
5. Farmyard manure (FYM)						
1 mt/3 years	0.6	0.6	-	-	-	0.2% S in FYM
2 mt/3 years	-	-	1.2	1.2	1.2	0.2% S in FYM
6. Crop residues	-	-	-	-	-	All removed or burned[b]
Total Additions	4.6	6.6	18.2	26.2	50.2	
Removals						
1. Crops						
L_{00}	4.6	-	-	-	-	Yield less than 1 mt/ha (mean yield of India 1970)
L_{01}	-	6.9	-	-	-	Irrigated subsistence (yield 50% higher)
L_1, intensive cropping	-	-	36.0			L_1 = 6 mt/ha food grain/year for 2-3 crops
L_2, intensive cropping	-	-	-	72.0	72.0	L_2 = 12 mt/ha food grain/year for 2-3 crops
2. Drainage or leaching loss	0.6	0.6	-	-	-	1/2 of estimate of Nigeria and Kenya
	-	-	1.8	3.6	9.6	Higher leaching because of higher SO_4 content and higher irrigation
3. Adsorbed or immobilized S in irrigation water	0.0	0.5	1.5	1.5	7.5	1/4 of S from irrigation water
Total Removals	5.2	8.0	39.3	77.1	89.1	
Balance						
Balance (deficit) I	-0.6	-1.4	-21.1	-50.9	-38.9	Similar share of S in fertilizer as in 1980-81 in India (1/15 of nutrients)
Balance (deficit) II	-1.6	-2.4	-29.1	-66.9	-54.9	Completely S-free fertilizers used
Replacement Requirements						
Fertilizer S required, I	1.1	2.5	36.9	88.1	68.1	S deficit I x 1.75
Fertilizer S required, II	2.8	4.2	50.9	117.1	96.1	S deficit II x 1.75
Fertilizer S required, I	2.2	5.0	73.8	176.2	136.2	S deficit I x 3.50
Fertilizer S required, II	5.6	8.4	101.8	234.2	192.2	S deficit II x 3.50

a. Assuming all the SO_4 remains within the root zone which is not likely.
b. If burned, some SO_4 may be retained by Ca, K, and Mg in ash. However, empirical estimates are not available.

very high. In three scenarios under modern agriculture, the sulfur deficit is estimated to be 21.1, 50.9, and 38.9 kg/ha, depending upon the level of production, fertilizer use, and sulfate content of irrigation water. The sulfur deficit will rise to 29.1, 66.9, and 54.9 kg/ha if the applied fertilizers have no sulfur in them.

The amount of fertilizer sulfur required to replenish these amounts is also indicated in the table. If the use efficiency of fertilizer sulfur is only 28.5% (replacement coefficient 3.50), i.e., one-half of the assumed use efficiency of 57.14% (replacement coefficient 1.75), the amount of fertilizer sulfur required will be twice as much. It may be further observed that with irrigation water containing 10 ppm SO_4-S the sulfur deficit is considerably reduced but not completely eliminated. If the small amount of sulfur being incidentally applied were absent, the situation would be very serious. Under these circumstances, the use efficiency and productivity of fertilizers (NPK) and of other inputs such as irrigation would be greatly reduced.

Such intensive cropping and exploitive agriculture depletes the sulfur reserves of the soil and has an adverse effect on crop yields. As shown in Figure 2, the available sulfur content of the soil declined under intensive cropping and continuous use of sulfur-free fertilizers in 7 years in an alluvial soil in India. This is an indication of the situation that will develop elsewhere unless sulfur-containing fertilizers are used to supply sulfur. Such long-term experiments should be monitored to study the changes in sulfur supply and requirements and to formulate sound fertilizer management practices for different soils and cropping systems.

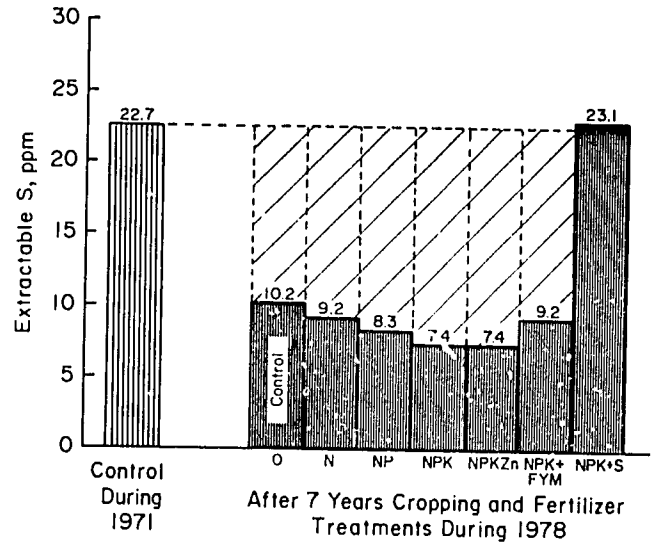


Figure 2. Changes in S Status Under Intensive Cropping and Different Fertilizer Treatments at IARI, New Delhi, India.

Magnitude of Sulfur Deficiency in Tropical Soils

There is general lack of consistent and accurate data about the extent of sulfur deficiency in the tropics. Available estimates indicate that about 52 million ha of high base soils (11% of total) and 745 million ha of infertile acid soils (71% of total) of Latin America have a sulfur deficiency problem. Campo Cerrados soils of Brazil, the highlands and eastern plains (Llanos) of Colombia, and highly weathered volcanic soils of the West Indies and Central America are good examples of sulfur-deficient areas. There is evidence that soils of the upland savannas of Africa have low reserves of total and available sulfur and are likely to become more deficient in sulfur under the present land management system. There is greater likelihood of sulfur deficiency in the savannas of Nigeria than in the forest zone soils.

There are about 452 million ha of sandy soil areas in the semiarid tropics, stretching from Latin America to the savannas of Africa and the alluvial soils of Asia, that also are likely to be deficient in sulfur. Evidence from Brazil and Nigeria confirms that newly cleared tropical lands show sulfur deficiency after a few years of cropping. Different researchers have made different estimates of the rate of disappearance of sulfur in organic matter, and they range from 2% in Nigeria to 10% in Latin America.

There is general consensus that sulfur in organic matter disappears faster than does nitrogen in organic matter; thus, the problem of sulfur fertility management is even more difficult. The lack of systematic studies that correlate sulfur deficiency with differences in soil taxonomic groups precludes a correct assessment and delineation of the sulfur-deficient areas, but broad conclusions can be drawn about the countries where such sulfur-deficient soils exist. A total of 46 tropical countries (10 in Asia, 21 in Africa, and 15 in Latin America) have been identified as having serious sulfur-deficiency problems.

Determining Sulfur Deficiency in the Tropics

National and international fertilizer and agricultural research organizations concerned with sulfur research in the tropics need to consider the following important conclusions and recommendations.

First, the limitations of the soil tests for determining the availability of sulfur to the plants have been pointed out by many; a combination of soil test and plant analysis seems preferable, and the diagnostic techniques need to be standardized.

Second, most researchers have found monocalcium phosphate solution preferable to other extractants for available sulfur from soils; however, the method for estimating sulfur in the extract needs to be refined, and critical values for different crops need to be established.

Third, the usefulness of pot culture and greenhouse tests to assess the need for fertilizer sulfur is limited because the system may overemphasize the nutrient need as a result of conditions under which the plants are grown. Field experimentation is most reliable for diagnosis of the need for sulfur fertilization.

Fourth, for preliminary screening of different sources of sulfur, greenhouse studies could be valuable, provided the researchers consider the actual soil environments and crops for which the proposed sulfur fertilizer is to be used.

Crop Response to Fertilizer Sulfur

Data on responses to fertilizer sulfur from field experiments are rather limited; the information is mostly confined to areas where, year after year, deficiencies have been observed or where, under the impact of modern agriculture, the full potential of inputs is not being realized because of induced sulfur deficiency. Cases of sulfur deficiency in Sulawesi in Indonesia and in northeast Thailand, Indian Punjab, Zimbabwe, central Kenya, northern Nigeria, and the Campo Cerrado soils of Brazil are examples of sulfur deficiencies attributable to imbalanced fertilizer use in modern agriculture. However, despite the inadequacy of the data, the following seven conclusions emerge from results based on field experiments in a number of tropical countries.

First, the deficiency of sulfur in the tropics is widespread, though not so spectacular as nitrogen and phosphorus deficiency. Significant responses to application of SO_4-S are expected. In some cases significant increases in crop yield have been obtained in greenhouse studies, and they could be considered as indicative of crop response to sulfur and thus the need for sulfur research in the field. The studies also indicate that responses to fertilizers, specifically to nitrogen and phosphorus, will increase if the limiting factor, sulfur, is supplied.

Second, sulfur as a nutrient has an important place in food production and thus alleviation of hunger and malnutrition, especially in the developing tropical countries in Asia, Africa, and Latin America.

In Asia sulfur responses were obtained in the 1970s with medium to high doses of fertilizers N, NP, or NPK and improved varieties of cereals (rice or wheat). Marked responses to sulfur were observed in oil seeds (groundnuts, soybeans, rape, and mustard), legume forages such as alfalfa and berseem (Trifolium alexandrinum L.), and potatoes. It appears that most of the work was confined to coarse-textured soils and was done after the introduction of high-yielding varieties. Whether the problem is localized or extends to a larger area has not been determined; nor has the question of whether the sulfur application is needed for every crop in the rotation or once for each rotation really been studied.

In Africa most of the research deals with commercial crops like cotton, groundnuts, and tea, and it was done before the introduction of high-yielding varieties, i.e., before the 1970s. Since the introduction of high-yielding varieties, or the post independence period, very little research on sulfur fertilization seems to have been done on any crops and least on food crops. In view of the great food deficit in this region, there is a need for intensive and well-coordinated research to assess the need for sulfur fertilizers for food crops in the region.

In Latin America most of the research reported in literature relates to improved varieties of rice, maize, soybeans, cotton, coffee, beans, and pasture legumes. Marked responses were obtained in the Campo Cerrado soils of Brazil, the highly weathered soils of the uplands, and the soils of volcanic origin.

Third, at present the sulfur deficiency under high-yielding varieties may appear to be localized to those soils that were inherently poor. As the intensity of cropping and level of fertilization increases, sulfur deficiency may become a serious limiting factor, especially because of the decline in sulfur input from high-analysis fertilizers that are free from sulfur or have low sulfur contents.

There are clear indications that in Asia, particularly in India, Bangladesh, and Indonesia, intensive cropping combined with the use of high-yielding varieties and heavy applications of sulfur-free fertilizer may be overstraining the sulfur supply reserves of the soil ecosystem and may be limiting the full potential of new technology.

Evidence of this is provided by the data on sulfur uptake and incidental sulfur supply through fertilizers in India and Indonesia. In 1980 the amount of sulfur taken up by field crops was estimated to be 784,000 and 130,000 mt, whereas the addition through fertilizers was hardly 250,000 and 48,000 mt in India and Indonesia, respectively.

The implied large sulfur deficits could have overstrained the sulfur reserves of the soil and lowered crop production potential. It is also possible that irrigation water high in SO_4 may counteract this effect in many situations; in other cases, sulfur-containing fertilizers may be needed. Crops like oilseeds, pulses, legumes, and forages, which remove relatively larger amounts of sulfur per metric ton of dry matter than do the cereals, may become more responsive to sulfur fertilizers with the introduction of their high-yielding varieties. Thus, in the future the sulfur problem will become much more serious.

Fourth, a comparison of sulfur supply sources indicates that generally gypsum or other sulfate sources have proved to be the most effective for most of the soils and crops. The modifying effects of time and the method and dose of application have also been evident in many studies. Even a less efficient substance could become an effective sulfur source if the cost:benefit relationship is favorable. However, economic evaluation of sulfur supply sources has generally been ignored. Thus, the evaluation of alternative sulfur supply sources should be based on analytical studies done by interdisciplinary teams of scientists dealing with technological, agronomic, and economic aspects of fertilizer sulfur research.

Fifth, in most of the tropical countries the sources of sulfur are gypsum, pyrite, or other sulfur-containing byproducts of agriculture and industry. Technology needs to be developed for the use of these substances as economic sources of sulfur for plant nutrition. This is a challenge which the technologists, agronomists, and economists have to face in order to determine whether to modify the fertilizers to incorporate sulfur from these sources or to consider selection of compound fertilizers and mixtures for different situations. It is the technological, agronomic, and economic considerations that should determine the sulfur supply source suitable for the tropical soils and crops.

Sixth, long-term studies with tea, coffee, and coconuts have shown that sulfur-containing fertilizers, if continuously applied, build up reserves of adsorbed SO_4 in soils which, in turn, reduce the amount of sulfur to be used annually. The results of two long-term experiments, one at Samaru (northern Nigeria) and the other at New Delhi (northern India), clearly indicate changes in sulfur supply from soil under extensive and intensive cropping systems in Africa and Asia, respectively. Long-term studies and monitoring of changes in the status of nutrients in the soils through long-term experiments elsewhere may also be desirable.

Seventh and finally, the experience with tropical agriculture also shows that both phosphate and lime accelerate losses of SO_4-S; thus, acid soils of the tropics, high in exchangeable aluminum (Al), require fertilizer management practices or fertilizer products that can reduce such losses without affecting the usefulness of the lime and phosphate applications.

Priority Areas for Fertilizer Sulfur Research

Though the data are scanty, the published information about sulfur deficiency suggests that the priority areas identified in Table 5 are of greatest concern and should be examined to assess the extent and intensity of the sulfur problem, to determine economic sources of sulfur supply, and to formulate appropriate sulfur programs. Research and development programs in these areas may have the greatest economic benefits.

The areas where severe sulfur deficiency has been observed should be selected for assessing the magnitude of the problem and the degree of crop responses to applied fertilizer sulfur. A coordinated program of simple fertilizer trials on farmers' fields, based on the missing nutrient concept and using treatments such as control, N, NP, NPK, NPKS, NPKS + micronutrients, might be tried. The soil and plant analysis may be used to support such studies. Where possible, ^{35}S could be used.

Sulfur Deficiency and Strategies for Meeting the Challenge

Identification of those factors responsible for creating sulfur deficiency in the tropics is prerequisite to designing strategies for solving the sulfur problem. The important factors are soil, climate, cropping systems, fertilizer, irrigation, intensification of agriculture, industrialization, environmental programs, and extension of agriculture to marginal lands.

Table 5.
Priority Areas for Fertilizer Sulfur Research and Policy in Asia, Africa, and Latin America

Region	Country	Areas Within the Country	Crops
Asia	India	Coarse-textured sandy soils of alluvial plains of Punjab, Haryana, Uttar Pradesh, Rajasthan, and certain pockets of Gujarat	Groundnuts, rape & mustard, wheat, maize, chickpeas, soybeans, berseem, potatoes
	Bangladesh	Lowland rice area	Rice, wheat, mustard
	Thailand	Plateau of northeast Thailand	Rice, soybeans, pulses, pasture
	Indonesia	Sulawesi, East Java	Rice, pasture
Africa	Nigeria	Northern Nigeria	Maize, sorghum, roots & tubers, cowpeas, groundnuts
	Senegal	Central and southern Senegal	Groundnuts, cotton, millet, maize
	Kenya	(1) Coastal sandy soils (2) Sandy loam soils of Kitale and Songhor Regions (3) Volcanic soils near Kilimanjaro (4) Bottom lands of Machakos area	Maize, cotton, pastures
	Zimbabwe	Sandy soils	Maize, groundnuts, tea
Latin America	Brazil	Highly weathered soils of Brazilian Plateau	Maize, rice, cotton, pastures, soybeans, coffee
		Campo Cerrado soils of Sao Paulo Region	
	Colombia	Bogota Highlands Eastern plains (Llanos)	Maize, soybeans, beans, pasture, legumes, coffee

Although soil and climatic influences are difficult to change, understanding them helps in better management of sulfur fertilizers. Most serious are the leaching and erosion losses due to rain and adsorption of sulfate under certain conditions. Any strategy for improving the sulfur situation in tropical soils should emphasize the management of soil, fertilizer, and crops.

In some areas, because of the high sulfate content, the irrigation water could supply the sulfur needs of the crop. In other areas, where waters of low sulfate content are used, sulfates may be leached and the soil impoverished. Analytical studies dealing with the effects of irrigation, fertilizer application, and cropping system combinations under field conditions are essential to understand the phenomenon.

Lysimetric studies under controlled environments are, no doubt, good for understanding the principles involved, but for solving the field problem and for improving sulfur economy of soil it is better to conduct such studies on the soil in situ where the effect of growing a crop can also be studied simultaneously.

Intensification of agriculture, use of high-yielding crop varieties, and increasing use of fertilizers low in sulfur are aggravating the sulfur-deficiency problem. Corrective measures need to be taken through use of fertilizers with higher sulfur content to lower the N:S ratio or P:S ratio in the fertilizers.

From the long list of sulfur-containing substances it appears doubtful that the use of fluid fertilizers will be feasible in the developing tropical countries in the near future. However, dry fertilizers rich in sulfate may become more attractive. The need for modified, economically efficient fertilizer technology is of high priority. Sulfur-fortified TSP, concentrated superphosphate, partially acidulated rock phosphate, and sulfate-enriched diammonium phosphate (DAP) may become more acceptable. Appropriate technologies need to be developed to supply them.

Strategies to supply sulfur to soils and crops in every country should be based on the use of waste products from the fertilizer industry, chemical industry, and agricultural industry; on local sulfur resources; or on incorporation of sulfur in the popular fertilizer products. Ammonium sulfate and single superphosphate have important places in the agriculture of these countries, and strategies can be developed to make their use more efficient and economical. Use of sulfur-coated urea and sulfur-enriched fertilizers in sulfur-deficient soils and for certain crops needs to be given a fair trial.

Gypsum, elemental sulfur, and pyrites will be preferable for alkaline and calcareous soils of the semiarid tropics. However, for highly acid soils the use of elemental sulfur and other acid-forming substances is questionable. More emphasis should be placed on the use of phosphogypsum directly or through incorporation in fertilizers. In fact, there is a need for interdisciplinary research by teams of fertilizer technologists, agronomists, and economists to develop suitable fertilizer products to supply sulfur for different soils and cropping systems while keeping in view the locally available sulfur resources.

Estimating Fertilizer Sulfur Requirements and Gaps

In order to design nationally acceptable and economically viable supply strategies to correct sulfur deficiency and improve the production and quality of food, there is a need to accurately estimate the fertilizer sulfur requirements, sulfur supplies, and implied sulfur gaps.

Fertilizer sulfur estimates are based on simple statistical analysis. The sulfur requirement estimates are divided into two broad categories. These are (1) requirements by field crops for sulfur as a nutrient and (2) sulfur requirements in the fertilizer industry. The requirements for sulfur as a plant nutrient for crops are based on (a) crop production levels, which account for area under different crops and average crop yields; (b) average sulfur uptake by crops; and (c) use efficiency of applied sulfur. In this context the estimated sulfur requirements do reflect the impact of factors such as changing cropping pattern, expanding crop yields, and multiple cropping.

The requirement for sulfur as a plant nutrient is further classified into three categories. These are (1) sulfur uptake requirements; (2) sulfur replacement I requirements that assume a sulfur-replacement coefficient of 1.75, which implies fertilizer sulfur use efficiency of approximately 60%; and (3) sulfur replacement II requirements that assume a sulfur replacement coefficient of 3.50, which implies fertilizer sulfur use efficiency of one-half, approximately 30%.

The fertilizer sulfur uptake and the replacement requirements are based on actual crop production from 1960 to 1980 and on projected crop production from 1985 to 2000. The results refer to 3-year simple averages centered on years shown in order to avoid the effect of weather-related variations in crop production. On the other hand, sulfur requirements in the fertilizer industry are based on fertilizer production needed to meet projected fertilizer consumption requirements from 1980/81 to 2000/01. Estimated sulfur requirements in the fertilizer industry are based on sulfur needed to manufacture ammonium sulfate, single superphosphate, triple superphosphate, and ammonium phosphates.

The estimates of fertilizer sulfur requirements are based on production of 25 important field crops. These crops are then divided into 15 broad crops/crop groups including wheat, rice, maize, millet, sorghum, pulses, oilseeds, soybeans, groundnuts, oil palm, root crops, sugarcane, cotton, coffee, and tobacco. Each country under study does not necessarily grow all these crops. Furthermore, the relative importance of individual crops varies from one country to another. These 25 crops, however, account for most of the chemical fertilizer consumption in developing countries of the tropics.

The estimates for fertilizer sulfur requirements are made for 11 tropical countries and 3 regions in addition to the world as a whole. The 11 countries include India, Indonesia, and the Philippines from Asia; Kenya, Niger, Nigeria, Sudan, and Zimbabwe from Africa; and Brazil, Colombia, and Mexico from Latin America. The three regions include the Far East, Africa, and Latin America (as developing market economies). The crop production levels are specific to each country and region.

However, average sulfur uptake by crops/crop groups broadly represents developing tropical countries and is assumed to be the same for all the countries and regions. Finally, the assumed two levels of use efficiency of applied sulfur (replacement coefficients) are not specific to any crop, country, or fertilizer; rather, they represent typical conditions prevailing in temperate and tropical countries. In this context, the estimated fertilizer sulfur requirements presented here are good first-order approximations.

The estimated aggregate sulfur requirements by field crops and the world fertilizer industry are summarized in Tables 6 and 7. India and Brazil stand out since the largest sulfur requirements are in Asia and Latin America, respectively. With the exception of Mexico, all the other countries studied are net sulfur importers. The sulfur requirements in the world fertilizer industry are much more than the sulfur uptake requirements. However, only a small percentage of sulfur used in the fertilizer industry is transferred to the agricultural sector through sulfur-containing fertilizers.

The estimated proportion of sulfur requirements by cereal and noncereal food crops is shown in Figure 3. A large share of sulfur uptake requirements is by cereal crops. However, the share varies not only by country or region but also over time. A shift in the cropping pattern in favor of those crops that, on the average, remove relatively large quantities of sulfur would increase aggregate sulfur uptake and hence the fertilizer sulfur replacement requirements. The production of soybean in Brazil highlights such a transformation.

The estimated aggregate fertilizer sulfur requirements, supply, and gaps for selected countries during

Table 6.
Estimated Aggregate Sulfur Requirements by Field Crops in Selected Developing Tropical Countries and Regions, 1960-2000

Country/Region	Sulfur Requirements[a]								
	Uptake			Replacement I			Replacement II		
	1960	1980	2000	1960	1980	2000	1960	1980	2000
	('000 mt of S)								
Asia									
India	509	784	1,333	891	1,372	2,332	1,782	2,743	4,665
Indonesia	64	130	294	112	227	514	225	454	1,028
Philippines	21	45	108	38	80	190	75	159	379
Africa									
Kenya	9	15	21	15	26	37	31	52	73
Niger	6	13	29	11	22	51	22	44	103
Nigeria	56	66	98	99	116	171	197	231	343
Sudan	29	30	64	51	53	113	102	107	225
Zimbabwe	7	16	29	12	29	51	25	58	101
Latin America									
Brazil	157	349	708	275	611	1,239	550	1,222	2,477
Colombia	21	38	86	36	67	150	72	134	301
Mexico	64	137	240	113	239	419	225	478	838
Africa	224	327	411	392	573	720	783	1,146	1,440
Far East	776	1,340	2,463	1,358	2,345	4,310	2,717	4,690	8,620
Latin America	404	844	1,603	707	1,477	2,805	1,413	2,954	5,610
World	**4,582**	**7,911**	**14,238**	**8,018**	**13,844**	**24,917**	**16,037**	**27,687**	**49,835**

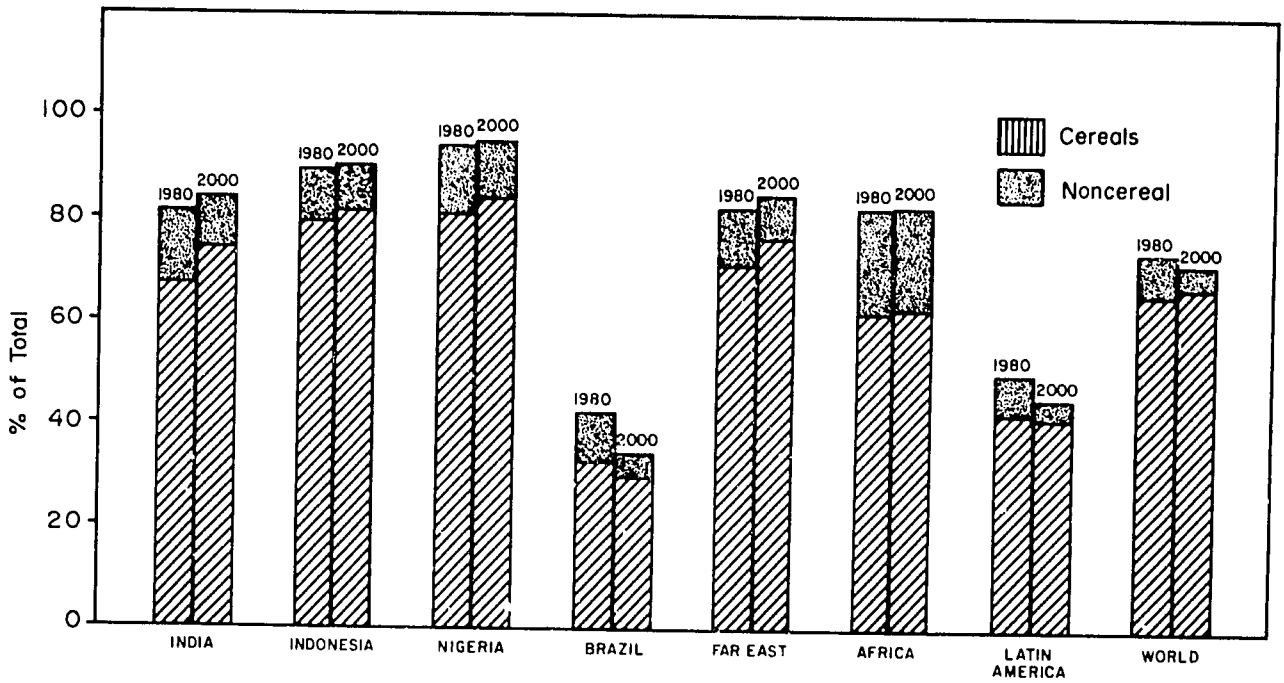
a. Uptake: Sulfur uptake by field crops; replacement I: uptake * sulfur replacement coefficient of 1.75 (implies use efficiency of about 60%); and replacement II: uptake * sulfur replacement coefficient of 3.50 (implies use efficiency of about 30%).

1980 are reported in Table 8 and in Figure 4. The results indicate that, with the possible exception of Mexico, the sulfur gaps are rather large in relation to the current fertilizer sulfur supply. Furthermore, the projected fertilizer sulfur gaps are estimated to increase from 1980 to 2000. For example, the estimated sulfur gap III (fertilizer sulfur supply minus fertilizer sulfur replacement II requirements) in India is estimated to increase from 2.5 million mt in 1980 to 3.1 million mt in 1990, and to 4.0 million mt in the year 2000.

These large sulfur gaps have important policy implications for fertilizer research, sulfur supply, fertilizer material selection, fertilizer imports, fertilizer distribution, sulfur promotion, capital investment, and foreign exchange allocation. Unless something is done to bridge these large sulfur gaps and to correct the sulfur-deficiency problem, national and international efforts to accelerate food production will be seriously handicapped. This is a real challenge and a great opportunity for all those involved in fertilizer policy formulation, fertilizer research, and fertilizer production, distribution, and use to make a major contribution to food production of developing tropical countries.

Table 7.
Estimated World Sulfur Requirements as Crop Nutrient and for the Fertilizer Industry, 1980-2000

Type of Sulfur Requirements	Sulfur Requirements During		
	1980	1990	2000
	(million mt of S)		
Sulfur as Crop Nutrient			
Uptake	7.9	10.5	14.2
Replacement I	13.8	18.4	24.9
Replacement II	27.7	36.9	49.8
Sulfur for Fertilizer Industry			
AS/SSP	6.5	10.0	16.3
TSP/AP	20.0	31.1	48.4
Total	26.5	41.1	64.7



Cereals: Wheat, Rice, Maize, Sorghum and Millet

Noncereals: Pulses, Root Crops and Groundnuts

Figure 3. Estimated Proportion of Sulfur Uptake Requirements by Cereal and Noncereal Food Crops in Selected Countries and Regions in the World.

Table 8.
Estimated Sulfur Requirements, Fertilizer Sulfur Supply, and Sulfur Gaps in Selected Tropical Countries During 1980

Country	Sulfur Requirements: Uptake	Sulfur Requirements: Replacement I	Sulfur Requirements: Replacement II	Fertilizer Sulfur Supply	Sulfur Gaps[a]: I	Sulfur Gaps[a]: II	Sulfur Gaps[a]: III
	('000 mt of S)						
Asia							
India	784	1,372	2,743	250	-534	-1,122	-2,493
Indonesia	130	227	454	48	-82	-179	-406
Philippines	45	80	159	30	-15	-50	-129
Africa							
Kenya	15	26	52	11	-4	-15	-41
Niger	13	22	44	<1	-12	-21	-43
Nigeria	66	116	231	17	-49	-99	-214
Sudan	30	53	107	b	b	b	b
Zimbabwe	16	29	58	b	b	b	b
Latin America							
Brazil	349	611	1,222	482	+133	-129	-740
Colombia	38	67	134	5	-33	-62	-129
Mexico	137	239	478	338	+201	+99	-140

a. Fertilizer sulfur supply minus sulfur requirements. Gap I is supply minus uptake; Gap II is supply minus Replacement I; and Gap III is supply minus Replacement II.
b. Not available.

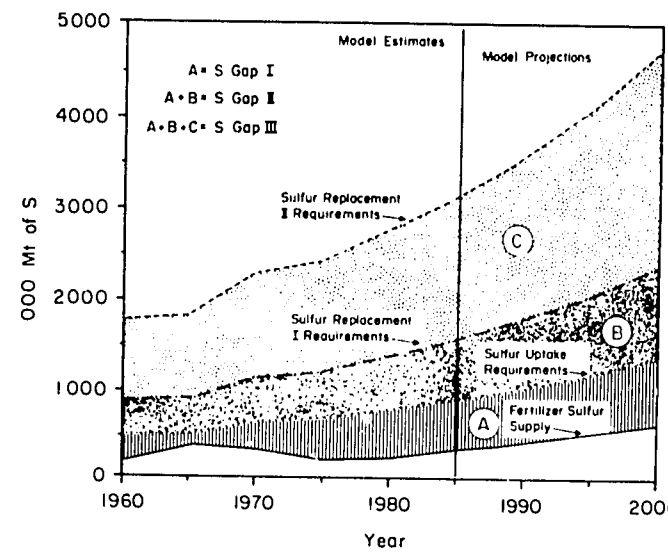


Figure 4. Estimated Sulfur Requirements, Fertilizer Sulfur Supply, and Sulfur Gaps in India: An Example

Evaluation of Alternative Fertilizer Sulfur Materials

In order to deal with increasing sulfur deficiencies and projected sulfur gaps, there is a need to identify, develop, evaluate, and transfer fertilizer sulfur technology and strategies that would be appropriate, technically and economically, for tropical countries. Alternative sulfur supply strategies include all or some of (1) conventional sulfur-containing fertilizers; (2) modified sulfur-containing fertilizers; and (3) indigenous sulfur supply sources such as gypsum, phosphogypsum, and pyrites.

In developing and recommending any of these sulfur-containing fertilizers, it is extremely important to keep in mind the climatic conditions, cropping systems, soil types, socioeconomic conditions, and natural resource endowments of those tropical countries that are the target of such technology. All the existing and modified sulfur-containing fertilizer technologies must be evaluated with respect to the following criteria:

1. The technical feasibility of production, distribution, and use of sulfur-containing fertilizers.
2. Agronomic effectiveness under farmers' field conditions.
3. Preferences and general attitudes of those involved in production, distribution, and use of these materials.
4. Economic effectiveness under free-market conditions.
5. Economic effectiveness under prevailing government policy with respect to fertilizer sulfur.
6. Foreign exchange use, earnings, and savings.
7. Economic and financial aspects of research, production, distribution, and use of these materials.
8. Existing and suggested government policies dealing with fertilizer sulfur raw materials, production, distribution, promotion, regulation, pricing, subsidies, trade, and research.

The technology for each proposed sulfur-containing fertilizer needs to be evaluated within an interdisciplinary context from the moment a technology is conceived until it is ready for transfer and general use by farmers in the tropical countries.

Economic and Policy Analysis of Fertilizer Sulfur

Despite the need for sulfur as an essential plant nutrient and the substantial returns expected from its use, very limited analytical or empirical research has been done that is related to the economic and policy analysis of fertilizer sulfur in tropical countries. There are several reasons for this situation. The primary reason, however, is that the economic importance of fertilizer sulfur has not been recognized. In order to formulate appropriate sulfur policy at the national level, there is a need for the following:

1. Determination of economic returns to sulfur use under different agroclimatic conditions and cropping systems.
2. Comparative economic evaluation of existing, modified, and indigenous sulfur-containing fertilizers and amendments.
3. Economic evaluation of phosphogypsum as a source of sulfur for plant nutrients and raw material for manufacturing sulfuric acid and nitrogenous, phosphatic, and potassic fertilizers.
4. Economic analysis that accounts for the residual effects of sulfur, the interaction of sulfur with other nutrients, and the productivity of fertilizer sulfur under different scenarios of crop technology and cropping systems.
5. Determination of the delivered price of sulfur to farmers.
6. Economic evaluation of price and the transportation subsidy that must be paid by the government on sulfur-containing fertilizers and other sulfur supply sources.
7. Economic evaluation of sulfur-containing fertilizers from indigenous sulfur supply sources as opposed to imported sulfur or sulfur-containing fertilizers.

Pricing of Fertilizer Sulfur

Sulfur is not a free commodity. The international sulfur prices, expressed in constant dollar terms, generally declined from 1955 to 1978, with the exception of two price upswings that peaked during 1968 and 1975. In any case, the current sulfur prices during this period were less than $50/mt. However, the market changed in 1978 with international dry sulfur prices (f.o.b. U.S. Gulf) rising from approximately $60/mt in January 1979 to

$130/mt in March 1980 and then declining to $118/mt in March 1982 and to $96/mt in April 1983. Clearly, sulfur prices play an important role in determining appropriate sulfur supply strategy and prices for sulfur-containing fertilizers.

Sulfur-containing chemical fertilizers, including popular fertilizers such as ammonium sulfate and single superphosphate, are rarely priced for their sulfur content. As long as sulfur in chemical fertilizers is considered merely a bonus, the fertilizer industry will have no economic incentive to manufacture sulfur-containing fertilizers as main products.

In those areas facing serious sulfur deficiency, the returns to the use of sulfur-containing fertilizers priced for sulfur appear extremely favorable, both at the farm and national levels. However, sulfur pricing does raise extremely important policy questions that can be resolved only after sound economic and policy analysis. Some of these questions are as follows:

1. How should the production costs be allocated and the fertilizer be priced when the sulfur-containing fertilizer is produced as a coproduct or as a byproduct?
2. How should the price of sulfur-containing fertilizers be determined at the retail level in comparison with other competitive sulfur-free fertilizers?
3. Would the farmers pay for sulfur in sulfur-containing fertilizers?
4. What would be the reaction of the fertilizer industry with respect to creation of new capacity to produce sulfur-containing fertilizers?
5. How would the costs and benefits of the sulfur-pricing policy be distributed among producers, distributors, farmers, and consumers?

Sulfur Situation, Resources, Trade, and Outlook

Sulfur is considered one of the most abundant elements on earth. However, only a small fraction of large sulfur resources is recoverable at current levels of knowledge, technology, and prices. The key points concerning the sulfur industry as it relates to the fertilizer sector and tropical agriculture are discussed as follows.

First, during 1981 world production of sulfur was about 53.8 million mt. Four countries (United States 23.7%, U.S.S.R. 18.0%, Canada 12.6%, and Poland 9.2%) accounted for almost two-thirds of world sulfur production. Approximately 63% of the estimated production was brimstone, and this proportion is expected to increase because of increased production of recovered sulfur. During 1981 the estimated share of developing tropical regions in world sulfur production was only 7.8%, and Mexico alone accounted for 50% of this production (Table 9). However, the oil-producing countries, especially in the Middle East, are expected to increase their sulfur production.

Second, a large share of sulfur (80%-90%) is used to manufacture sulfuric acid. The share of developing tropical regions in worldwide sulfur consumption (55.0 million mt) was only about 12.4% during 1980. This is a rather small amount in the context of their relative share in world population, agricultural production, and food needs. During 1980, the share of individual developing tropical regions in world sulfur consumption was estimated to be 3.3% in Africa, 4.6% in Asia, and 4.5% in Latin America.

Third, during 1981 world production of sulfuric acid was 138 million mt. Four countries (United States 26%, U.S.S.R. 17%, China 6%, and Japan 5%) accounted for 54%

Table 9.
Sources of Sulfur and Sulfur Production in Developing Tropical Regions of the World During 1981

Region	Production	Share in World Production	Sources of Sulfur, % Share			
			Brimstone	Pyrites	Other Forms	Total
	('000 mt)	(%)				
Africa[a]	178	0.3	6	27	67	100
Asia[b]	1,335	2.5	74	8	18	100
Latin America	2,699	5.0	90	3	7	100
Regions Total	4,212	7.8	82	5	13	100
World	53,727	100.0	63	21	16	100

a. Excluding South Africa with a total production of 636 thousand mt.
b. Excluding Japan with a total production of 2,706 thousand mt. China is also excluded.

of world sulfuric acid production. Among the developing tropical countries, the major producers of sulfuric acid are India 2%, Mexico 2%, Brazil 1.7%, Morocco 1.7%, and Tunisia 1.6%. The developing market economies as a group accounted for about 13%.

Fourth, for the world as a whole, 55% of the sulfuric acid was used in the fertilizer industry during 1981. The share allocated to the fertilizer industry varies from 45% in Asia (including Japan) to 67% in Latin America and 75% in Africa (including South Africa). A large share (90% in the western world) of the sulfuric acid used in the fertilizer industry goes to manufacture phosphate fertilizers. Most of the sulfur used in the phosphate fertilizer industry (with the exception of SSP) is discarded in byproduct phosphogypsum.

Fifth, during 1981 about 30% (16 million mt) of world sulfur production was traded in the international market, most of it in the form of brimstone. Canada and Poland accounted for about 70% of brimstone exports. Among the developing countries, Mexico is a net exporter of sulfur. The potential sulfur exporters include countries from the Middle East. With the exception of Mexico, most of the developing countries are net importers of sulfur, which is essential to develop their agricultural and industrial sectors.

Sixth, the amount of known sulfur reserves in the world is estimated to be between 1.8 and 2.2 billion mt, which does not include vast sulfur resources contained in anhydrite, gypsum, and sea water. Of these reserves the developing tropical countries are estimated to account for about 33%, including 5% in Mexico, 8% in Iraq, 14% in other countries in the Near East, and 6% in other developing tropical countries of Asia, Africa, and Latin America.

The developing tropical countries are also known to have sulfur resources in the form of anhydrites, gypsum, pyrites, and nonferrous sulfides, as well as elemental sulfur deposits. The following important questions need to be addressed: (1) What is the agronomic effectiveness and technoeconomic feasibility of these sulfur resources? and (2) How should the indigenous sulfur resources be used to meet the sulfur requirements of developing tropical countries in Asia, Africa, and Latin America?

Fertilizer Sulfur Trade Policies

Most tropical countries with serious sulfur-deficiency problems are also net importers of sulfur, usually brimstone. The available information indicates that most of these countries also impose some form of trade restrictions, especially tariffs, on imported sulfur.

Tariffs may be good sources of government revenue, but they can also result in high social costs. The immediate impact of a tariff is that the price of imported sulfur goes up and the increase is reflected in the price of fertilizers such as phosphate fertilizers that use sulfur or sulfuric acid in their manufacture. Tariffs are generally imposed under the pretext of protecting the domestic industry (infant industry argument), but they also encourage inefficiency. For a low-income country with widespread sulfur deficiency, tariffs on sulfur imports may not be in the best interests of the general population since they encourage both inefficiency and inequity.

Phosphogypsum: A Source of Fertilizer Sulfur

Phosphogypsum, a byproduct of wet-process phosphoric acid, is generally considered a waste product, even though it contains all of the sulfur from the sulfuric acid used in the process. The cumulative world production from 1967 to 1985 is estimated to be 1.6 billion mt of phosphogypsum, which includes 265 million mt of sulfur, of this amount, 37 million mt of sulfur equivalent will have been produced in the tropical countries of Asia, Africa, and Latin America.

While large stocks of phosphogypsum are accumulating, the crops in many tropical countries are suffering from sulfur deficiency. Naturally, these countries cannot afford to throw away phosphogypsum, and hence imported sulfur, especially when it was bought with scarce foreign exchange. Furthermore, the technical and economic problems associated with correcting sulfur deficiencies may not be serious at all when phosphogypsum is used as a source of fertilizer sulfur in agriculture. Herein lie a great challenge and a golden opportunity to meet that challenge through the use of phosphogypsum in agriculture to provide both sulfur and calcium for increased food production.

There is a need to initiate research to determine (1) the agronomic effectiveness of phosphogypsum as a source of sulfur; (2) the technical problems related to drying, transporting, storing, handling, and converting phosphogypsum to ammonium sulfate and sulfuric acid and for upgrading popular fertilizers with sulfur; and (3) the economic viability of phosphogypsum as a raw material source for manufacturing modified nitrogenous, phosphatic, and potassic fertilizers, mixtures, and compounds.

Need for Information Related to Fertilizer Sulfur

Appropriate information with respect to sulfur supply, use, response, uptake, prices, and economics is extremely vital in the formulation of policies concerning fertilizer sulfur. Yet most national and international organizations engaged in collecting and publishing information do not include sulfur in fertilizer-related statistics. Consequently, most of this information is not available to either policymakers or researchers.

Sulfur data must be made an integral part of national fertilizer data collection systems. These data must include information related to sulfur raw materials, reserves, and resources; sulfur production, consumption, and trade; sulfur freight and prices; sulfur uptake by crops; and sulfur response. International organizations such as the Food and Agriculture Organization of the United Nations (FAO), IFDC, and the United Nations Industrial Development Organization (UNIDO) can play an important role in stimulating such programs at the national level, particularly in developing countries.

Fertilizer Sulfur Use Recommendations

With the exception of a few isolated examples, fertilizer recommendations do not include sulfur as one of the plant nutrients. Only the primary nutrients are generally included in the fertilizer recommendations. Any effort directed at correcting sulfur deficiency must involve a set of recommendations that include the use of sulfur at the farm level.

It is extremely important to develop sulfur recommendations based on farm-level data under actual farming conditions. These recommendations must be crop-specific and must also specify the amount to use, the time of application, the method of application, and the source of fertilizer sulfur. Furthermore, the recommendations must be based on sound information regarding crop response to applied fertilizer sulfur and economics of sulfur use.

Fertilizer Sulfur Regulation and Labeling

Lack of use of fertilizer sulfur in countries with severe sulfur-deficiency problems results in a high social cost in terms of lost agricultural production. Under these circumstances, it is economically justifiable to implement government regulations with respect to sulfur supply. These regulations should ensure a fertilizer sulfur supply at the retail level through the availability of popular sulfur-containing fertilizers and/or the requirement that different NPK fertilizer materials contain a certain minimum amount of sulfur.

The existing quality control regulations in most countries require labeling of only the primary plant nutrients, including N, P_2O_5, and K_2O, on fertilizer bags. This is true even when the fertilizer also contains sulfur. The labeling of fertilizer bags with sulfur contents would provide additional information to the farmer who purchases the fertilizer. The additional cost for sulfur labeling is expected to be rather negligible.

Sulfur, Environmental Protection, and Food Production

In the industrialized countries environmental pollution, partly caused by sulfur dioxide and acid rain, is at the center of public debate. These countries have various laws restricting the emissions of sulfur dioxide to the atmosphere. However, in most of the nonindustrialized developing countries environmental pollution, primarily by sulfur dioxide emission, is not a serious problem. Even in industrialized countries sulfur dioxide is not solely responsible for acid rain although problems may be more serious around localities with industrial complexes.

Obviously there is a need for some restrictions on emissions of sulfur dioxide and other industrial pollutants in order to protect the environment and public health. However, sulfur dioxide emission standards that are too strict may be counterproductive. Atmospheric sulfur is an important source of sulfur as a plant nutrient. Further restriction on sulfur dioxide would reduce the sulfur supply from the atmosphere at a time when sulfur replacement requirements as a plant nutrient alone are expected to increase worldwide from 28 million mt in 1980 to about 50 million mt in the year 2000.

Furthermore, extremely restrictive sulfur dioxide emission standards would add to social costs in four

different ways. These added social costs include (1) cost of enforcing regulations, (2) capital investment in equipment to reduce sulfur dioxide emissions, (3) cost of fertilizer sulfur to supply sulfur that would otherwise be missing as a plant nutrient, and (4) loss in agricultural production if the loss from atmosphere is not made up through alternative sulfur supply sources. Clearly, there is a tradeoff between environmental protection and food production, and environmental policy must be based on a careful analysis of costs, benefits, and the distribution of costs and benefits.

Implications for Research and Public Policy

It must be recognized that sulfur deficiency is either inherent or being induced. There is a widening gap between sulfur supply and withdrawal from the soil environments as a result of a changing agricultural system that involves the use of high-yielding crop varieties, intensive cropping, and the increasing use of sulfur-free fertilizers. The problem calls for a high priority on research and development programs by the national and international organizations.

Priorities for National Research Programs

The national research institutions and policymakers should give priority to the following programs:

1. Recognize that sulfur deficiency may be limiting crop production and adversely affecting the quality of agricultural production, as well as the health of animals and human beings. The sulfur problem is likely to become more serious in the future; thus, it calls for an immediate appropriate coordinated action.
2. Identify soils deficient in sulfur, using soil and plant tissue testing methods, and give high priority to coarse-textured soils, intensively cropped soils, highly weathered soils, and old volcanic ash soils, i.e., Ultisols, Oxisols, Alfisols, Andepts, and the Inceptisols.
3. Organize coordinated simple fertilizer trials on farmers' fields to study responses to sulfur. The sulfur-responsive crops and their improved varieties should be used on soils identified as deficient or thought to be deficient or responsive to sulfur, with or without lime. It should be recognized that correction of the acidity, the use of nitrogen, phosphorus, and potassium fertilizers, and other factors affecting nutrient availability are essential to getting the best results from sulfur application.
4. Encourage research on the dynamics of sulfur applied to soils through fertilizers and manures in long-term experiments for agriculture based on high-yielding crop varieties and intensive cropping.
5. Assess the sulfate content of irrigation water and its contribution to the sulfur status of soil, crops and nutrition, and sulfur losses in drainage waters.
6. Monitor sulfur accretion to the ecosystem from the atmosphere through rain, dust, and gaseous deposition at a few selected sites representative of the major agricultural areas.
7. Identify local sources of sulfate/sulfur, characterize their chemical attributes, determine their supply status, and develop strategy for their use as economic sources of sulfur-containing fertilizers.
8. Develop a strategy for the use of such byproducts of the fertilizer industry as phosphogypsum to enrich the nitrogenous, phosphatic, and potassic fertilizers with sulfur.
9. Develop strategies and economic policies for encouraging the production, distribution, and use of sulfur-containing fertilizers or soil amendments in order to improve crop yields and quality.
10. Organize workshops and seminars to collect, assess and disseminate information on the problem of fertilizer sulfur and its implications for increasing food production and improving human nutrition.

Priorities for International Research Programs

International research organizations should establish the following priorities:

1. Recognize that sulfur problems exist and can be solved through timely action by research and development agencies concerned with food production and nutrition.
2. Improve fertilizer technology to reduce costs for production of high-analysis fertilizers that incorporate 5%-10% sulfur.
3. Develop technology for improving use efficiency of sulfur applied to crops in tropical environments, using sulfur-deficient soils and sulfur-responsive crops and crop varieties.
4. Standardize the chemical methodology for analyzing sulfur in soil and plants and standardize the technique used to study sulfur problems of tropical countries.
5. Realizing the serious limitations of greenhouse and laboratory studies of sulfur, place more emphasis on field studies. The greenhouse studies should investigate principles and determine the relative use efficiencies of various test materials in order to form the basis for field experimentation, but they should not be considered the end point of research.

6. Coordinate and collaborate in an international network of field trials to study the effect of sulfur-containing fertilizers on the yield and quality of tropical crops, using high-priority areas and selected crops, varieties and cropping systems. Use of ^{35}S in research may be made at a few selected sites where facilities for such work provide the necessary support.
7. Determine economic viability and farmers' preferences for various fertilizer products designed to supply sulfur for major agricultural areas in the tropics.
8. Formulate fertilizer sulfur-related economic policies appropriate for the developing tropical countries in order to accelerate food production through judicious production, trade, distribution, and use of fertilizer sulfur.
9. Arrange international workshops for planning a coordinated program of research with the scientists in the developing countries of the tropics, and provide training facilities as needed.
10. Assist developing countries in finding alternative technological options to be included in strategies for improving sulfur nutrition of crops, increasing food production, and alleviating hunger and malnutrition.