PN-ABQ-684
ISN 86193

Phosphate Fertilizers and the Environment - A Discussion Paper

IFDC International Fertilizer Development Center

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Library of Congress Cataloging-in-Publication Data

Schultz, J. J.
Phosphate fertilizers and the environment : a discussion paper / prepared by James J. Schultz, D. Ian Gregory, and Orvis P. Engelstad.
p. cm. -- (Paper series ; P-16)
Includes bibliographical references (p.
ISBN 0-88090-097-0 : $4.00
1. Phosphatic fertilizer industry—Environmental aspects. 2. Phosphatic fertilizers—Environmental aspects. I. Gregory, D. Ian. II. Engelstad, Orvis P. III. International Fertilizer Development Center. IV. Title. V. Series: Paper series (International Fertilizer Development Center) ; IFDC—P-16.
TD195.P47S38 1992 92-30388
363.17'92—dc20 CIP

IFDC publications are listed in *IFDC Publications—1991*, General Publication IFDC—G-1, which is available free of charge.

ACKNOWLEDGMENT

The data and observations contained in this paper could not have been assembled without the large body of information that was so generously provided by the public- and private-sector fertilizer industry, its associations, and the regulatory agencies charged with the promulgation of environmental legislation.

The authors also wish to acknowledge the contribution made by IFDC staff agronomists, policy economists, engineers, and research associates in the collection and analysis of much of the data presented in this paper.

PREFACE

This paper is designed to provide a basis for an objective analysis and discussion of the environmental issues that are facing the global phosphate fertilizer sector.

The environmental issues described in this paper and the rationale used to address them are dynamic and constantly changing in response to new information and criteria. Therefore, the data presented in this paper should not be viewed as final; instead they represent only a phase in the continuing development process.

Lately, some of these issues have taken on a heightened sense of urgency due largely to the increased level of worldwide public awareness and concern about protecting the environment. It appears that no industrial endeavor, regardless of its type, size, or location, is being spared from this environmentally focused public scrutiny and accountability.

Terms such as "environmental protection and restoration" or "environmentally sound or acceptable" have no quantitative or universal meaning. Therefore, an objective analysis of the issues is often clouded by lack of scientific documentation on the one hand and public pressure on the other.

This paper takes no position on the merits of the environmental initiatives currently being proposed and debated. Instead, it focuses on quantifying the possible impact that a number of proposed environmental initiatives may have upon the production and use of phosphate fertilizers should they be enacted into law on a widespread basis. Also, the authors emphasize that the mention of industrial or regulatory organizations or bodies for the purpose of illustration does not imply that these groups agree with or endorse the data and issues described in this paper.

The increased level of environmental awareness has already resulted in the formulation, and in some instances the implementation, of restrictive legislation relative to fertilizer production and use. In some cases, the rationale for increased regulatory intervention to safeguard the environment may be technologically founded, whereas in other cases a credible scientific basis for increased regulation is either lacking or open to broad interpretation and debate.

The phosphate fertilizer production sector is especially vulnerable in the environmental debate because it is part of two major industrial sectors—mining and chemical processing. Thus, the industry is called upon to respond to a broad spectrum of real or perceived adverse effects including those attributed to mine development and operation, chemical processing, and the management of process byproducts and wastes. Also, because the phosphate fertilizer industry, including the commercial trade of raw materials and products, is global in nature, the impact that national or local environmental issues may have upon the availability and cost of phosphate fertilizers takes on global proportions. The level of environmental regulation and compliance also varies widely throughout the world. The impact of this disparity on the competitive advantage of certain producers could adversely influence the availability and farm-level cost of phosphate fertilizers.

While it is not possible to quantify the precise impact that the production and use of phosphate fertilizers may have upon the environment from one region of the world to another, this paper does attempt to raise the major environmental issues facing the producer and user of phosphate fertilizers. It also strives to sufficiently quantify the technical and economic impact that some of the regulatory scenarios currently under study may have upon the supply and cost of phosphate fertilizers: fertilizers that continue to be urgently needed to provide food and fiber for the world's more than 5 billion people, a population that is currently growing at an annual rate of 1.8%.

Public- and private-sector planners and policymakers should find much of the technical and economic data described herein particularly useful as they continue to strive to reconcile environmental concerns attributed to industrialization, on the one hand, with an ever-increasing need to maximize agricultural production on the other.

PHOSPHATE FERTILIZERS AND THE ENVIRONMENT

ABSTRACT

Sustained production of food and fiber depends heavily upon the continuous addition of nutrients to the soil to replace those removed by the harvested crop or through a number of other pathways including leaching, runoff, erosion, and, in the case of nitrogen, gaseous losses.

While recognizing the importance of all nutrients, this paper is limited to phosphorus, which ranks among the most essential nutrients required for crop production. The paper examines the impact that current phosphate fertilizer industry practices, including mining, land reclamation, beneficiation, and chemical processing, may have upon the environment. It also indicates the technical scope available for mitigating any negative impact that may occur.

Current annual world production of phosphate fertilizers amounts to about 41 million tonnes of P_2O_5. More than 95% of these phosphate products are chemically processed to increase their solubility. The great majority (about 70% of total) of all fertilizer P_2O_5 is derived from wet-process phosphoric acid. The production of 1 tonne of water-soluble P_2O_5, derived from wet-process phosphoric acid, results in the production of about 5 tonnes of phosphogypsum. Additionally, in most cases the phosphogypsum is associated with contaminated process water, which must be contained or otherwise managed. World production of phosphogypsum amounts to about 150 million tonnes annually. To date, technical and economic constraints have limited the uses for phosphogypsum; therefore, its management and disposal have given rise to an increasing number of environmental and cost concerns. Estimates described in this paper indicate that the farm-level cost of the most important phosphate fertilizers produced in existing facilities could increase anywhere from about 10% to 50% depending upon the regulatory scenario examined.

Agronomic evidence shows that, except for certain short-season crops grown in relatively cool soils, the high water solubility of the phosphate fertilizers currently being produced is not necessary for many crop production systems. A moderate level of water solubility in the range of 40%-60% of the total P_2O_5 is usually satisfactory for most of the world's important food- and feed-grain crops, provided the remainder of the P_2O_5 is "available" as measured by traditional laboratory test methods.

Although the agronomic potential exists for decreasing the water solubility of most phosphate fertilizers, and thus the consumption of wet-process phosphoric acid, the farm-level cost of P_2O_5 derived from these less water-soluble sources continues to be higher than that of P_2O_5 derived from the more water-soluble phosphoric acid-based products even if the production cost of phosphoric acid is increased as much as 50% above its current level.

This paper focuses on the impact that certain environmentally driven regulatory scenarios may have upon the cost and availability of phosphate fertilizers and therefore the production of the world's major food- and feed-grain crops. Government policy initiatives and other actions that may be required to alleviate the constraints attributed to environmental protection are indicated.

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1. INTRODUCTION

The global agricultural sector, including the chemical fertilizer industry, is faced with a number of sensitive political and economic issues rooted in the increased worldwide awareness of the need to protect, and in many cases restore, the global environment. This paper identifies the major environmental issues facing the phosphate subsector of the fertilizer industry, attempts to quantify the costs for mitigating certain indicated impacts upon the environment, and suggests policy initiatives that may be required to ensure that adequate supplies of phosphate fertilizers continue to be available to sustain global agricultural productivity.

Production of food and fiber for a world population of approximately 5.3 billion, which is increasing 1.8% annually, takes place on about 950 million ha of cultivated land, of which about 25% is irrigated in some fashion [48,24]. Sustaining this production depends upon the continuous addition of essential nutrients to the soil, not only to replace those removed by the harvested crops (Table 1) but also to improve the fertility of marginal lands. Worldwide annual consumption of the three primary nutrients derived from manufactured fertilizers—nitrogen (N), phosphate (P_2O_5), and potash (K_2O)—currently amounts to about 146 million tonnes (Figure 1). On a regional basis, there is a wide disparity in the use of these three primary nutrients ranging from a high of about 270 kg/ha in Western Europe and China to a low of about 9 kg/ha in sub-Saharan Africa. Likewise, P_2O_5 consumption varies quite widely, from almost 70 kg/ha in Western Europe to only about 3 kg/ha in sub-Saharan Africa (Table 2). Current annual world phosphate fertilizer consumption amounts to about 38 million tonnes of P_2O_5 and is expected to reach about 43 million tonnes P_2O_5 by the end of the century [23,13]. The distribution of current world phosphate fertilizer consumption on a regional basis is shown in Figure 2 while the trend in consumption of the three primary nutrients since 1970 is shown in Figure 3.[1]

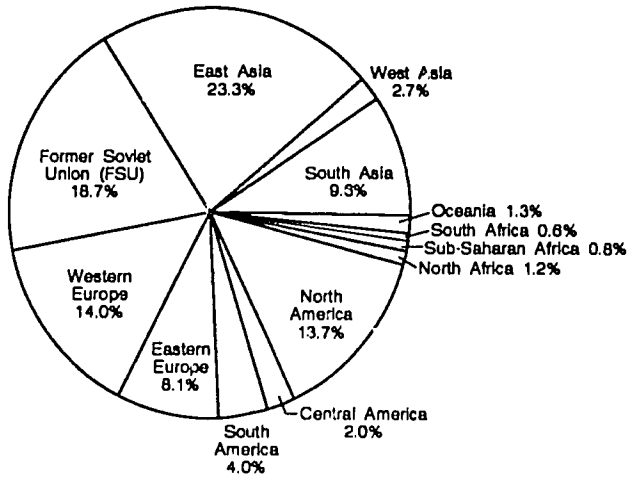
Ever since about 1840, when a German scientist, Justus von Liebig, first stressed the importance of replacing mineral elements removed from the soil by crops, the benefits of nutrients supplied by manufactured (chemical) fertilizers have been clearly established as a means for increasing agricultural production [8,30,32,33]. The recognized need for fertilizers in today's agriculture necessitates the continued effort to implement production and use strategies designed to minimize any adverse impact upon the world's air, land, and water resources.

1. Author's Note: Refer to Appendix B for regional classification of countries used throughout this paper. Dates cited for fertilizer statistical data throughout this paper, for example, 1988 or 1989, may actually be 1987/88 or 1988/89, respectively, depending upon source of data.

Table 1. Estimated Quantity of Nutrients Removed by Selected Harvested Crops[a]

	World Average Yield[b] (1989)	Grain	Yield[c]	Nutrients Removed: Total Nutrients	Nitrogen (N)	Phosphorus (P_2O_5)	Potassium (K_2O)
	(t/ha)	(t/ha)	(bu/acre)	(kg/ha)			
Wheat	2.38	2.7	40	101	56	28	17
Rice (paddy)	3.46	4.0	80	89	56	22	11
Barley	2.35	2.2	40	67	39	17	11
Maize	3.63	9.4	150	255	151	59	45
Sorghum	1.31	3.8	60	101	56	28	17
Oats	1.82	2.9	80	95	56	22	17
Rye	2.10	1.9	30	61	39	11	11
Soybeans	1.84	2.7	40	269	168	39	62

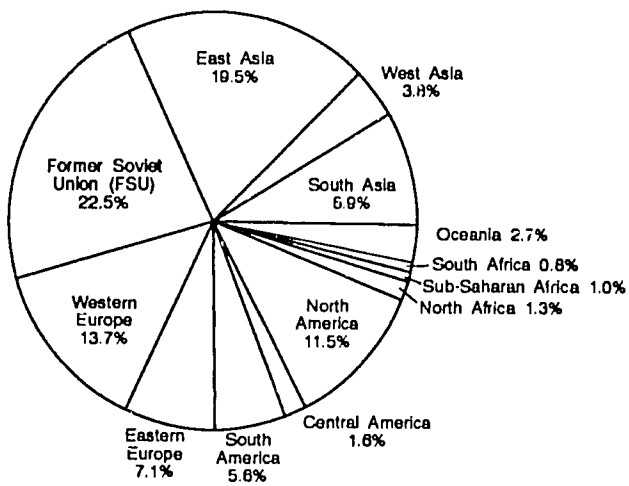
a. Calculated from data in Table 2, *The Fertilizer Handbook* [58].
b. FAO [24].
c. Yield assumed for calculation of indicated nutrient removal.



Total World Nutrient Consumption ($N+P_2O_5+K_2O$)–146 Million Tonnes (1989).

Source: FAO [23].

Figure 1. Distribution of total world nutrient consumption by region, 1989.



Total World P_2O_5 Consumption–38 million tonnes (1989).

Source: FAO [23].

Figure 2. Distribution of world phosphate fertilizer consumption by region, 1989.

Nitrogen fertilizers have received the most attention with regard to their contribution to elevated nitrate levels in some aquifers underlying large areas of land committed to intensive agricultural production. A number of initiatives are underway to curb the intrusion of nitrogen into the groundwater, particularly in developed countries where the consumption of nitrogen fertilizers is relatively high. These initiatives include (1) legislation, including use taxes, to limit the amount of applied nitrogen and regulate its time of application, (2) improved application practices, (3) nitrogen product modifications to better regulate the nitrogen release rate according to the crop's need, and (4) the use of crop rotations and deep-rooting crops that intercept nitrate moving downward in the soil profile.

In contrast to nitrogen, applied phosphate is quite immobile in most soils. Except for unique situations such as the occurrence of P-saturated soils, its intrusion into the groundwater is very limited [8,32,38,39]. Because phosphate reacts with constituents of the soil, only a portion of the phosphate is utilized by the crop to which it is applied. However, because the phosphate is so intimately associated with the topsoil particles, it is more easily transported to surface waterways through soil erosion [32].

The great majority of the phosphate fertilizers currently used worldwide are highly soluble in water (Figure 4). The remainder, though less soluble in water, are still relatively available to the crop, depending upon a number of soil, crop, and climatic factors discussed later.

Most of the highly water-soluble phosphate fertilizers are derived from wet-process phosphoric acid. Wet-process phosphoric acid is produced by reacting sulfuric acid with phosphate rock and then separating the resultant dilute phosphoric acid from unwanted solid reaction products, silica, and other impurities in the phosphate rock. This solid residue is essentially calcium sulfate-dihydrate, or gypsum, commonly referred to as phosphogypsum.

Other methods for producing water-soluble phosphate fertilizer are also based on the reaction of acids with phosphate rock. When a limited amount of sulfuric acid is used, single superphosphate (SSP) is produced. This product, although relatively low in P_2O_5, typically 16%-20%, is very soluble and currently accounts for about 17% of world P_2O_5 consumption. When phosphate rock is treated with nitric acid, unwanted calcium is most often removed from the reaction liquor as solid calcium nitrate, which can be further processed into ammonium nitrate fertilizer and byproduct calcium carbonate. Variations of the nitric acid-type processes range from almost total calcium removal to yield a very highly water-soluble phosphate fertilizer to no calcium removal, which yields a less concentrated and moderately soluble product. Some nitric acid-based processes also use varying amounts of sulfuric acid and/or phosphoric acid to adjust the nitrogen-to-phosphorus ratio and the level of water-soluble phosphorus in the final product.

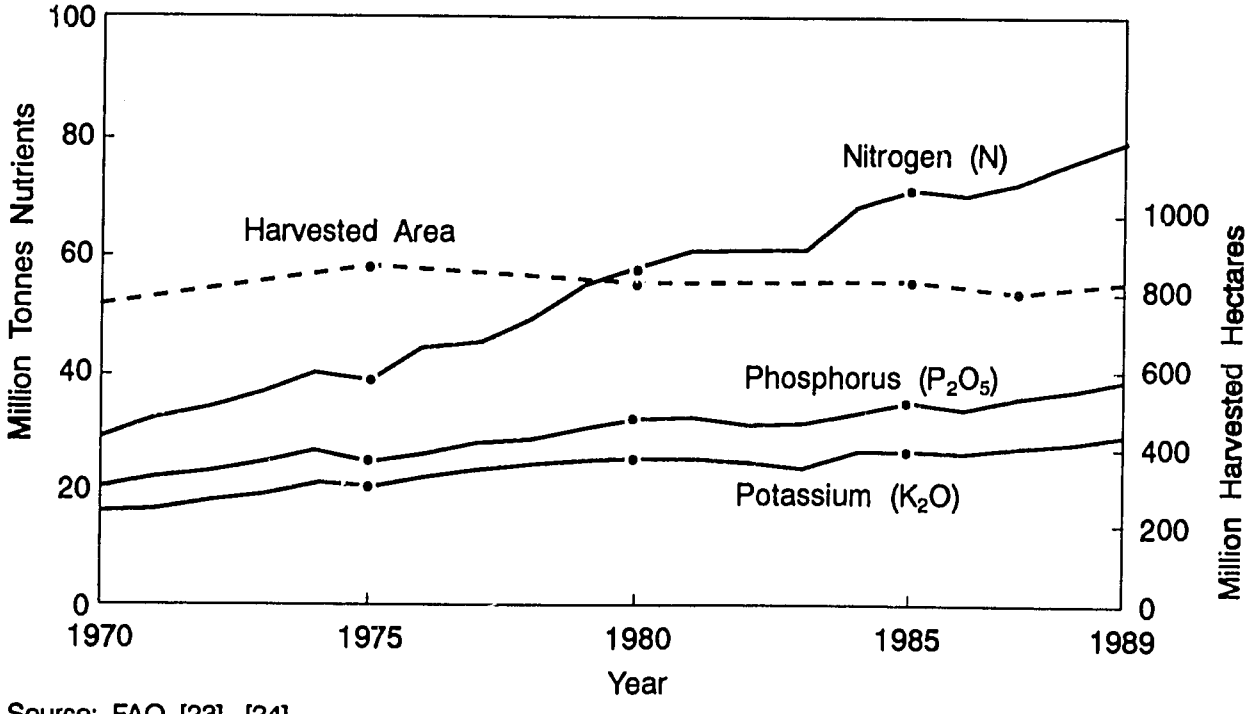
The water solubility of a phosphate fertilizer is roughly proportional to the amount of calcium removed during processing. Most phosphate rock (concentrate) typically contains about 1 tonne of calcium for each

Table 2. Phosphate Fertilizer and Total Fertilizer Consumption Per Hectare of Arable Land, 1989[a]

Region[b]	Phosphate Fertilizer Consumption: Total	Phosphate Fertilizer Consumption: Arable Land	Total Fertilizer Consumption
	(million t P_2O_5)	(kg P_2O_5/ha)	(kg $N+P_2O_5+K_2O$/ha arable land)
U.S.S.R. (Former Soviet Union)	8.56	38	119
Western Europe	5.19	69	271
China	5.16	55	271
North America	4.35	19	87
Canada	0.62	14	47
United States	3.73	20	95
South Asia	3.39	16	68
Eastern Europe	2.69	53	233
East Asia (excluding China)	2.24	32	123
South America	2.12	18	50
West Asia	1.46	29	77
Oceania	1.03	22	40
Central America	0.61	18	89
North Africa	.48	21	75
Sub-Saharan Africa	.37	3	9
South Africa	.32	26	67
World	38	28	106

a. Does not include arable land in permanent crops.
b. Refer to Appendix B for regional classification of countries.

Source: FAO [23,24].



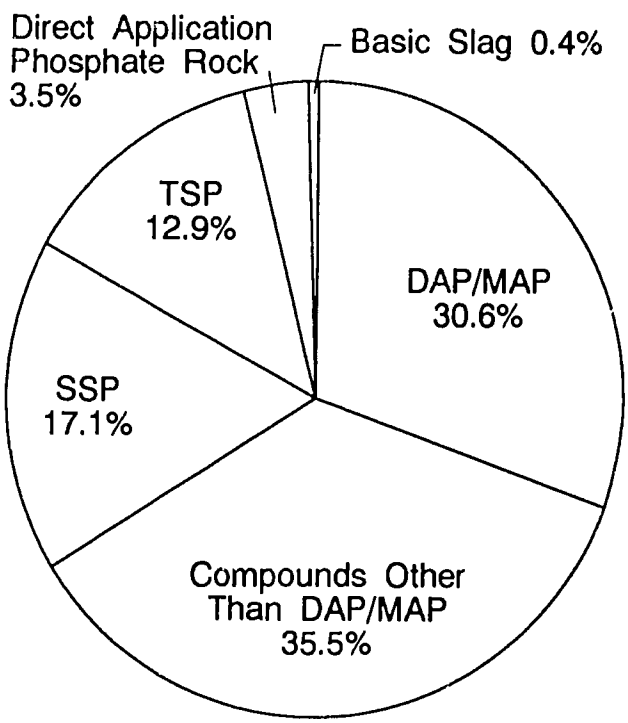
Source: FAO [23], [24].

Figure 3. Trend in world total nutrient consumption and harvested area, 1970-89.

tonne of P_2O_5. Thus, the production of the more soluble phosphate fertilizers, which are derived from phosphoric acid, results in the production of about 150 million tonnes of byproduct phosphogypsum annually on a worldwide basis. This large quantity of phosphogypsum has given rise to concerns relative to the management and disposal of this solid material and its associated process water in an environmentally acceptable manner.

In searching for ways to meet the growing need for phosphate fertilizers in an economic way, and at the same time address the environmental concerns directed at the phosphate fertilizer producer and user, this paper raises the following issues (questions) for debate and evaluation:

1. Is the current family of highly water-soluble phosphate fertilizers necessary from an agronomic point of view?
2. What are acceptable phosphate fertilizer water solubilities for the significant cropping systems in the world's major agroclimatic zones?
3. What are the costs associated with responding to the environmental concerns currently directed at the phosphate industry?
4. What alternative and more environmentally benign phosphate product options are available and what is their cost?
5. What are the technical, economic, and policy barriers (constraints) that would have to be overcome to change current phosphate fertilizer production and use practices?



Source: Various published data by British Sulphur Corporation Ltd., FAO, and IFA.

Figure 4. Distribution of world phosphate (P_2O_5) fertilizer consumption by product type (world total in 1989 was 38 million tonnes).

2. AGRONOMICS OF PHOSPHATE FERTILIZER USE

The production of the world's most important food- and feed-grain crops (Figures 5 and 6) removes anywhere from about 20 to 60 kg/ha of P_2O_5 from the soil for each crop harvested (Table 1). Because the crop is usually removed and consumed elsewhere, little of this phosphorus is recycled back to the soils from which it was taken. Add to this the phosphorus that is lost through erosion of topsoil or through reactions with soil components to form compounds that are only slightly soluble or entirely unavailable to crops, and one can quickly appreciate the need for continuously replenishing the soil's phosphorus supply through the application of manufactured fertilizers, manures, and recycled crop residues.

2.1 Phosphate Fertilizer Product Characterization

For agronomic purposes, phosphate fertilizer products are most often characterized by (1) solubility, (2) particle size, and (3) the chemical form of phosphate they contain, for example, monocalcium phosphate or dicalcium phosphate.

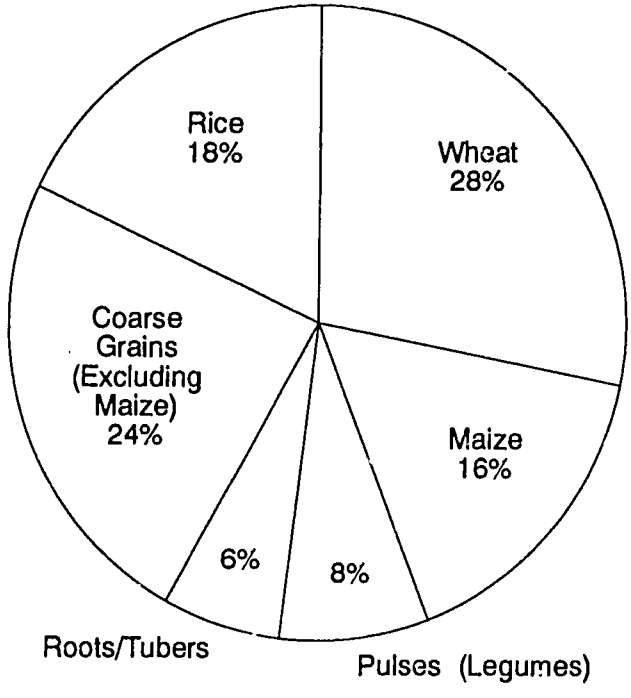
The solubility of fertilizer phosphate is measured by a number of laboratory methods around the world. The differences in indicated solubility depend largely upon the test method used [34,37,62].

Particle size is easily measured using test screens. As with solubility test methods, there are also a number of screen standards and test procedures used [65]. The particular chemical form of the phosphate, or the mix of chemical forms found in a fertilizer, largely determines the solubility of the product as determined by laboratory test methods. However, particle size and porosity can influence the rate at which the phosphate dissolves when it is applied to the soil.

2.2 Behavior of Applied Phosphate Fertilizers in Soil

Upon application, water-soluble phosphates react quite rapidly with soil components to form compounds of lower solubility. In the process, there is some localized movement of dissolved phosphorus away from the particle or granule site. Because only a small volume of soil (about 2% of the plow layer) is normally affected by the applied fertilizer phosphate, placement of phosphate near the seed is an important management practice used to increase the chances of the young seedlings absorbing phosphorus when it is most needed.

Only about 10%-20% of applied phosphorus fertilizer is taken up by the crop to which it is applied. The remainder contributes to "build-up" of residual phosphorus in the soil, which is usually in less soluble forms. In acid soils, these are primarily iron and aluminum phosphates of low solubility; in calcareous soils, they are calcium phosphates of varying solubility. Formation of such compounds explains why phosphorus is quite immobile in the soil and why so little is taken up by the first crop.



Source: FAO [24].

Figure 5. Distribution of major food- and feed-grain crops (821 million harvested hectares), 1989.

2.3 Phosphate Solubility Needs for Selected Crops

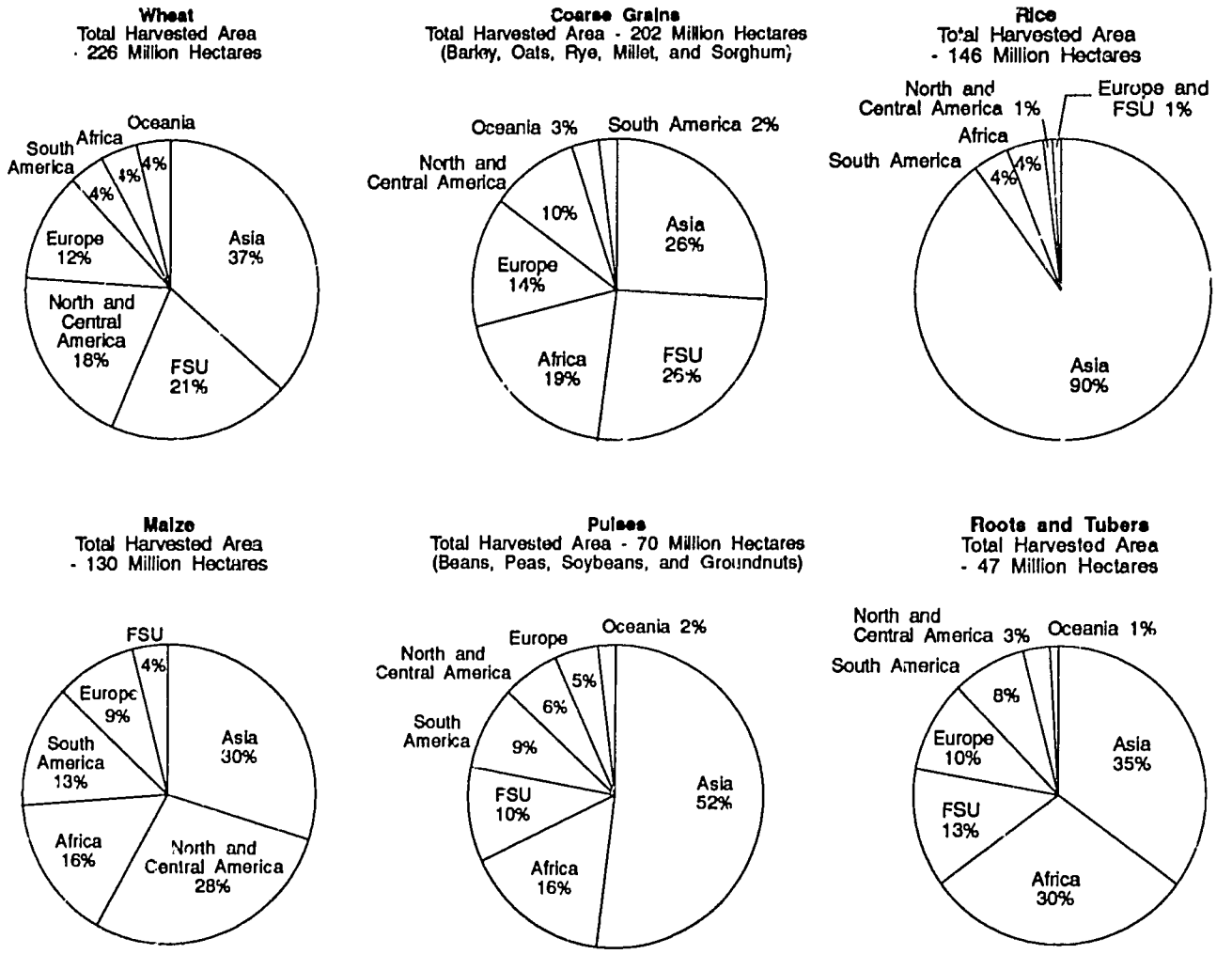
Many factors affect the response of a crop to water-soluble phosphorus; however, minimum levels of water-soluble phosphorus needed for certain crops can be estimated. Although this is a subjective judgment, the water-solubility seldom needs to be as high as currently found in most commercial phosphate fertilizers. For most crops, 40%-60% of the total phosphorus in the water-soluble form is considered adequate provided that most of the remainder is "available" as measured by conventional laboratory test methods. For short-season vegetable crops, the water solubility should be higher; for longer season crops, it can be lower. Most vegetable crops are grown over a fairly short period of time with root systems that are not well developed, whereas long-season crops are characterized by well-developed root systems. Because the phosphorus is quite immobile in the soil, a large and vigorous root system is more likely to intercept and absorb phosphorus from the soil.

A summary of the estimated phosphate solubility requirements for major food- and feed-grain crops follows:

Crop	Estimated Water Solubility Requirement, % of Total P_2O_5[a]
Coarse grains	40-60
Maize	40-60
Plantation crops (for example, coconut, cocoa, oil palm, rubber, sugarcane)	0-30
Pulses	40-60
Rice	40-60
Roots/tubers (excluding potatoes)	40-60
Vegetables (including potatoes)	60-80
Wheat	40-60

a. Except for plantation crops, the non-water-soluble P_2O_5 fraction is assumed to be soluble in neutral ammonium citrate (NAC) solution. NAC solubility often may not be required for some plantation crops depending upon soil and climatic factors. Refer to Chapter 4 for specific phosphate fertilizer product characteristics and use criteria.

Source: IFDC [35].



Source: FAO [24].

Figure 6. Regional distribution of harvested area for major food- and feed-grain crops (821 million harvested hectares), 1989.

2.4 Irrigated Agriculture

Irrigated agriculture, which accounts for about 25% (about 240 million ha) of the current world total harvested crop area (Figure 7), may require special fertilizer materials to facilitate application. Flooding and overhead sprinkling account for the majority of irrigated agriculture, with flooding and furrow water application techniques being the most common, representing about 90% of the total. Currently, drip-type irrigation systems account for less than 1% of the total, but the application of such systems is increasing. In general, if the fertilizer is not applied with the irrigation water, phosphate fertilizer products and application methods used for upland agriculture are appropriate for irrigated agriculture.

2.5 Summary

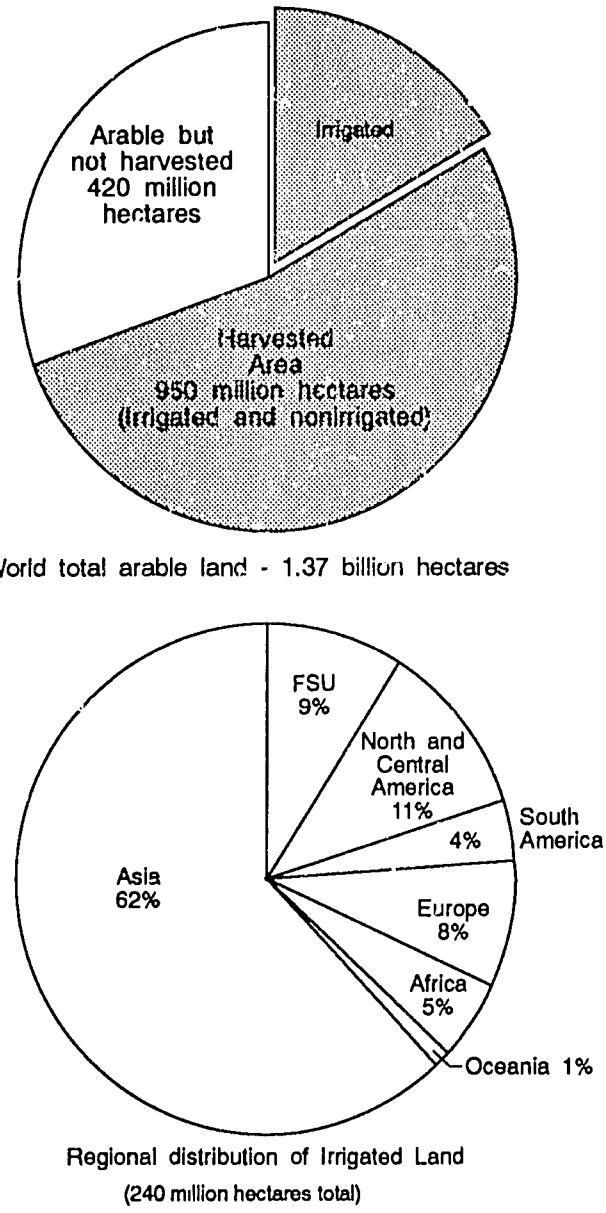
In summary, from an agronomic point of view, the application of highly water-soluble phosphate fertilizers is not necessary for the majority of cropping systems. A more moderately water-soluble family of phosphate fertilizers would be appropriate in most cases. A more complete discussion of the factors affecting the level of phosphate solubility required under specific crop production systems can be found in a recent IFDC literature review [35].

3. A BRIEF HISTORY OF THE PHOSPHATE FERTILIZER INDUSTRY

The reported gathering of human and other animal bones (containing about 25% P_2O_5) from battlefields and burial sites in the early 1800s for use as fertilizer testifies to the importance attributed to phosphate. By 1830, the effectiveness of ground bones was enhanced by treatment with sulfuric acid to increase their solubility and therefore the availability of applied phosphate to the crop. In 1842, Sir John Bennet Lawes of England patented a technology for the acidulation of coprolites (phosphate-bearing petrified excrement) and began operation of the world's first commercial plant in Suffolk to produce a phosphate fertilizer product called single superphosphate, now commonly referred to as SSP. The technology was quickly adopted, and by the mid-1850s SSP was being produced from a number of phosphate sources in several countries, including the United States. The SSP product from these early plants usually contained 10%-15% P_2O_5. By 1928 about 8.5 million tonnes of phosphate rock was being used worldwide to produce about 15 million tonnes of SSP. Except for converting the process from the original batch-type operation to a continuous process and improving machinery, materials of construction, and the recovery of effluents, the SSP industry of the early 1900s is much the same today. Currently, world production of SSP, usually containing 16%-20% P_2O_5, amounts to about 40 million tonnes of product accounting for about 17% of the world's total fertilizer P_2O_5 consumption (Figure 4). A thorough review of the early phosphate mining and superphosphate industry (1842-1930) is provided by Gray [27].

With the first commercial production of dilute phosphoric acid (10%-15% P_2O_5) in Germany in the early 1870s and in the United States in 1890, the production of an enriched SSP was possible [53]. The partial or total substitution of phosphoric acid for sulfuric acid in the acidulation step resulted in an enriched or concentrated superphosphate product often referred to as CSP, containing about 30% P_2O_5, the predecessor to today's triple superphosphate (TSP) product containing 46% P_2O_5. The early phosphoric acid plants, like the early SSP and TSP plants, were operated on a batch basis. Wood and lead were the available and preferred materials of construction in these early plants. It was not until 1915 that a continuous process for producing phosphoric acid was introduced by the Dorr Company of the United States [53]. This process, besides being operated on a continuous basis, produced a more concentrated product acid containing about 25% P_2O_5. The technology was quickly adopted, and by 1929 there were some 31 companies in North America and Europe using the Dorr continuous wet-process phosphoric acid process. By today's standards these early plants were small, typically producing from 10 to 50 tpd P_2O_5; nevertheless, they provided the technological basis for today's phosphoric acid industry. The phosphoric acid industry has grown steadily since the mid-1900s, and currently about 70% of the world's fertilizer P_2O_5 is derived from phosphoric acid.

The commercial availability of wet-process phosphoric acid, usually containing from 28% to 54% P_2O_5, facilitated the large-scale production of TSP (0-46-0), ammonium phosphate-sulfate (16-20-0), diammonium



Source: FAO [24].

Figure 7. Total and regional distribution of irrigated land area, 1988.

phosphate (DAP, 18-46-0), monoammonium phosphate (MAP, 11-52-0), and a number of compound (NPK) products. However, it was not until the late 1960s that DAP became the dominant solid phosphate fertilizer. Today, a total of about 20 million tonnes of DAP and MAP (mostly DAP) is produced annually accounting for about 31% of the world's P_2O_5 fertilizer consumption. Since the mid-1960s, TSP has given way to DAP and MAP and now TSP accounts for only about 13% of the world's phosphate (P_2O_5) consumption (Figure 4).

Many other phosphate fertilizer production processes enjoyed brief periods of development and industrial prosperity over the years. Among the most notable was the direct production of phosphoric acid from elemental phosphorus. Elemental phosphorus is produced by reduction of phosphorus-bearing ore in an electric arc furnace. The first electric furnace in the United States was built in 1896 at Niagara Falls [45]. The Tennessee Valley Authority (TVA) began development work on the production of elemental phosphorus by the electric-furnace method in 1933; by 1974, TVA and nine other plants in the United States were producing a total of nearly 0.5 million tonnes of elemental phosphorus annually. Of this, the majority was converted into phosphoric acid for nonfertilizer industrial uses (mostly superphosphoric acid having a P_2O_5 content of as much as 76%-80%). However, for a brief period in the late 1960s and early 1970s, a significant quantity of superphosphoric acid (about 1 million tonnes of P_2O_5) was converted into very concentrated and pure solid and liquid fertilizer products. This acid consumed about 20% of U.S. elemental phosphorus production at that time [28]. However, the cost of energy and the environmental compliance expenditures required for the electric furnace reduction process became prohibitive, and many of the plants were shut down. Today, annual world production of elemental phosphorus is estimated at about 1 million tonnes, and the Former Soviet Union (FSU) accounts for about one-half of the total [12]. About 15 plants are still operating, including 4 in the United States and 1 in Canada, producing elemental phosphorus that is used mostly in the nonfertilizer industrial sector.

Other thermally produced phosphate fertilizers that have been manufactured in relatively minor quantities include calcium-magnesium phosphate, Rhenania phosphate, defluorinated phosphate rock, calcium metaphosphate, and potassium metaphosphate. Their heavy dependence on energy currently makes them uneconomical to produce. Today, world production of thermally produced phosphate fertilizers is small; Brazil, China, Japan, and Vietnam are reportedly among the few remaining producing countries.

The steel industry also produces a small amount of fertilizer-grade phosphate in the form of byproduct basic slag (also referred to as Thomas slag). This material usually contains from 10%-20% P_2O_5 in the water-insoluble form. In 1988, world production of basic slag amounted to the equivalent of about 205,000 tonnes P_2O_5.

4. THE PHOSPHATE FERTILIZER INDUSTRY OF TODAY

Today, the world's phosphate fertilizer industry produces about 41 million tonnes of P_2O_5 annually not including that used for animal feed supplements (about 1.8 million tonnes P_2O_5) and other industrial purposes (about 2 million tonnes P_2O_5). This amount of P_2O_5 is contained in about 140 million tonnes of fertilizer products in which about 70% of the P_2O_5 is derived from wet-process phosphoric acid.

The industry is characterized by (1) the concentration of raw material production in relatively few countries; (2) integrated processing; (3) extensive intra- and interregional trade in raw materials and increasingly in intermediate and finished products; and (4) excess capacity relative to demand.

4.1 Global Overview of Phosphate Fertilizer Production and Use[2,3]

In the last two decades, processed phosphate (phosphoric acid and finished products) trade has increased steadily, whereas phosphate rock concentrate trade has declined. Transport cost savings for the more concentrated phosphate materials and economies of scale attributed to the integration of mining and processing have been the main reasons for the trend.

Because the production, consumption, and trade statistics of phosphate raw materials, intermediates, and finished products are difficult to describe in narrative form, the reader is referred to Appendix A. Appendix A contains a number of two-way tables which quantify the phosphate production, consumption, and trade patterns on a regional basis. The country composition of each region is given in Appendix B. A discussion of these data follows.

4.1.1 *Profile of Basic Phosphate Raw Materials*

4.1.1.1 Phosphate Rock Concentrate—The annual production of 41 million tonnes of fertilizer P_2O_5 requires the mining of about 650 million tonnes of ore. About 80% of the mined ore is of sedimentary origin

while the remainder is of igneous origin. This ore is processed into about 140 million tonnes of phosphate rock concentrate having a typical P_2O_5 content of about 31% for the sedimentary material; the P_2O_5 content of concentrate derived from some igneous ores may exceed 36%. An additional 15-20 million tonnes of phosphate rock concentrate is used annually for nonfertilizer purposes. In 1989, total production of phosphate concentrate amounted to about 163 million tonnes [14]. Although 34 countries currently produce phosphate concentrate, only 4 countries (United States, FSU, Morocco, and China) account for about 75% of all production (Table 3 and Figure 8).

Exports of phosphate rock concentrate account for about 27% of total deliveries (46.4 million tonnes in 1988, 43.1 million tonnes in 1989). Fourteen countries exported concentrate in 1988, but Morocco (14.3 million tonnes), the United States (9.3 million tonnes), and Jordan (5.6 million tonnes) accounted for 63% of export deliveries. Europe (62%) and Asia (22%) were the predominant regional destinations for these exports.

Over the past decade, world exports of phosphate concentrate declined from about 53 million tonnes to about 46 million tonnes today. During this period, North African (Morocco and Tunisia) and West Asian (Jordan and Israel) producers emerged as major exporters while exports from the United States declined. This trend is expected to continue. Overall, it is expected that phosphate concentrate exports will stagnate or even decline slightly until the end of the century with European imports declining by 3-4 million tonnes and Asian imports increasing by 2-3 million tonnes over the next decade [20]. Jordan seems likely to continue its steady growth (8% annually) and currently is the most competitive exporter to the growth regions of Asia because of its favorable freight advantages over the United States and, to a lesser extent, over Morocco.

Currently, there is world capacity for about 200 million tonnes of phosphate concentrate per year [56]. This excess capacity will act as a major constraint to price increases for phosphate fertilizers.

4.1.1.2 Sulfur—The second major raw material required for phosphate fertilizer production is sulfur. Annual world production of sulfur in all forms has increased from 52 million tonnes in 1975 to almost 61 million tonnes today. Almost half (29 million tonnes) is used for the manufacture of phosphate fertilizers, and an additional 4.3 million tonnes is used for the production of other fertilizers such as ammonium sulfate. All but 8% of the total production of sulfur/sulfur equivalent is used to manufacture sulfuric acid.

There have been marked changes in the sources of sulfur production over the past 15 years with an increase in the proportion of sulfur recovered from sulfur-containing (sour) natural gas and oil (41% in 1990). This has been accompanied by stagnation or decline in the percentage of Frasch (mined) sulfur (23%) and sulfur obtained from pyrites (17%) and other sources (19%). These trends are expected to continue, resulting in some two-thirds of all sulfur output coming from nonvoluntary production sources by 1995 [11].

Although more than 50 countries produce sulfur, only 4 (Canada, United States, FSU, and Poland) account for 60% of world production. Thus, there is considerable world trade in elemental sulfur, whereas trade in pyrites is limited to Europe. There is also limited trade in sulfuric acid amounting to 1.5 million tonnes of sulfur equivalent annually. Data on regional production and use of sulfur are shown in Figure 9.

4.1.2 *Profile of Wet-Process Phosphoric Acid Production*

World production of wet-process phosphoric acid was equivalent to 28.6 million tonnes of P_2O_5 in 1988. Production declined 5% in 1989, primarily because of the previously mentioned Morocco-India commercial dispute, but recovered in 1990. Because of freight

2. Authors' Note: In 1988 (1987/1988 depending on the source of data), the base year used in this analysis, the Former Soviet Union (FSU) accounted for about 25% of world phosphate concentrate production and about 17% of world sulfur production while domestic consumption of phosphate fertilizers (P_2O_5 basis) in the FSU amounted to about 22% of the world total. More than 90% of this production and consumption occurred in only 5 of the 15 former republics (Byelorussian S.S.R., Kazakh S.S.R., Russian S.F.S.R., Ukrainian S.S.R., and Uzbek S.S.R.). The recent demise of the Soviet Union along with its centrally planned economy will most certainly cloud the issues surrounding phosphate fertilizer production, consumption, and trade in the short term. The pressures on the FSU to generate foreign exchange will undoubtedly affect the global phosphate industry. The export of fertilizer, particularly nitrogen and potash products, ranks second only to petroleum products as a source of foreign exchange in the FSU. Therefore, the reader is cautioned not to view the historical data described in this paper as necessarily indicative of future trends, especially as the trends in international trade of phosphate fertilizer products are influenced by the FSU.

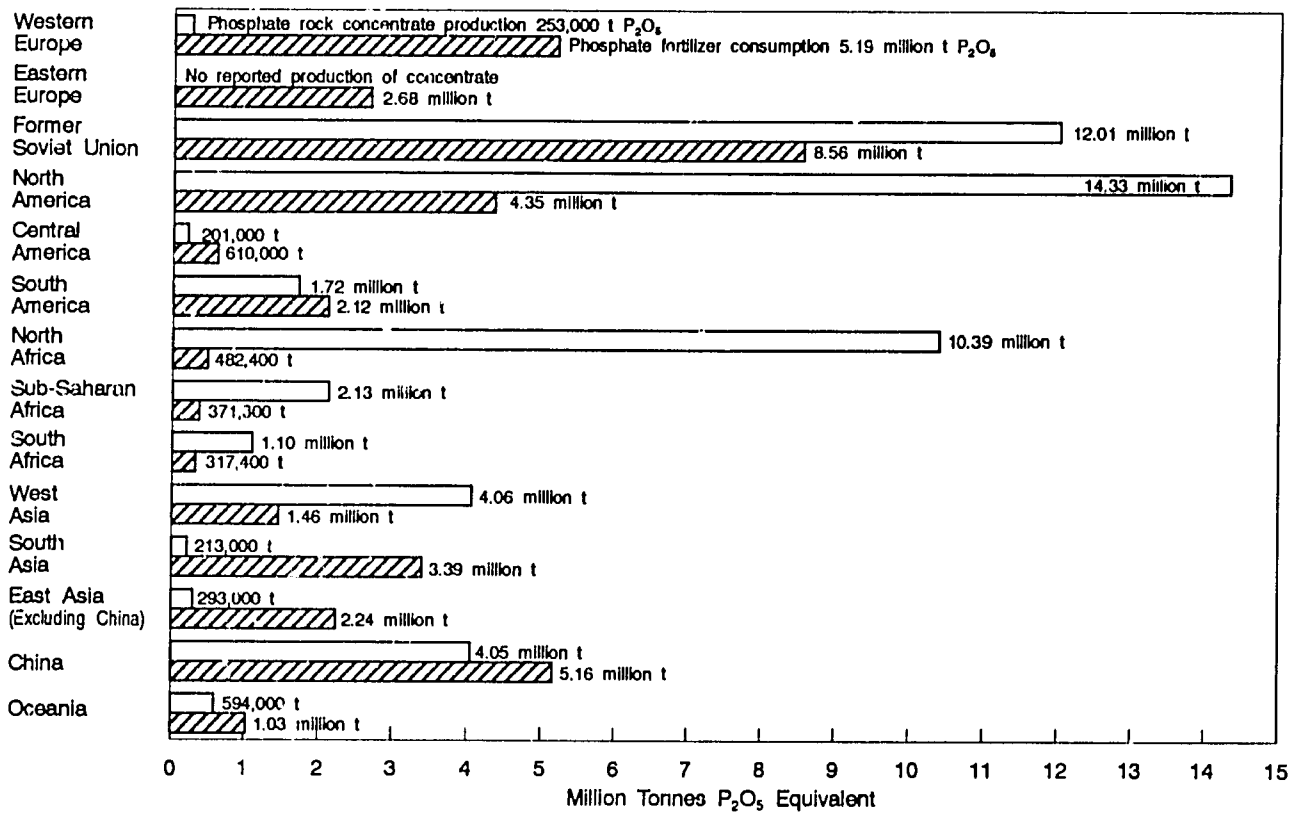
3. Author's Note: The year 1988 (1987/1988 depending on the source of data) was chosen as a reference year for analysis because in 1989 the world phosphate trade was disrupted by a commercial disagreement between India and Morocco which led to 1989 being atypical in the trade of phosphate fertilizer materials. Following resolution of the commercial differences, a return to the established trade patterns was again apparent in 1990. Data for 1991 are incomplete at this writing and, as previously noted, the trends for 1992 are uncertain.

Table 3. Major Producers of Phosphate Concentrate and World Phosphate Reserves

Country	Mine Production, 1989[a]	Reserves[a,b]	Reserve Base[a,b]
	(million t)		
United States	49.8	1,230	4,440
Former Soviet Union	39.0	1,330	1,330
Morocco and Western Sahara	18.0	5,900	21,440
China	17.0	210	210
Jordan	6.7	90	480
Tunisia	6.6	-	270
Israel	3.9	10	10
Togo	3.4	-	60
South Africa	3.0	2,530	2,530
Senegal	2.3	-	160
Others	13.8	690	2,860
World Total[c]	163.4	12,480	33,790

a. Marketable phosphate concentrate.
b. Refer to U.S. Department of the Interior, Bureau of Mines, Mineral Commodity Summaries 1991 for basis for determining quantity of reserves.
c. Totals may not add due to rounding.

Source: U.S. Bureau of Mines [14].



Source: Derived from published statistical data and IFDC data file (1988 and 1989).

Figure 8. Regional production of phosphate rock concentrate compared with total phosphate fertilizer consumption, 1989.

advantages, there has been a trend to integrate phosphate mining and processing operations. Additionally, because sulfur may represent 40% of the cost of production, phosphoric acid plants are most viable when located near economic supplies of sulfur/sulfuric acid.

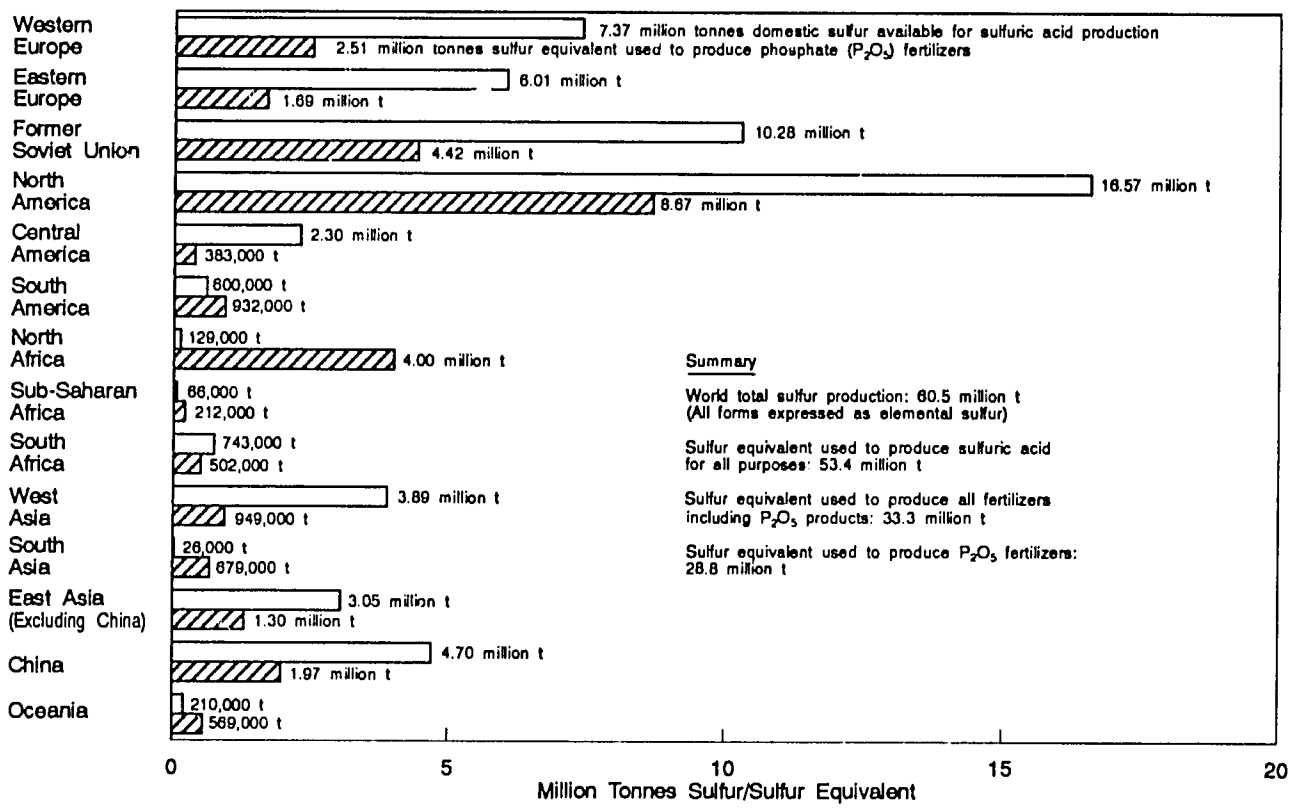
Of 40 producing countries worldwide, only 4 (United States, FSU, Morocco, and Tunisia) account for two-thirds of the world production of wet-process phosphoric acid. About 4.4 million tonnes of P_2O_5 as phosphoric acid was traded in 1988. Morocco is the largest exporter with 1.7 million tonnes P_2O_5 shipped in 1988, mostly to India and Western Europe. The United States, the second largest exporter, exports about 0.9 million tonnes P_2O_5, of which about 70% goes to the FSU. Within Western Europe, about 0.5 million tonnes P_2O_5 is traded, sourced primarily from Belgium and Spain.

About 1.9 million tonnes P_2O_5 as phosphoric acid (about 7%) is consumed for nonfertilizer uses. About 70% of this industrial use occurs in Western Europe, North America, and Japan.

Very little net new production of phosphoric acid is expected to come on stream during the next 5 years because there is a current excess of capacity. China is expected to increase its very small phosphoric acid capacity by about 2 million tonnes over the next 5 years; this production will be based on the use of domestic rock. Morocco, Jordan, FSU, and Israel are expected to increase capacity, but this will most likely be offset by declines in capacity in Europe and Japan. Production in the United States is expected to remain static.

4.1.3 *Profile of Finished Phosphate Fertilizer Products*

Almost 40% of the current annual production of approximately 41 million tonnes P_2O_5 as finished products is in the form of ammonium phosphates (DAP and MAP), and a further 13% is produced as TSP. This production accounts for approximately 83% of the phosphoric acid used in fertilizer production. These data for 1988 are summarized in the following table.



Source: British Sulphur Corporation Ltd. and other published statistical data.

Figure 9. Availability of domestic sulfur or sulfur equivalent compared with sulfur used to produce phosphate (P_2O_5) fertilizers, 1988.

Product Type	P_2O_5	Percent of Total P_2O_5	Percent of Total Phosphoric Acid Use
	(thousand tonnes)		
DAP/MAP	16,235	39.2	62.2
TSP	5,507	13.3	21.1
Phosphoric acid-based NPKs	4,338	10.5	} 16.6
Nitric acid-based NPKs	3,879	9.4	
SSP		7,083	17.1
Other phosphate fertilizers	2,888	7.0	
Direct application phosphate rock	1,310	3.2	
Basic slag	205	0.5	
TOTAL[a]	41,445	100.0	100.0

a. Totals may not add due to rounding.

The regional distribution of finished phosphate fertilizer production for 1988 is shown in Table 4. Two-thirds of total production occurred in the United States, FSU, China, and Western Europe. Production derived from phosphoric acid varies from around 80% or more in North and Central America, North Africa, and West and South Asia to around 50%-60% in other regions except Oceania and China, where phosphoric acid contributes only about 14% and 1% of the P_2O_5, respectively.

4.1.4 *Trade in Finished Phosphate Fertilizer Products*

International trade in finished phosphate fertilizers is limited primarily to DAP, TSP, and compound NPKs.

Exports of DAP have doubled in the past decade to around 4.8 million tonnes P_2O_5 annually. DAP, containing 18% N and 46% P_2O_5, is now the most internationally traded phosphate fertilizer.

The United States accounts for 60%-70% of all DAP and MAP exports (about 3 million tonnes P_2O_5). Morocco, Jordan, and Tunisia follow with approximately 10%, 7%, and 5%, respectively. Almost 60% of all ammonium phosphates are exported to Asia; China accounts for around one-third, and India, Iran, and Pakistan together account for more than 25% of the exports made to Asia. Recent estimates of landed costs for DAP to the Chinese market indicate comparative advantages from the United States while the North Africa and West Asia exporters have cost advantages in the South Asia and Western Europe markets [20].

Exports of TSP, 1.9 million tonnes P_2O_5 in 1988, have lagged behind that of DAP, presumably because TSP has a lower total nutrient content than DAP. Production of TSP is concentrated in the United States, FSU, North Africa, and West Asia. However, production in the FSU is utilized domestically, leaving the United States, Tunisia, Morocco, and Turkey as the major exporters. One-third of all exports go to Western and Eastern Europe, and about 15% go to the FSU. Another 33% is imported throughout Asia, including China, for use as a straight phosphate fertilizer.

Trade of compound NPKs amounted to almost 2.3 million tonnes P_2O_5 in 1988. Over 40% of this trade was within Western Europe, and another 10% was between Eastern Europe and Western Europe. Western Europe also accounts for 50%-55% of all other exports of P_2O_5 in the form of compound NPKs.

Because of the low concentration of P_2O_5, there is little trade in SSP, other phosphate fertilizers, or direct application phosphate rock.

4.1.4.1 Expected Trends in Traded Phosphate Fertilizer Products—The concentration of raw material supplies, favorable economics of integrated processing, and the freight advantages for more concentrated finished products have led to the current structure of production and trade of phosphate fertilizers. Growth in total production of finished products, which decreased in annual percentage terms from 7.8% in the 1960s to 1.5% in the 1980s, is now expected to stabilize. With a current overcapacity of about 2.5 million tonnes P_2O_5 in the form of finished products (6.5% of world P_2O_5 consumption) and a forecast growth in demand of only 1%-1.2%/year for the next 5-10 years, further rationalization within the industry can be expected. As the supply/demand balance comes into equilibrium during the next 5 years and prices improve, new capacity can be expected and is already being

Table 4. Finished Phosphate Fertilizer Production, 1988

Origin (Region/Country)[a]	Production (thousand t P_2O_5)	% of Total
Western Europe	4,354	10.5
Eastern Europe	2,824	6.8
Former Soviet Union	9,235	22.3
North America	10,005	24.1
Central America	406	1.0
South America	1,508	3.6
North Africa	1,954	4.7
Sub-Sahara Africa	108	0.3
South Africa	384	0.9
West Asia	1,471	3.5
South Asia	2,453	5.9
East Asia	2,156	5.2
China	3,607	8.7
Oceania	1,025	2.5
Total	41,490	100.0

a. Refer to Appendix B for regional classification of countries.

Source: Derived from published statistical data and IFDC data file.

planned in China, North Africa, and West Asia. The main surplus areas will continue to be the United States and North Africa. The deficit areas will include East Asia, China, Eastern Europe, and Central and South America.

4.1.5 *Demand for Phosphate Fertilizers*

World consumption of phosphate fertilizers increased from about 10 million tonnes P_2O_5 in 1960 to 38 million tonnes P_2O_5 in 1988, representing 36% and 26%, respectively, of total fertilizer nutrient ($N + P_2O_5 + K_2O$) consumption. During the 1960s, all regions exhibited growth in P_2O_5 consumption; growth averaged 7.3%/year and ranged from 4.0% in Western Europe to 20.2% in South Asia. During the 1970s, the growth rate slowed to 4.4%, but still all regions except Oceania maintained a positive growth. During the 1980s, there was considerable divergence in the regional growth rates due to climatic and micro- and macroeconomic policy changes [13]. Phosphate fertilizer use decreased in several regions, including significant declines in the mature markets of North America (-3.3%), Western Europe (-2.1%), Oceania (-2.9%), and Eastern Europe (-0.9%). The FSU, Asia, and sub-Saharan Africa, however, experienced more than 6%/year growth while Central America grew at almost 5%. Because of the disparity in regional consumption growth patterns, the regional shares of P_2O_5 consumption changed markedly between 1960 and 1988, as shown in Figure 10.

Over the next decade, total world consumption is expected to increase by 1%-1.2%/year to 43.3 million tonnes P_2O_5 by the end of the century. Regional phosphate fertilizer demand as forecast by the World Bank/FAO/UNIDO/ Industry Working Group is shown in Figure 10. Static or declining consumption is forecast for the developed market economies, Eastern Europe, and the FSU. Growth is confined to the developing countries and socialist Asia; over 75% of the growth is forecast to occur in South and East Asia including China.

4.1.6 *Current Phosphate Fertilizer Manufacturing and Farm-Level Cost Structure*

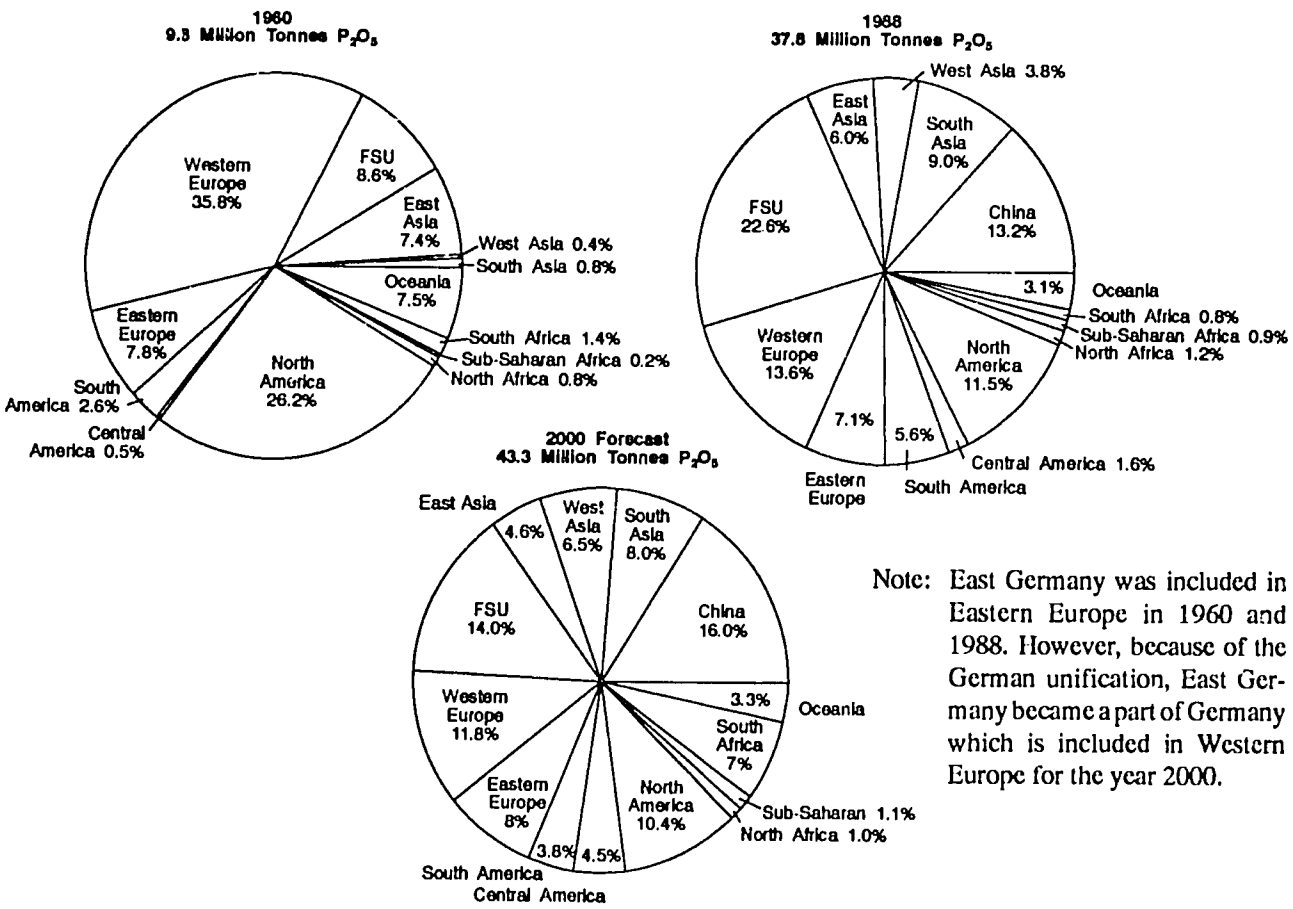
Prices for internationally traded phosphate fertilizers have fluctuated widely over the past few decades but have generally exhibited a downward trend (Figure 11). The international prices, shown in Figure 11 and quoted in current U.S. dollars, do not fully reflect the impact of supply and demand or the cost of raw materials and processing because of several distorting factors including the following:

- A limited number of buyers and sellers.
- Increased government ownership of the industry.

- Limited entry and exit of producers to and from the industry.
- Long-term lags in adjustment to achieve commercial equilibrium.
- Imperfect short-term knowledge of market conditions.
- Effects of countertrade and bartering.
- Effects of tariffs, quotas, and production and end-user subsidies.
- Impact of fluctuating international freight rates.

The industry is characterized not only by a regional concentration of raw material resources but also, over the past decade, by an increasing concentration of production within regions under the control of fewer firms. Low or negative profit levels have led to industry rationalization in the developed market economies, while the expansion of production in developing countries and centrally planned economies has led to increased public sector ownership of production resources. In 1987, it was estimated that 64% of the ownership of the global fertilizer processing industry was in the public sector [51]. Similar proportions are estimated to apply to the production of phosphate concentrate (66%) and sulfur (61%).

Assuming a new plant with relatively high capital charges, the cost of raw materials for phosphate fertilizers accounts for 40% to 60% of the total production costs [52]. However, for established plants with lower capital charges, such as those in the United States, raw materials account for as much as 80% of the total production cost [60]. With these proportionally high costs for raw materials, price distortions can be significant where government policy initiatives (in the form of subsidized production or lack of environmental control legislation and enforcement) are designed to generate foreign exchange for use in other sectors of the economy. Nonsubsidized private sector production is only able to compete against such price distortions through more efficient use of capital, raw material cost advantages, and plant operating efficiencies.



Note: East Germany was included in Eastern Europe in 1960 and 1988. However, because of the German unification, East Germany became a part of Germany which is included in Western Europe for the year 2000.

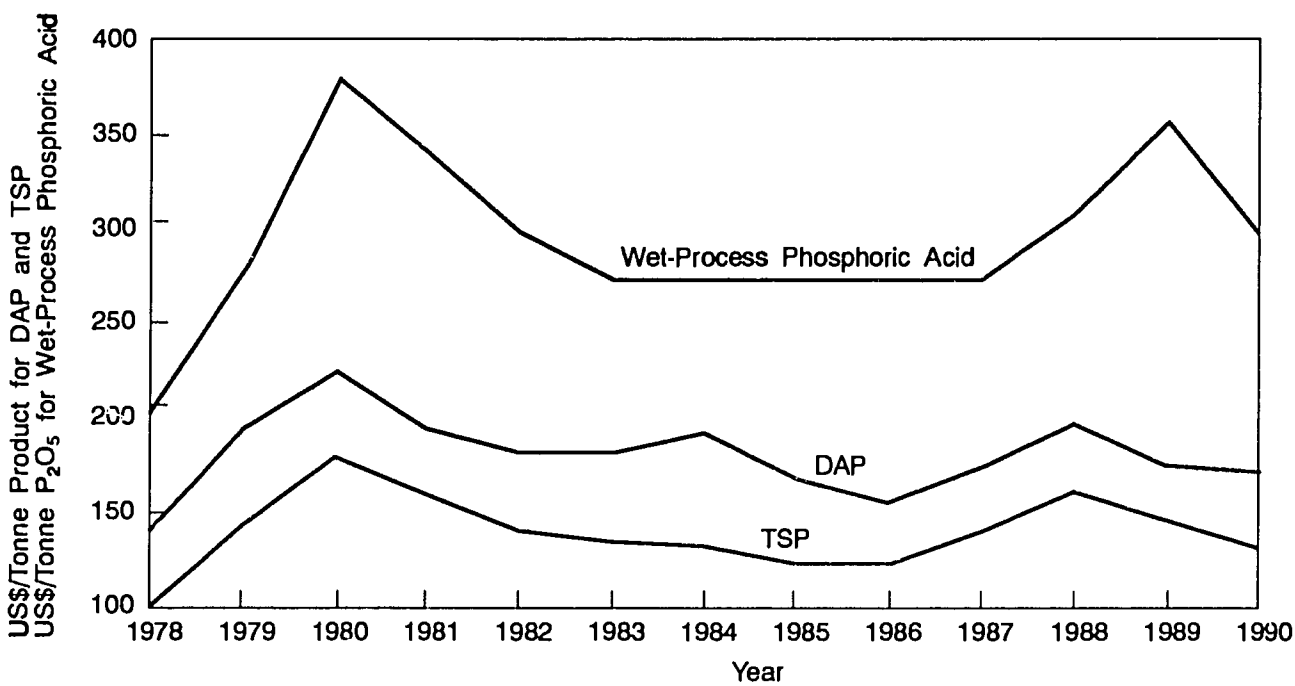
Source: Derived from FAO and World Bank/FAO/UNIDO/Industry Working Group statistical data.

Figure 10. Trend in regional share of world phosphate (P_2O_5) consumption.

4.1.6.1 Estimated Current Cost Structure Assuming New Production Facilities—Estimates of conventional and alternative phosphate fertilizer production and farm-gate costs were made by IFDC in 1988, based on new capital investments in developing country locations [52]. These estimates assumed capital recovery at 12% annual interest over 15 years and delivered raw material costs of $135/tonne for sulfur, $60/tonne for phosphate concentrate, and $145/tonne for ammonia. These costs, including credits for nitrogen and sulfur where applicable, are summarized in Figure 12. With the exception of direct application phosphate rock, the estimated farm-gate cost for all processed fertilizers is quite similar, at close to $700/tonne P_2O_5.

In order to examine more thoroughly the expected regional differences in farm-gate costs for major phosphate fertilizers, estimates were based on the above processing costs, including capital recovery and regional supply and consumption estimates, using 1988 as a base year. The delivered cost of phosphate rock concentrate was derived from an estimated domestic production cost of $107.6/tonne P_2O_5 for all regions except the United States ($61.5/tonne P_2O_5), FSU ($143/tonne P_2O_5), North Africa, sub-Saharan Africa, and West Asia ($98.4/tonne P_2O_5) and from an average export price of $123/tonne P_2O_5 f.o.b. plus estimated international freight and port-handling costs. The delivered cost for sulfur was estimated at $135/tonne for all regions, and phosphoric acid production costs and international freight costs were estimated. Where supplies of finished products were imported, the landed costs were derived from the estimated production costs in the region of origin plus freight and handling.

To arrive at the farm-gate cost, the domestic distribution and marketing costs were assumed to be $30/tonne of product for all regions except sub-Saharan Africa, where a value of $80/product tonne was assumed (refer to Chapter 6). Farm-gate product costs were then expressed per tonne P_2O_5, and credits for nitrogen or sulfur were deducted, where applicable, at $520/tonne for nitrogen and $135/tonne for sulfur at the farm level. The results are summarized in the following table.



Source: IFDC Data File as Derived from Green Markets Fertilizer Market Intelligence Weekly.

Figure 11. Price trends in current U.S. dollars for internationally traded phosphate materials (f.o.b. U.S. Gulf Coast, bulk).

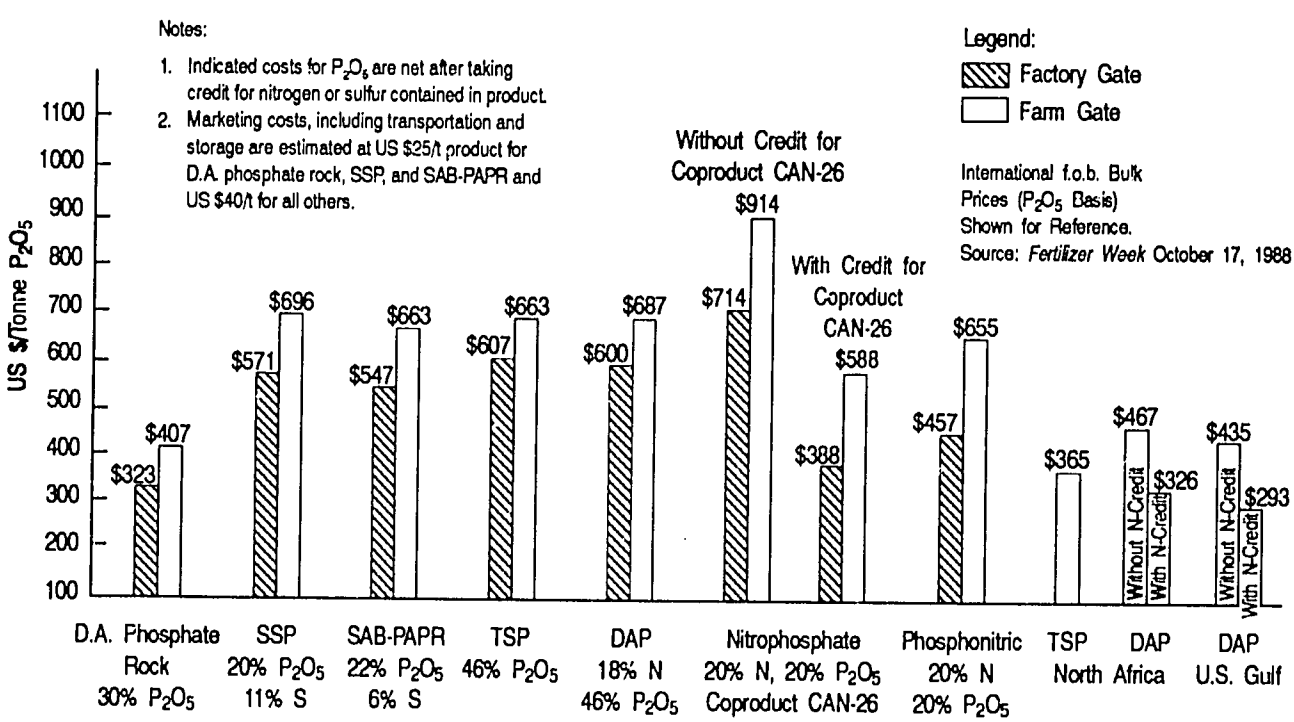
Region/Country	Estimated Farm-Level Cost of Phosphate Fertilizer[a] (US $/tonne P_2O_5)
Western Europe	559
Eastern Europe	634
Former Soviet Union	484
North America	469
Central America	621
South America	580
North Africa	575
Sub-Saharan Africa	844
South Africa	627
West Asia	578
South Asia	633
East Asia (excluding China)	638
China	541
Oceania	702
World Average	582

a. Based on new plant facilities (1988 basis) and current world product mix and phosphate trade. Values do not include estimated incremental costs for environmental compliance described in Chapter 5.

Although an attempt was made to incorporate the impact of international movements of raw materials, intermediates, and finished products and differences in the cost of phosphate rock among the major exporting regions, the resultant farm-level costs should be regarded only as indicative values.

The results of this analysis indicate an average current world cost of about $582/tonne P_2O_5 at the farm gate, with a low of US $469/tonne P_2O_5 in North America and a high of US $844/tonne P_2O_5 in sub-Saharan Africa. Apart from direct application phosphate rock, DAP, at an average cost of $551/tonne P_2O_5, is the least-cost source of phosphate followed closely by compound NPKs at $573/tonne P_2O_5. The cost of TSP is $630/tonne P_2O_5, and SSP is the most expensive source at $682/tonne P_2O_5. The cost structure for the various products is described more fully in Chapter 6.

This analysis indicates that the current industry structure and product mix, based heavily upon wet-process phosphoric acid, is providing the least-cost supply of phosphate fertilizers on a global basis.



Source: Schultz and Le [52].

Figure 12. Estimated factory- and farm-gate cost of P_2O_5 from various products (new production facilities with full capital charges are assumed using 1988 cost basis).

4.2 Overview of Environmental Regulations in the Phosphate Fertilizer Sector

4.2.1 *Summary of Environmental Regulations*

A 1983 survey of member countries by the International Fertilizer Industry Association (IFA) indicated that "environmental concerns were not regarded as a problem in developing countries, where food supplies are often insufficient, organic manure in short supply, and fertilizer use in a decline" [31].

A similar survey by IFA in 1989 showed that the situation has changed markedly: "The environmental movement has become a strong political force and is spreading to some developing countries, whether or not the conditions are appropriate" [31].

A sampling of existing environmental regulations directly affecting the phosphate fertilizer industry in selected countries is given in Tables 5 and 6. These data indicate a great deal of variability in the permitted values and the basis used for calculation.

In addition to legislation regarding discharges to the environment, some countries have established workplace environmental standards. These standards, expressed as threshold limit values (TLVs), are designed to protect people who are exposed to toxic and hazardous substances in the workplace for long periods of time [1,66].

4.2.2 *Industry Compliance With Environmental Regulations*

Environmental legislation most often precedes compliance by several years. Most legislation contains a compliance schedule based on the implementation of best available technology over a period of time. The ultimate level of compliance routinely accomplished is often influenced by the level of inspection and monitoring by the authorities charged with enforcement and by the severity of penalties imposed for noncompliance.

It is beyond the scope of this discussion to examine the current level of compliance in the global phosphate fertilizer sector. However, it is clear that the increased public awareness of industrial pollution and the growing body of health-related scientific evidence that may incriminate certain sectors of the industry will undoubtedly result in an increased level of enforcement of legislation designed to protect the environment and those in the workplace.

4.3 Phosphate Fertilizer Manufacturing Technology

In the following discussion of existing or possible industry practices and environmental considerations, reference is made to the United States Environmental Protection Agency (U.S.-EPA) and the United States phosphate industry. This is because of the availability of considerable information in the public sector and the major role played by the U.S. industry in providing the global supply of phosphate materials. Reference to the U.S.-EPA and the U.S. industry is for illustration purposes only and does not imply their endorsement of the data described by the authors.

4.3.1 *Phosphate Mining, Land Reclamation, and Beneficiation*

As indicated earlier, the phosphate industry is characterized by the movement and processing of large tonnages of overburden, ore, and concentrate. The phosphate concentrate used to prepare the intermediate and finished products is derived from naturally occurring phosphate-bearing ore. Typically, the naturally occurring ore contains 15%-30% P_2O_5 comingled with sand, clay, and other impurities. Current world phosphate reserves amount to the equivalent of about 12 billion (12×10^9)tonnes of marketable concentrate, and the reserve base amounts to more than 30 billion tonnes (Table 3) [14].

The great majority of the world's phosphate ore is obtained using surface mining techniques. These mining operations often require the removal and eventual replacement and reshaping of as much as 5 tonnes of overburden per tonne of ore, or several times that amount of material per tonne of recovered P_2O_5, because not all the P_2O_5 contained in the mined ore is recovered as a marketable phosphate concentrate. Depending upon the characteristics of the ore, as much as one-third of the P_2O_5 can be lost in the process of separating the phosphate from its parent ore consisting of sand, clay, limestone, and other materials. The separation (beneficiation) process may range from a crude dry-screening process to a very sophisticated process that may involve washing, wet screening, magnetic separation, hydraulic separation, centrifugation, flotation, calcination, settling/decantation, and drying.

Prior to about 1925, losses of phosphate in many of the operations, such as those in Florida (U.S.A.), were very high and the quantity of water required per tonne of recovered P_2O_5 for the mining operations was large as compared with that used today. For example, the Florida (U.S.A.) phosphate mining and beneficiation industry as a whole, even as recently as 1970, had a net consumption of about 15 tonnes of water/tonne of marketable concentrate (about 50 tonnes of water/tonne of P_2O_5) compared with only about one-half that amount today [25]. These early operations, circa 1925, were successful in recovering only the large phosphate

Table 5. Sampling of Existing Environmental Regulations Affecting the Phosphate Fertilizer Industry—Indicative Values for Selected Countries[a]

Component	Austria[b]	Belgium	Germany (FR)	Greece	India	Iran[c]	Italy
	(limit)						
Particulate (dust)	75 mg/m^3		50-75 mg/m^3	150 mg/m^3	150 mg/m^3		
NH_3	20 mg/m^3		50-300 mg/m^3[h]				(15 mg/L)
HF	5 mg/m^3		5 mg/m^3				
HCL	30 mg/m^3		30 mg/m^3				
F		(300-600 mg/L)[f]	(1 kg/t P_2O_5)[i]	100 mg/m^3	25 mg/m^3	(2.0-2.5 mg/L)	(6 mg/L)
				(6 mg/L)	(10 mg/L)[n]		
NH_4^+-N[d]		(150 mg/L)	(2 kg/t N)[i]		(50 mg/L)	(0.5-2.5 mg/L)[k]	
NO_3^--N[d]		(225 mg/L)	(2 kg/t N)[i]		(10-20 mg/L)[o]	(1.0-50 mg/L)[k]	(20 mg/L)
NO_x[e]			350 mg/m^3 (ammonia plant primary reformer)				
			450 mg/m^3 (nitric acid plants)			5 kg/t HNO_3[j]	
			500 mg/m^3 (other plants)				
Cd		(2-0.3 mg/L)[g]	(100 mg/t P_2O_5)[i]			(0.01-1.0 mg/L)	
P		(50-300 mg/L)[f]	(0.5 kg/t P_2O_5)[i]	(10 mg/L)	(5 mg/L)	(1.0 mg/L)	(10 mg/L)
SO_2				10 kg/t H_2SO_4[j]	4 kg/t H_2SO_4[j]		
SO_3				0.8 kg/t H_2SO_4[j]		(300 mg/L)[l]	
Sulfuric acid mist					50 mg/m^3[j]		
Chemical oxygen demand		(300-450 mg/L)[f]					
Total suspended solids		(200-600 mg/L)		(40 mg/L)	(100 mg/L)	(30 mg/L)	
pH		(5-9.5)		(6-9)	(6.5-8.0)	(6.5-8.5/5-9 [well])	
Temperature				(35°C)			

(Continued)

Table 5. Sampling of Existing Environmental Regulations Affecting the Phosphate Fertilizer Industry—Indicative Values for Selected Countries[a] (Continued)

Component	Jordan[m]	Mexico	Saudi Arabia	Turkey	Zimbabwe	United States
	(limit)					
Particulate (dust)				200 mg/m^3		(Refer to Table 6 for U.S. regulations)
NH_3	(2.5 mg/L)					
HF						
HCL						
F		(20 mg/L)		10 mg/m^3	(1 mg/L)	
				(15 mg/L)		
NH_4^+-N[d]		(50-150 mg/L)[p]	(5 mg/L)	(50 mg/L)	(10 mg/L)[r]	
NO_3^--N[d]				(50 mg/L)		
NO_x[e]				800 mg/m^3		
Cd	(0.01 mg/L)			(0.5 mg/L)	(0.01 mg/L)	
P		(40 mg/L)	(0.5 mg/L)	(35 mg/L)	(1 mg/L)	
SO_2		3-28 kg/t H_2SO_4[j,q]	380 mg/L			
SO_3				0.4 kg/t H_2SO_4[j]		
Chemical oxygen demand	(100 mg/L)			(200 mg/L)		
Total suspended solids	(30 mg/L)	(30 mg/L)	(15 mg/L)	(100 mg/L)	(25 mg/L)	
pH	(6.5-9)	(6-9)	(6.8-7.2)	(6-9)	(6-9)	
Temperature	(5°C above ambient outfall temperature)		(30°C)	(35°C)		

a. Derived from IFA Environmental Legislation Survey (1989) and other reported data. Values in parentheses ( ) indicate liquid effluents; all others indicate gaseous effluents. Values not shown do not necessarily indicate lack of legislated limit. Gaseous values assumed to be expressed in normal cubic meters (m^3).
b. Values for Austria pertain to new installations.
c. For Iran, lower values refer to wastewater discharged into wells and higher values refer to surface discharge.
d. Allowable limit calculated as N existing in indicated form.
e. NO_x calculated and indicated as concentration of NO_2.
f. Higher value pertains to brackish water applications.
g. Lower value pertains to brackish water applications.
h. NH_3 regulated at discretion of local authorities; values indicate the range of limits.
i. Proposed limit using best available technology.
j. Based on 100% H_2SO_4 or 100% HNO_3.
k. Concentration indicated as NH_4^+ and NO_3^-.
l. Concentration indicated as $SO_4^=$.
m. Jordan currently has no regulations pertaining to emissions to atmosphere.
n. Fluoride value may be as low as 1.5 mg/L depending upon recipient stream of outfall.
o. Higher value (20 mg/L) is applicable to phosphate fertilizer production units.
p. Higher value (150 mg/L) is applicable to urea plants only; values refer to total N equivalent regardless of form.
q. Limits vary depending upon location, age, and capacity of sulfuric acid plant.
r. Total N equivalent regardless of form.

Table 6. Selected Federal Environmental Regulations Pertaining to the Fertilizer Sector in the United States

Substance	Source of Effluent—Production Unit/Operation						
	Sulfuric Acid	Nitric Acid	Wet-Process Phosphoric Acid	Superphosphoric Acid Concentration	Diammonium Phosphate	Triple Superphosphate	Granular Triple Superphosphate Storage Facility
	(limit[a])						
Ammonia (NH_3)	(Ammonia discharged to the atmosphere is not covered by federal regulations; may be regulated by state and local authorities)						
Ammonia (expressed as N)		0.45-4.5 g/t HNO_3[b,c,d] (wastewater)					
Acid mist	0.075 kg/t H_2SO_4[b]						
Fluorides (expressed as F)			10 g/t P_2O_5 25-75 mg/L[c] (wastewater)	5 g/t P_2O_5 25-75 mg/L[c] (wastewater)	30 g/t P_2O_5 25-75 mg/L[c] (wastewater)	100 g/t P_2O_5 25-75 mg/L[c] (wastewater)	0.25 g/h-t P_2O_5[e]
Nitrogen oxides (expressed as NO_2)		1.5 kg/t HNO_3[b]					
Nitrate (expressed as N)		23-170 g/t HNO_3[b,c,d] (wastewater)					
Phosphate (expressed as P)			35-105 mg/L[c] (wastewater)		35-105 mg/L[c] (wastewater)	35-105 mg/L[c] (wastewater)	
Sulfur dioxide (SO_2)	2 kg/t H_2SO_4[b]						
Stack opacity	Less than 10%	Less than 10%					
Total suspended solids			50-150 mg/L[c] (wastewater)		50-150 mg/L[c] (wastewater)	50-150 mg/L[c] (wastewater)	
pH			6.0-9.0 (wastewater)				

(Continued)

Table 6. Selected Federal Environmental Regulations Pertaining to the Fertilizer Sector in the United States (Continued)

Substance	Source of Effluent—Production Unit/Operation		
	Phosphate Rock Calciner	Phosphate Rock Grinder	Phosphate Rock Dryer
	(limit[a])		
Ammonia (NH_3)			
Ammonia (expressed as N)			
Acid mist			
Nitrogen oxides (expressed as NO_2)			
Nitrate (expressed as N)			
Particulate (dust)	120 g/t rock[f] 55 g/t rock	6 g/t rock	30 g/t rock
Sulfur dioxide (SO_2)			
Stack opacity	Less than 10%	0%	Less than 10%

a. Indicated limits for phosphate operations refer to phosphate rock or P_2O_5 equivalent fed to process. Except for wastewater as noted, all values refer to discharges to the atmosphere. Additional state and local regulations may also apply.
b. Based on acid produced; 100% H_2SO_4 or HNO_3. Atmospheric discharge values refer to a maximum 2-h average.
c. Lower value is average of daily values for 30 consecutive days; higher value is maximum for any one day. Limit for total suspended solids is waived if water is treated to remove phosphates and fluorides.
d. Standard for new facility based on gaseous ammonia raw material.
e. Based on tonnes P_2O_5 equivalent in storage facility.
f. Refers to calcination of unbeneficiated rock or blends of beneficiated and unbeneficiated rock. Lower value (55 g/t) pertains to calcination of beneficiated rock.

Source: United States Code of Federal Regulations July 1, 1989 and July 1, 1990.

agglomerates (pebble); the smaller phosphate particles were lost with the washwater, which was normally discharged to streams and rivers [47]. Economic pressures on the phosphate industry during the first two decades of the 1900s brought about labor-saving innovations in mining and beneficiation. By 1925, P_2O_5 recovery improved, but still more than 50% was lost. Improved recovery was accomplished through the adoption of better screening methods and the use of hydraulic classifiers (cyclones) designed to separate small phosphate particles that were previously lost with the washwater. These improvements coupled with the introduction of flotation technology in 1927 greatly increased the level of P_2O_5 recovery to about 70% of that contained in the ore. By 1940, beneficiation technology as practiced worldwide today, including flotation, was in general use among the Florida producers.

The disposal of phosphatic clay waste is the most troublesome problem faced in most beneficiation processes. Even after years of settling, these very fine particles seldom consolidate to more than 20% solids [29]. Besides the large land area required for settling and storage of this material, careful management of the containment site is essential to prevent an accidental spill of contaminated water which normally covers the settled clay waste to a depth of several meters. This water is used to transport the clay waste from the beneficiation unit to the disposal site; therefore, it is contained and continuously recirculated for this purpose.

All phosphate ore contains traces of uranium and its radioactive decay products (Table 7) and a number of metals which are being studied in relation to the health of humans and other animals (Table 8) [5,64].

Studies of the ultimate fate of radioactive decay products and potentially harmful metals in the processing of phosphate ore to finished fertilizer products are yielding some interesting observations. For example, the concentration of radionuclides is reportedly higher in the small particle size fraction (minus 30 μm) of phosphogypsum [21], whereas in the beneficiation of central Florida phosphate ore, which is naturally low in cadmium, about one-third of the cadmium is removed with the phosphatic clay that is discharged to a disposal site [64]. The fate of certain metals and radioactive decay products, including their entry into the food chain through the soil and plant tissue, continues to receive considerable study [2,16,26,49].

These metallic constituents, most notably cadmium, have received a great deal of attention in recent years, especially regarding international trade of phosphate concentrate containing elevated levels of cadmium. Techniques for removing cadmium from phosphate concentrate, for example, high-temperature calcination, have been evaluated and used to a limited commercial extent with generally unsuccessful and costly results. Removal of cadmium and other metals from phosphoric acid to achieve tolerable levels seems to offer more promise. Such removal techniques, though currently not widely practiced commercially in the fertilizer industry, involve ion-exchange or solvent extraction methods [5,15]. Removal of cadmium from phosphoric acid using coprecipitation techniques is also being studied.

4.3.1.1 Environmental Factors Related to Phosphate Mining, Land Reclamation, and Beneficiation—Phosphate mining and beneficiation operations, depending upon a number of site-specific factors, may affect the environment to varying degrees in one or more of the following ways:

- Topography changes including the loss of aesthetic value, soil fertility, and soil moisture-holding capacity.
- Loss of natural plant and wildlife habitat.
- Loss of recreational, historical, and archaeological values.
- Disturbance of shallow aquifers.
- Contamination of surface and groundwater resources caused by the intrusion of contaminated water from mine sites and phosphatic clay and sand tailings disposal sites.
- Temporary depletion of groundwater resources due to extraction of water used for processing.

Table 7. Approximate Radioactivity of Selected Phosphate Materials and Background Soil

Material	Radioactive Element	
	U-238	Ra-226
	------(pCi/g)------	
Phosphate concentrate[a]		
Sedimentary origin	40	38
Igneous origin	2	1-2
Phosphogypsum[b]		
Central Florida	3	31
Background soil	0.3	0.5

a. Source: Economic Commission for Europe and FADINAP/ESCAP [22].
b. Source: Berish, Proceedings of the Third International Symposium on Phosphogypsum [18].

- Erosion caused by wind and water.
- Concentration and/or escape of radionuclides that may be harmful to human health.
- Atmospheric contamination due to exhaust fumes and noise from mining/reclamation equipment.

Fortunately, for the most part, the level of environmental degradation caused by these factors is minimized, and in some cases eliminated, through responsible and innovative technical management of the mining, reclamation, and beneficiation operations. In some cases, mined-out sites have been restored to an aesthetic and economic level far exceeding that of the original site. It is also important to note that some unreclaimed mine sites offer very favorable habitat for wildlife and natural vegetation that would otherwise be lost if the areas were reclaimed for agricultural or commercial development.

In some locations it is possible to integrate mine-site reclamation with the disposal of large quantities of phosphatic clay, sand tailings, and phosphogypsum discharged from the ore beneficiation and phosphoric acid units.

Reported costs for reclamation of mined-out land as practiced in Florida (U.S.A.) range from about US $5,000/ha to US $25,000/ha depending upon the site, desired end use, and the method used to manage the surface water. In the example cited for Florida, about 15,000 tonnes of marketable concentrate (about 4,600 tonnes P_2O_5) is extracted per hectare. Thus, the cost of reclamation per tonne of P_2O_5 is in the range of about US $1-$5.

Because mining and beneficiation will continue to be essential for the preparation of phosphate fertilizers regardless of the product type, it is expected that the adoption of environmentally sound mining and land reclamation procedures will continue to be expanded on a global basis. A discussion of the environmental aspects of the Jordanian phosphate industry by Taqieddin [57] is indicative of this trend. Also, it is expected that more sophisticated operational procedures in all aspects of mining and beneficiation will be implemented as the higher grade phosphate ores become depleted and thus necessitate the processing of lower grade material.

Table 8. Summary of Potentially Hazardous Elements in Selected Phosphate Concentrates

	Element[a]						
Phosphate Concentrate	As	Cd	Cr	Hg	Pb	Se	V
	(ppm)	(ppm)	(ppm)	(ppb)	(ppm)	(ppm)	(ppm)
Sedimentary Origin							
Israel (Arad)	4-7	12-17	-	-	-	-	-
	(5.5)	(14)	(130)	(480)	(2)	(3)	(203)
Jordan (El Hassa)	5-12	3-12	50-127	-	-	-	60-81
	(8)	(5)	(92)	-	(2)	(3)	(70)
Morocco (Khouribga)	10-25	3-27	188-212	-	2-29	-	-
	(13)	(15)	(200)	(1,000)	(10)	(4)	(106)
Morocco (Youssoufia)	-	4-19	-	-	21-22	-	-
	(10)	(15)	-	-	(21.7)	-	-
Senegal (Taiba)	4-28	60-115	-	-	2-10	-	237-810
	(17)	(87)	(140)	-	(6)	(5)	(524)
Togo	8-14	48-67	-	-	8-9	-	-
	(10)	(58)	(101)	(600)	(8.3)	(5)	(60)
Tunisia	4-5	30-50	-	-	-	-	-
	(4.5)	(40)	(144)	-	(4)	(9)	(27)
United States (Central Florida)	4-25	3-20	37-100	25-200	9-55	2.6-3	70-160
	(11)	(9)	(60)	(171)	(17)	(2.8)	(108)
United States (North Florida)	-	3-10	62-68	-	10-13	-	98-109
	(7)	(6)	(65)	-	(12)	-	(102)
United States (North Carolina)	7-13	20-51	129-197	85-400	3-20	-	19-32
	(11)	(38)	(158)	(261)	(8)	(5)	(26)
United States (Western Deposits)	14-40	40-150	330-1,000	-	5-16	4-13	300-1,737
	(24)	(92)	(637)	(500)	(12)	(9)	(769)
Igneous Origin							
Republic of South Africa	5-27	1-1.6	-	-	-	-	-
(Phalaborwa)	(13)	(1.3)	(1)	-	(11)	(4)	(8)
Former Soviet Union (Kola)	-	0.3-2	-	-	-	-	-
	(10)	(1.2)	-	(33)	-	-	-

a. Values in parentheses ( ) indicate average concentration of element based on indicated range. A dash (-) indicates lack of sufficient data.

Source: Derived from Baechle and Wolstein [5], Tennessee Valley Authority [64], IFDC data file, and other reported data.

The production of phosphate fertilizers that are less water-soluble may benefit the mining and beneficiation operations in two ways. First, less beneficiation may be required, resulting in lower losses of P_2O_5. In some cases it may even be possible to produce phosphoric acid by the direct acidulation of the ore and avoid beneficiation entirely [9]. Second, the use of lower grade phosphate ore containing a higher level of impurities, such as magnesium, iron, and aluminum, will have the net result of increasing the level of phosphate reserves and increasing the economic life of existing production facilities.

4.3.2 *Wet-Process Phosphoric Acid*

Phosphoric acid is the major intermediate used to produce phosphate fertilizer. As previously stated, approximately 70% of all fertilizer P_2O_5 is derived directly from wet-process phosphoric acid. Most of the balance is derived from phosphate concentrate that is usually treated with phosphoric or other acids (sulfuric or nitric acid) to increase its solubility. Additionally, small amounts of fertilizer-grade phosphates are derived from direct application phosphate rock, basic slag, thermophosphates, guano, bonemeal, and other minor sources.

Except for a small amount of phosphoric acid prepared from elemental phosphorus (furnace-grade acid) that may be used to prepare speciality fertilizers used in irrigation and greenhouse culture, all fertilizer-grade phosphoric acid, including about 2.2 million tonnes P_2O_5 in the form of superphosphoric acid containing about 70% P_2O_5, is produced using a variety of wet processes in which the phosphate concentrate is digested in a dilute mixture of recycled phosphoric acid and fresh sulfuric acid. The amount of sulfuric acid required to produce 1 tonne of P_2O_5 in the form of wet-process phosphoric acid is most heavily influenced by the specific characteristics of the phosphate concentrate. Sulfuric acid consumption values (100% H_2SO_4 basis) typically vary from a low of about 2.5 tonnes acid/tonne P_2O_5 for high-purity phosphate concentrates such as those found in Russia (Kola), Finland, Togo, and Brazil to about 3.1 tonnes acid/tonne P_2O_5 for less pure concentrates. Values in the range of 2.6-2.9 tonnes acid/tonne P_2O_5 are typical for most major phosphoric acid producers.

The digestion process results in a slurry of phosphoric acid and solid calcium sulfate. The insoluble calcium sulfate, formed from the reaction of calcium contained in the concentrate and sulfuric acid, is separated from the phosphoric acid solution by filtration. The concentration of the phosphoric acid as it exits the filter (filter-grade acid) varies from about 27%-30% P_2O_5 to about 40%-50% P_2O_5, depending upon the specific process. The acid may then be further concentrated and clarified, depending upon its final use. Likewise, the calcium sulfate produced in the digestion step may be in the hemihydrate ($CaSO_4 \cdot 1/2H_2O$) or dihydrate ($CaSO_4 \cdot 2H_2O$) form, depending upon the specific process. In some of the hemihydrate processes, the calcium sulfate is recrystallized to the larger and easier to filter dihydrate (gypsum) form before filtration; in others, the calcium is removed in the hemihydrate form. The major wet-process phosphoric acid process routes are well described in the literature [7,53,54].

In most cases, calcium sulfate (phosphogypsum) discharged from the filter is slurried to a concentration of about 20% with recirculated process water and pumped to a disposal site. In some cases, the gypsum is purified or otherwise processed for use in the manufacture of construction materials or other industrial products including sulfuric acid, aggregate, and cement.

In addition to industrial uses, a relatively small amount of phosphogypsum is used as a source of agronomic calcium and sulfur (land plaster). Phosphogypsum is especially useful as a soil amendment for soils containing high levels of exchangeable sodium. Thus, phosphogypsum can often become an integral component in the reclamation of soils containing elevated levels of exchangeable sodium.

About 15% of the world production of wet-process phosphoric acid is traded in the form of merchant-grade material having a P_2O_5 content of 52%-54% and an undissolved solids content of less than 1%. The balance is used at the various production sites for the production of phosphate fertilizers, such as DAP, MAP, TSP, and compound NPKs. Also, as already mentioned, some acid is used to produce nonfertilizer products such as animal feed supplements. The average P_2O_5 content of acid used for the production of fertilizers at the basic production sites is usually in the range of about 40%-45%. Also, the undissolved solids content in this acid may be well above 1% depending upon the product produced.

4.3.2.1 Environmental Factors Related to Wet-Process Phosphoric Acid Production—As already indicated, each tonne of P_2O_5 produced as wet-process phosphoric acid results in the production of about 5 tonnes (dry basis) of phosphogypsum and often about twice that amount of process water that must be dealt with. Additionally, large quantities of sulfuric acid are required. A discussion of the environmental aspects of wet-process phosphoric acid follows.

4.3.2.1.1 *Sulfuric Acid Production*—Worldwide, about 1,000 producers manufacture about 160 million tonnes of sulfuric acid (100% basis) annually [10]. About 60% (nearly 100 million tpy) of this acid is used for the manufacture of fertilizers. The manufacture of wet-process phosphoric acid, alone, accounts for the great majority (about 82%) of the sulfuric acid consumed in the fertilizer industry; the remainder is used mostly for the production of ammonium sulfate. The sulfuric acid plants found in the phosphoric acid industry are usually large compared with those found elsewhere, and capacities in excess of 2,000 tpd are not uncommon.

Modern sulfuric acid plants, based on two-stage absorption of sulfur trioxide (SO_3), the double absorption process, and multiple passes of the process gas through the catalytic converter system, routinely obtain conversion/recovery efficiencies equivalent to 99.5%-99.8% of the sulfur fed to the process. A conversion efficiency of 99.8% exceeds an SO_2 emission level equivalent to about 2 kg SO_2/tonne H_2SO_4.

The level of acid mist (aerosol) discharged to the atmosphere has also been greatly decreased in the industry through the use of unique absorber design and operating procedures that minimize the formation of acid mist and effectively collect mist that happens to be formed.

Older single-absorption sulfuric acid plants that fail to meet established emission criteria may be fitted with scrubbers designed to collect residual sulfur oxides and acid mist from the exhaust gas (tailgas). These water-type scrubbers may use lime, ammonia, or other caustic additives to collect the acidic emissions from the absorber. Tailgas scrubbers are well suited for applications where the need for sulfur recovery in the form of sulfuric acid is less important than is the need for complying with ambient emission standards. For example, some of the older plants operating with conversion efficiencies in the order of 95%-97% emit 6-10 times the amount of sulfur oxides emitted by the more efficient modern plants; thus they often are good candidates for the relatively inexpensive retrofitting of tailgas scrubbers provided the scrubber effluent liquor can be utilized, for example, to produce ammonium sulfate, or discarded in an environmentally acceptable manner.

The sulfuric acid production process also produces large amounts of heat. This heat is sufficient to produce nearly 2 tonnes steam/tonne H_2SO_4. However, in most sulfuric acid plants installed prior to the mid-1980s, only about 50%-55% of this heat is recovered [61]. The energy is recovered in the form of steam which is used to produce electricity, power steam turbine-driven process equipment, and provide heat for concentration of phosphoric acid. Recovery of process heat is very favorable from an environmental viewpoint because it indirectly decreases the amount of pollution that would otherwise be caused by burning fossil fuel to produce the equivalent amount of steam and electric power required by the phosphoric acid and phosphate fertilizer complex.

Advances in energy recovery systems for sulfuric acid plants during the past decade have resulted in an increased production of steam (up to 1.8 tonnes/tonne H_2SO_4) to yield an overall recovery of heat, in the form of steam, in the order of 95% [55].

In summary, modern sulfuric acid plants operated within a phosphate fertilizer complex can have a very favorable impact upon the environment in that they are capable of providing more than enough heat and electrical energy needed for the fertilizer complex, thus eliminating the need for imported energy produced by burning fossil fuels that have an unfavorable impact upon the environment. For example, a modern well-operated sulfur-burning sulfuric acid plant with a capacity of 2,250 tpd acid has the potential to produce about 34 megawatts of electric power, of which about 32 megawatts would be available for export outside the sulfuric acid production area [43]. The number of such plants and plant modifications is expected to grow provided the economics for exporting excess electric power are favorable.

4.3.2.1.2 *Phosphogypsum*—In some cases, the phosphogypsum is slurried with seawater and discharged to the sea beyond the low-tide beach. In other cases, it is discharged into rivers or integrated with mine reclamation projects where it is buried in mined-out areas. In very limited cases, the gypsum is processed into ammonium sulfate and calcium carbonate for use as a fertilizer and cement additive, respectively.

The technology for conversion of phosphogypsum to sulfuric acid, aggregate, and other useful products has been relatively well developed, but commercial adoption is constrained primarily for economic reasons. The integration of wet-process phosphoric acid production with coal-fired electric power production has been conceptualized and could result in the almost total utilization of phosphogypsum in the form of recovered sulfur dioxide for the production of sulfuric acid and lime for the production of cement [19]. Such integration may be the key to improving the economics of phosphogypsum utilization; however, the opportunities for economic integration are often quite limited because they depend heavily upon the availability of raw material resources on the one hand and

the economic pricing of coproducts, such as electricity and cement, on the other. Several methods for using phosphogypsum, although perhaps currently not economical, are well documented in the literature [17,41]. It should be noted, however, that the economics of phosphogypsum utilization will undoubtedly improve as the costs of alternative phosphogypsum disposal techniques increase.

For the most part, however, with the exception of a few locations, the phosphogypsum is stacked aboveground at disposal sites located near the phosphoric acid production units. Currently, it is estimated that by the year 2000 over 1 billion tonnes of phosphogypsum will be stored in stacks in the State of Florida (U.S.A.) alone. The central Florida stacks now exceed 600 million tonnes, not including the north Florida stacks, and are currently growing at an annual rate of about 30 million tonnes; the total annual production of phosphogypsum worldwide amounts to about 150 million tonnes. The design and operating criteria for phosphogypsum stacks are described by Baretincic in The Fertilizer Institute's (TFI) comments to the U.S.-EPA [59].

The closing or decommissioning of existing phosphogypsum stacks brings about another set of concerns, particularly because most of the existing stacks were not designed to accommodate closure requirements currently under consideration. According to options being considered by U.S.-EPA and local regulators, idle or inactive stacks that exhibit certain characteristics, for example, radon emanation levels above a certain threshold value, would have to be dewatered, reshaped, and covered with an impervious (plastic) membrane and a soil cap to support vegetation. Even if infiltration of fresh stormwater is eliminated by capping the stack, drainage from the stack may continue for many years. This drainage must be collected and properly dealt with. The cost for closing the approximately 30 active and 34 inactive stacks in the U.S. industry is estimated at about US $1.3 billion or an average of about US $20 million/stack [3]. This cost does not include the cost for long-term environmental monitoring and maintenance.

One such stack closure completed in mid-1991 in central Florida was described by Kleinschmidt at a recent symposium on phosphogypsum [18]. This particular stack had an original base area of about 140 ha and a height of about 70 m; the cost of closure was reportedly about US $5.5 million. Extrapolation of this cost to the above 64 stacks results in a total industry cost of about US $0.35 billion, much less than the US $1.3 billion indicated by Ardaman [3]. In still another case, the closure of a similar stack was recently estimated at US $18 million. The large variation in estimated and actual costs may be due to a number of unspecified site-specific technical features and regulatory criteria.

Replacement of the active phosphogypsum storage facilities according to a regulatory scenario examined by the U.S.-EPA is estimated to cost about US $2 billion [3]. This would amount to an average of about US $95 million per production site assuming such stacks would be constructed at the 21 sites examined. One such stack site currently under construction in central Florida is reported to cost in the order of US $50 million. This particular stack and process water storage/cooling pond site is about 160 ha in size and completely lined with an impervious synthetic membrane. Assuming the US $50 million estimate as a base and an estimated active life of 10 years, the capital cost alone, not including operation, per tonne of P_2O_5 manufactured over a 10-year period would amount to about US $6.4 at a 14% annual interest rate and an annual production of phosphoric acid P_2O_5 of 1.5 million tonnes.

4.3.2.1.3 *Recirculated Process Water*—A more troublesome issue than the phosphogypsum is the recirculated process water that is used to slurry the phosphogypsum and transport it to the disposal site. This recirculated process water is also used to remove heat and gaseous and particulate emissions from the wet-process phosphoric acid concentration unit and the finished product processing units. The acidic process water, referred to as "process wastewater" by the U.S.-EPA, dissolves and holds in solution a number of metallic elements originally contained in the phosphate rock. Also, slippage of phosphoric acid to the phosphogypsum during filtration, and the collection of particulate from other processing units, adds to the water small quantities of solubilized metallic ions in addition to phosphates, sulfates, and fluorides. Furthermore, because the process water is recirculated on a closed-loop in an effort to obtain a zero-discharge mode of operation, the concentration of these dissolved species increases quite markedly with time.

Estimates by the U.S.-EPA indicate that in 1988 the U.S. phosphoric acid industry managed about 1.8 billion tonnes of contaminated process water. This is equivalent to an average of 84 million tpy for each of the 21 production facilities or about 130 tonnes/tonne of P_2O_5 produced, assuming a total annual production of 14 million tonnes of P_2O_5 in all forms including about 10 million tonnes in the form of wet-process phosphoric acid [21]. According to U.S.-EPA, the amount of contaminated process water managed among the

facilities varied widely from about 13 million tpy to 280 million tpy. Most of this process water is reused in the process loop; fresh makeup water, including rainwater, may amount to only about 7-10 tonnes/tonne P_2O_5 produced. The ultimate fate of the managed process water, thus requiring the 7-10 tonnes/ tonne P_2O_5 fresh makeup, includes evaporation, water of hydration required to form gypsum, entrained water in the phosphogypsum stack, seepage into the ground, and, in some cases, permitted discharge to surface waterways after appropriate treatment. An example of the typical composition of the recirculated process water for a selected number of phosphoric acid producers is given in Table 9. Because the overall process water balance is heavily influenced by rainfall, it may be necessary to intentionally discharge water from the containment site from time to time. In the United States, such discharges must be treated to comply with federal and state discharge permit criteria.

Treatment and containment of this contaminated process water are currently the subjects of major concern among both the regulatory agencies and the producers. Proposals put forth by some regulators include the use of impervious liners for the gypsum stacks and process water cooling ponds and the continuous treatment of the recirculated process water with lime to elevate the pH to at least 3.5 to promote the precipitation of unwanted dissolved fluorides.

Although treatment of the recirculated process water may be technically feasible, total containment without an intentional discharge is not technically possible in some locations because of gypsum stack design constraints and unfavorable rainfall and evaporation balances.

Although treatment of recirculated process water is currently not practiced in the industry, the costs associated with such treatment of process water to comply with a regulatory scenario examined by the U.S.-EPA were estimated by an engineering firm on behalf of TFI and are given as an example (Table 10) [36]. Besides the capital and operational costs directly related to treatment (equipment and lime), it is important to note, though speculative because of a lack of actual experience, that the loss of precipitated P_2O_5, which may amount to about 4% of the total processed P_2O_5, could have a major influence on the net P_2O_5 recovery for the facility. Also, because of the loss of acidity, additional sulfuric acid must be fed to the digestion process to replace the acidic process water.

Furthermore, because the recirculated process water is an integral part of the phosphogypsum transport and management system, studies indicate that its treatment would adversely influence the stacking and drainage properties of the phosphogypsum. Laboratory tests indicate that the presence of precipitated compounds from the process water, including silica gel, increases not only the settled volume of the phosphogypsum but also its moisture retention properties, thus making dewatering (draining) more difficult and adversely influencing its stacking properties [4].

The ultimate disposal of the precipitated solids from the process water presents still another technical/cost concern. Laboratory, as well as limited commercial, experience indicates that the insoluble compounds resulting from liming of the recirculated process water to pH 3.5 consolidate to only about 15% solids after 5 years, making soil/vegetation capping (reclamation) of such settling ponds impractical [4].

Additionally, it is important to determine what, if any, collateral impact the proposed process water containment and treatment schemes may have on the performance of the process and final product cost, as well as on the environment. The cost of P_2O_5 production is likely to be increased by process inefficiencies and increased downtime due to blinding of the filter media and scaling of process equipment. It is also necessary to consider the costs associated with transport and handling of lime and to recognize that the increased production of lime will have other effects related to quarry operations, lime kiln emissions, and the consumption of energy.

In summary, the wet-process phosphoric acid industry may affect the environment in several ways. The degree of potential impact is very process- and site-

Table 9. Typical Composition of Recirculated Process Water (Cooling Pondwater)—Wet-Process Phosphoric Acid Production

Component	Weight
	(%)
P_2O_5	2.05
F	0.82
$SO_4^=$	0.53
CaO	0.27
Na_2O	0.23
MgO	0.10
Fe_2O_3	0.09
Al_2O_3	0.09
N	0.06
K_2O	0.04
pH	Less than 3.5

Source: Jacobs Engineering Group Inc. [36].

specific as are the definitions and criteria used by the regulators and general public in assessing the level of impact. The reader is therefore cautioned not to generalize. The main possibilities include the following:

- Disturbance of land used for phosphogypsum and contaminated process water storage.
- Contamination of water resources caused by the disposal of phosphogypsum and its associated process water, including acidity, dissolved metals, and radionuclides.
- Fluoride emissions to the atmosphere from the phosphoric acid process.
- Escape of radionuclides that may be harmful to human health.
- Airborne solid and liquid particulates including those caused by wind erosion of phosphogypsum stacks.
- Release of contaminated cooling water, plant site storm water drainage, and boiler blowdown residue.
- Sulfur dioxide and acid mist emissions from the sulfuric acid production units.
- Release of metals and other residues from the regeneration or disposal of spent catalyst from sulfuric acid production units.
- Release of solvents, oils, and other contaminants from plant maintenance and workshop activities.

As with phosphate mining, the potential impact of phosphoric acid processing can be minimized through skilled technical management of the production facilities. However, new investments may be required to more completely control the long-term fate of some process wastes.

4.3.3 *Finished Phosphate Fertilizer Products*

Except for relatively small quantities of basic slag, thermophosphate-type products, and miscellaneous organic fertilizer products, the current family of finished phosphate fertilizers can be grouped into the following basic categories:

Direct application phosphate rock.
Superphosphates.
Ammonium phosphates.
Nitrophosphates.

A brief discussion of each of the basic product types, including their technical advantages and constraints, follows.

4.3.3.1 Direct Application Phosphate Rock Technology—The production of direct application phosphate rock (concentrate), of course, uses the simplest and least-cost process technology. It is also the basic building block for other more complex production technologies. For the purposes of this discussion, a beneficiated phosphate rock concentrate containing 30% P_2O_5 is assumed. However, beneficiation is not always needed, and thus the P_2O_5 content of such products can vary widely.

As indicated earlier, the agronomic performance of phosphate rock is heavily dependent upon the characteristics of the phosphate rock, soil, crop, and climatic conditions. In general, phosphate rock will perform

Table 10. Estimated Cost of Liming Recirculated Process Water to pH 3.5 in Typical U.S. Phosphoric Acid Facility

Cost Component	Estimated Cost Increase Per Tonne of P_2O_5 Produced as Wet-Process Phosphoric Acid (US \$/t P_2O_5)
Raw material (lime, CaO)	22.6
P_2O_5 lost due to precipitation from recirculated process water	5.3
Additional sulfuric acid required to neutralize excess calcium and replace acidic process water normally fed to digester	9.3
Lost production because of lower filtration rates due to presence of silica gel	24.8
Lost production due to scaling of process equipment	8.1
TOTAL	70.1

Source: Jacobs Engineering Group Inc. [36].

best in acidic soils low in available phosphorus and calcium and also low in reactive iron and aluminum; its performance is further enhanced if the soil is warm and moist and if the crop growing season is long.

Perhaps more important than the absolute P_2O_5 content is the observed effectiveness of the phosphate rock (concentrate) as a fertilizer. This effectiveness is, in part, dependent upon the origin of the rock and its inherent ability to dissolve in the soil and become available to the crop. This characteristic of the rock, generally referred to as its "reactivity," is measured by a number of laboratory test methods; one commonly used method to indicate a rock's reactivity is based on the amount of P_2O_5 that can be extracted from a sample using a neutral ammonium citrate (NAC) solution [63]. Caution should be taken when interpreting laboratory reactivity data because the results of the tests can vary widely depending upon the extractant used and the test procedure [34,37,62]. Another criterion, referred to as bioavailability, subjects the fertilizer to a greenhouse pot test to determine its performance. This test method is widely used to correlate chemical test methods with crop response, but the results must be treated with some caution. This is because plant responses under the carefully controlled conditions in the greenhouse, especially water regimes, may differ considerably from those in the field.

The reactivity of a phosphate rock is determined not only by its geological origin and mineral characteristics, but also by its particle size, which may be altered by grinding. Most phosphate rock materials used for direct application need to be quite finely ground, typically 90% minus 150 μm. The cost of this grinding operation, of course, has a major influence on the production cost of direct application phosphate rock. Typical data on the composition, reactivity, surface area, and grindability of selected phosphate rock materials are shown in Table 11. If the phosphate concentrate is sufficiently reactive and does not have to be finely ground, as is likely with such highly reactive phosphate rock concentrates as Sechura (Peru), North Carolina (U.S.A.), and Gafsa (Tunisia), a significant cost advantage is realized.

Advantages and Constraints—Despite the apparent major advantages of low capital investment and production costs, the use of direct application phosphate rock technology is limited by (1) the lack of widespread availability of reactive phosphate rock materials that give the appropriate agronomic performance; (2) the difficulty of handling finely ground material and the possible worker health concerns related to handling dusty material; (3) limited versatility of use, especially because not all soils are acidic; and (4) increased cost of P_2O_5 delivery to the farm gate because the rock has a lower nutrient content than do the more concentrated processed phosphates such as TSP or DAP. Consequently, as previously indicated (Figure 4), only about 3.5% of world P_2O_5 consumption is in the form of direct application phosphate rock.

From an environmental viewpoint, direct application phosphate rock is quite benign. Except for the impact of mining, the direct application products may require less beneficiation and thus generate less waste in the form of contaminated water, phosphatic clay, or atmospheric discharges as a result of calcination to remove unwanted carbonates or organic material. However, because of the small particle size caused by grinding, the rock is more difficult to handle, and special precautions must be taken to avoid the impact of airborne dust when it is transported, handled, and applied. Also, because the rock is not chemically or thermally treated, the level of cadmium and other unwanted constituents per tonne of applied P_2O_5 may be higher than that found in the processed phosphates.

4.3.3.2 Superphosphate-Type Product Technology—The superphosphate family of phosphate fertilizers includes two major products—SSP and TSP. With SSP, sulfuric acid is reacted with phosphate concentrate to produce a product usually containing 16%-20% plant-available P_2O_5 and about 10% sulfur. With TSP, phosphoric acid is used instead, and the product usually contains 46% available P_2O_5 and only a trace of sulfur. These basic products/processes can be altered to produce enriched superphosphate—basically a mixture of SSP and TSP—and some partially acidulated phosphate rock (PAPR) products in which the level of soluble P_2O_5 depends upon the characteristics of the phosphate rock and the amount of acid used [34].

Advantages and Constraints—The factory-gate cost of granular SSP and PAPR, on a nutrient basis, is often quite favorable when compared with that of granular TSP. However, the cost of delivering an equivalent amount of P_2O_5 to the farm gate in the form of the lower analysis SSP and PAPR products usually makes the more concentrated TSP product the most favorable choice, especially in the case of imports and when the delivery distance to the farmer is long. One possible disadvantage of TSP, in addition to its partial (approximately 70%) dependence upon phosphoric acid, is that the production complex, including the sulfuric acid and phosphoric acid plants, is quite costly and can remain economical only if operated at a relatively high capacity utilization. In contrast, the less costly SSP and PAPR units are affected less by a decline in capacity utilization. Another important potential disadvantage of TSP

is its lack of agronomic sulfur content despite the relatively heavy dependence upon sulfur in producing the phosphoric acid used in TSP production. This disadvantage is likely to prove more important in the future as atmospheric sulfur from industrial emissions continues to decline because of the increased adoption of "clean air" technologies.

The SSP and PAPR technologies have another significant advantage over TSP; their simplicity and lower investment requirements make them better suited for smaller scale operations that may often use locally available phosphate resources to supplement or replace more costly imported phosphate raw materials or intermediates such as phosphate concentrate or wet-process phosphoric acid.

With specific reference to environmental impact, the entire family of superphosphate products has less adverse impact at the production site than do the ammonium phosphate products. This is because a smaller amount of phosphoric acid is consumed per tonne of marketable P_2O_5. In the case of SSP and some PAPR products, no phosphogypsum and very little contaminated process water are produced. The recovery of fluorides further enhances the environmental integrity of these processes, whether the fluoride-based acid is recycled to the process as an acid source or is converted into a marketable byproduct. In some instances, however, the increased level of fluorine in these products has led to concern about increased levels of fluorides in groundwater in areas where the soil is sandy and the use of SSP is high.

4.3.3.3 Ammonium Phosphate Product Technology—DAP (18-46-0) is the most common ammonium phosphate product. However, the production of MAP with a typical analysis of about 11-52-0 is gaining in importance in those locations where ammonia is lacking or where, for transport cost reasons, it is important to maximize the level of P_2O_5 in the product. Also some production of MAP may be desirable in a DAP complex to utilize "phosphatic sludge" removed from phosphoric acid that is fed to the DAP production unit. In some cases MAP may be preferred over DAP when applied with, or close to, the seed because damage to the seed by ammonia is less likely. Another significant ammonium phosphate-based product, especially in parts of Asia, is 16-20-0. This product is basically a mixture of ammonium phosphate and ammonium sulfate. Unlike DAP or MAP, this product typically contains 8%-12% sulfur. All three of these products can be produced in the basic DAP-type plant provided precautions are taken to cope with the higher level of equipment corrosion normally encountered with the 16-20-0 product.

Advantages and Constraints—As a source of phosphate, the DAP and MAP products rank very favorably with regard to delivered cost and agronomic effectiveness when compared with other phosphate product alternatives. Additionally, these products usually exhibit very good physical properties even when mixed with other materials, and they usually store well. The

Table 11. Chemical and Physical Properties of Selected Phosphate Rock Concentrates

	Chemical Composition									Surface	
	P_2O_5	F	CaO	CO_2	MgO	Fe_2O_3	Al_2O_3	SiO_2	Na_2O	Area[a]	Grindability[b]
	(% by weight)									(m^2/g)	(kWh/t)
Khouribga (Morocco)	33.0	3.8	52.3	4.2	0.27	0.25	0.46	2.1	0.65	19.6	16.2
Nauru Island	38.4	3.5	52.8	2.6	0.49	0.19	0.23	0.14	0.13	12.9	9.8
Taiba (Senegal)	37.0	3.8	49.6	2.0	0.03	0.92	0.90	4.7	0.04	8.1	9.2
Central Florida (U.S.A.)	31.5	3.9	47.8	3.7	0.4	1.3	1.2	6.9	0.61	12.4	14.4
North Carolina[c] (U.S.A.)	30.1	3.6	49.0	6.0	0.58	0.56	0.37	4.3	0.93	20.9	18.9
El Hassa (Jordan)	33.5	3.9	53.7	5.4	0.20	0.20	0.15	2.4	0.46	16.8	12.8

a. BET nitrogen adsorption method.
b. Derived from Bond ball mill work index.
c. Uncalcined concentrate.

Source: McClellan, et al. [44].

most significant disadvantages of the ammonium phosphate products are similar to those cited for TSP, for example, (1) a large capital investment is needed, (2) they are heavily dependent upon sulfur (about 1 tonne of S/tonne of P_2O_5), (3) a relatively rigid specification for phosphate rock is required for economic production of phosphoric acid, and (4) costly sulfur is lost in the form of phosphogypsum. Furthermore, because these products depend entirely upon wet-process phosphoric acid as the source of P_2O_5, about 2.5 tonnes of phosphogypsum is produced for each tonne of DAP, or the equivalent of about 5 tonnes/tonne of P_2O_5. Additionally, the ammonium phosphate process requires ammonia, which must either be produced locally or imported.

Modern fully integrated ammonium phosphate plants producing sulfuric acid and phosphoric acid are energy efficient; except for the heat discharged from the phosphoric acid evaporation units, a relatively small amount of waste heat is discharged into the environment resulting in optimum production costs. It is important to note that heat discharged to the recirculated process water pond facilitates evaporation to help minimize or completely eliminate the need for treatment and discharge of process water from the closed-loop system. Additionally, small amounts of ammonia, fluorides, and solid particulate are discharged to the atmosphere. However, these pollutants are quite easy to control and their impact on the environment is generally minimal in a well-managed production facility.

4.3.3.4 Nitrophosphate-Based Product Technology—Nitrophosphate-based technology differs markedly from the previously discussed technologies in that nitric acid is used to digest and solubilize some or all of the phosphate rock. Therefore, in the basic nitrophosphate process (most often referred to as the Odda process), which originated in Norway, it is possible to produce a very water-soluble (in excess of 95%) phosphate fertilizer without using sulfur. This characteristic continues to attract interest, especially during times of sulfur shortages or high sulfur prices. Continued environmentally related pressures on the wet-process phosphoric acid industry are expected to focus additional attention on the merits of nitrophosphate technology.

Advantages and Constraints—The most often quoted advantages of the Odda-type nitrophosphate process over phosphoric acid-based processes are (1) its complete independence of sulfur, (2) the ability to use lower quality phosphate rock, (3) flexibility with regard to water-soluble P_2O_5 in the product, (4) its overall agronomically favorable ratio of N-to-P_2O_5 (2:1) for upland crops when all coproduct ammonium nitrate (AN) is utilized either in the form of AN or calcium ammonium nitrate (CAN) or when it is combined with the phosphate into a product such as 26-13-0, and (5) less environmental impact because the production of phosphogypsum and its associated process water is avoided. The following are some of the possible disadvantages of the process: (1) the production of coproduct AN/CAN is relatively high, and this amount of nitrogen in the nitrate form may not be appropriate for some crops, for example, flooded rice; (2) the relatively low P_2O_5 content of the product results in a higher delivered cost per unit of P_2O_5 nutrient; (3) the relatively complex process technology requires a large-scale operation to be economic; and (4) because the ammonium nitrate-containing products may be quite hygroscopic and are not chemically compatible with urea, mixed storage or blending with urea in the marketing system must be avoided. Also, because nitrophosphate-type processing is heavily dependent upon the use of ammonia and nitric acid, the collateral impact on the environment caused by these production units must be considered.

Variations of the basic nitric acid-type process may include the use of sulfuric and/or phosphoric acid or ammonium phosphate—the so-called phosphonitric or mixed acid processes. Such raw material additions are made to adjust the N/P_2O_5 ratio, convert calcium nitrate into a compound with more favorable physical properties, or add agronomic sulfur to the final product. These techniques add considerable flexibility to the basic process but increase dependency upon the need for sulfur and phosphoric acid.

Another variation of nitrophosphate-type processing involves the calcium precipitation process in which a soluble sulfate, typically ammonium sulfate, is used to precipitate and remove calcium from the digested liquor (as waste gypsum) while at the same time adding nitrogen to the mother liquor. In still another variation, ion exchange techniques are used to remove calcium. The ion exchange process has the added advantage of producing chloride-free NPK fertilizers, but the waste liquor from the ion exchange unit must be treated.

Another possible advantage of nitrophosphate-based technology is that it offers the opportunity to obtain a broad range of P_2O_5 solubility in the products. The P_2O_5 water solubility is dependent upon the amount of calcium removed from the digested slurry and/or the amount of phosphoric acid, or its derivatives, used in the process. In the Odda process, essentially all of the calcium can be removed as calcium nitrate by cooling (refrigeration) the digested liquor to about 5°C. As a result, the water solubility of the final P_2O_5 product is

quite high—approaching 100%. The calcium nitrate is subsequently converted into an AN or CAN coproduct. In contrast, in the phosphonitric or mixed acid processes, none of the calcium is removed and the water solubility of the P_2O_5 is dependent largely upon the amount of phosphoric acid (or alternatively solid ammonium phosphate) added to the process. In these processes, the water-soluble P_2O_5 may be as low as 30% of the total, whereas the plant-available P_2O_5 usually exceeds 95% of the total.

The phosphonitric (mixed acid) technology is less capital intensive and complex than the Odda nitrophosphate process—the level of capital investment and technology more closely approximates that of DAP—but the process depends upon the use of some sulfur and phosphoric acid and therefore the production of phosphogypsum, either directly or indirectly. The mixed acid process, in effect, combines many advantages of the ammonium phosphate and the Odda nitrophosphate processes. In those locations where the lower level of P_2O_5 water solubility obtainable with moderate dependence upon sulfur (phosphoric acid or ammonium phosphate) is agronomically acceptable, this technology appears to offer advantages over the more water-soluble phosphate products such as TSP, DAP, or the Odda-type nitrophosphates.

4.3.3.5 Environmental Factors Related to the Production of Finished Phosphate Products—The environmental impact resulting from the production of finished phosphate fertilizer products may vary widely depending upon the scale of operation and the level of process integration.

For example, a small superphosphate plant located far from the source of phosphate concentrate and acid (sulfuric or phosphoric) may very well have a more adverse impact upon the environment, despite its small size, than a large fully integrated facility. The small, remote facilities often lack financial resources to achieve the level of technical management, process technology, and integration of facilities needed to collect and recycle or market process wastes and byproducts, particularly fluorine-containing wastes. On the other hand, the large integrated facilities usually enjoy a higher level of technical skills and financial resources needed for the proper environmental management of the facility. This higher level of integration also results in the more efficient use of waste heat (energy) and thus decreases the collateral impact of fertilizer processing caused by the burning of additional fossil fuel to produce electricity and steam for the process.

The production of finished phosphate fertilizers may adversely affect the environment in one or more of the following ways:

- Release of airborne solid and liquid particulates.
- Release to the atmosphere of ammonia, fluorides, nitrogen oxides, carbon dioxide, and other gaseous compounds.
- Release of metals and other residues from the regeneration or disposal of spent catalyst (ammonia, sulfuric acid, and nitric acid production units).
- Release of contaminated cooling water, process water, plant site stormwater drainage, and boiler blowdown residue.
- Release of solvents, oils, and other contaminants from plant maintenance and workshop activities.

The technology for containing and treating these potential pollutants is well developed. However, the effective application of the technologies is heavily dependent upon economics on the one hand and technical/managerial skills and the level of emphasis placed on compliance with environmental regulations on the other. In many instances the economic constraints to compliance have resulted in the closure of facilities. For example, in the United States and Western Europe alone, more than 300 small to moderately sized plants engaged in the production of phosphate-based compound NPK fertilizers have closed since the mid-1970s [50]. The decision to close these plants, of course, involved a number of technical, market, and economic factors in addition to those directly associated with the environment.

5. THE COST OF ENVIRONMENTAL COMPLIANCE[4]

To estimate the possible future cost of complying with environmental regulations in the global phosphate fertilizer sector, a number of assumptions must be made. There are no uniform legislative compliance criteria; furthermore, compliance technologies are not uniformly applicable to all facilities because of the large variety of site-specific factors, including location of plant, climatic conditions, mine and plant site geology and hydrology, and population and political pressures coupled with land-use priorities. In some cases extraordinary measures are being taken to guard against

4. Author's Note: The term "environmental compliance," as used in this discussion, does not imply that the industry is currently out of compliance with existing regulations. Instead, the term is used to denote what incremental compliance costs may accrue if additional regulations are implemented in the future.

any real or perceived adverse impact that the industry may have upon the environment; in other cases less stringent measures are practiced.

For the purpose of this discussion, a regulatory/cost scenario is described to give the reader an impression of the range of costs that could possibly accrue in the global phosphate industry if the industry was required to substantially conform to certain environmentally driven regulatory initiatives currently being examined. In evaluating these costs, it is not practical to assume that the entire global phosphate industry will be equally affected with respect to the level of compliance technology used, estimated cost, and implementation timeframe. Therefore, the illustrated technology and estimated costs should be considered indicative only while still providing useful insight to those charged with formulating policy initiatives that are compatible with maintaining an ecologically and economically sustainable phosphate fertilizer industry.

With the exception of the United States, the authors found little environmental compliance cost information available in the public sector relative to the other major producers of phosphate (the former FSU, Morocco, China, Jordan, and Tunisia). Therefore, because considerable information is available in the public sector concerning the U.S. phosphate industry, and because the U.S. industry supplies about 35% of the world's basic phosphate materials, it is used to illustrate the broad range of compliance criteria and costs being examined. Information described in this paper was initially derived from data presented in the July 1990 U.S.-EPA Report to Congress on Special Wastes From Mineral Processing [21]. This U.S.-EPA Report, particularly Chapter 12, focuses on the environmental management of phosphogypsum and process water resulting from the production of wet-process phosphoric acid. The technical and cost data described in the U.S.-EPA Report were further expanded with information derived from a number of technical and economic evaluations developed by industry and engineering bodies during the course of preparing public comments on the U.S.-EPA Report to Congress.

The reader is reminded that the environmental issues facing the global phosphate fertilizer sector are very dynamic and subject to constant review and change. To illustrate, on May 20, 1991, the Administrator of the U.S.-EPA issued a Final Regulatory Determination regarding the 20 special wastes (including phosphogypsum and process water) addressed in the July 1990 U.S.-EPA Report to Congress. The Administrator has concluded that "the proposed regulation of the 20 special wastes as set forth in the July 1990 U.S.-EPA Report to Congress on Special Wastes From Mineral Processing is inappropriate." The Administrator goes on to say that "the U.S.-EPA plans to readdress 18 of the wastes possibly in a program being developed for mining wastes and to proceed with the development and promulgation of a program under the Toxic Substances Control Act (TSCA) that will address the management of the remaining two wastes (phosphogypsum and process water) from wet-process phosphoric acid production."

As further clarification of the current status of the U.S.-EPA's envisioned regulatory concept, a spokesperson for the agency states that "the U.S.-EPA's preferred option for managing phosphogypsum and process water from the wet-process phosphoric acid industry is to use existing regulatory authority to require containment and/or remediation at those facilities where current waste management practices are causing an imminent hazard to human health or the environment. In the longer term, the authority of the TSCA is to be used to develop tailored guidelines for these wastes. The TSCA provides the authority and flexibility, currently not provided by the highly prescriptive Subtitle C of the Resource Conservation and Recovery Act (RCRA), described in the July 1990 U.S.-EPA Report to Congress, to create guidelines that will be (1) protective of human health and the environment, (2) technologically feasible for the large volumes of waste involved, and (3) affordable to the industry. Guidelines developed under the TSCA would be ideally suitable for facilitating in-plant process changes with a goal of waste minimization and pollution prevention.

The U.S.-EPA will encourage the participation of industry, the affected states, environmental groups, and the interested public in the development of the TSCA guidelines for the phosphoric acid industry. This process is just now getting underway.

In the event that suitable guidelines under the TSCA cannot be developed, EPA has reserved the option of revisiting its May 20, 1991 decision not to regulate the phosphoric acid industry under the RCRA Subtitle C scenarios described in the July 1990 U.S.-EPA Report to Congress."

The regulatory criteria ultimately applicable to the U.S. industry and the related costs that may evolve as a result of this initiative are not known. Therefore, the reader is urged to view the data described in this paper in this context.

With regard to the global situation, if the same environmental compliance criteria described in this paper are applied to other locations, it is unlikely that

the average incremental cost of environmental compliance illustrated for the United States would change much. In fact, in locations such as the Middle East and North and West Africa where fresh water is scarce and the majority of the population depends on surface sources for water, the cost of possibly having to deal with land disposal of phosphogypsum and process water as an alternative to sea disposal may be higher than the costs indicated for the United States. Furthermore, it should be noted that the cost of complying with existing or proposed environmental standards is very site-specific, and it is beyond the scope of this discussion to attempt to more fully quantify these costs on a regional or country basis.

It is also important to note that, except for limited opportunities for industrial integration designed to utilize process wastes, technological innovations in the phosphate industry seem to offer little scope in the near term for significantly decreasing the quantity of basic process wastes encountered: e.g., phosphatic clay materials, phosphogypsum, and process water. Thus, the development and implementation of methods for dealing with these materials to minimize their impact upon the environment are expected to be expanded on a global basis.

5.1 Estimated Incremental Cost of Compliance

The estimated cost for environmental compliance for the scenario described herein is expressed as the "incremental cost of compliance" over and above the current cost of production which, of course, includes existing, but often unspecified, compliance costs. The estimates assume a U.S. industry aggregate annual production of 14 million tonnes of P_2O_5 in the form of phosphate concentrate of which the equivalent of 10 million tonnes of P_2O_5 is converted into wet-process phosphoric acid. The remainder (4 million tonnes) represents concentrate used for the domestic production of TSP, SSP, and animal feed supplements, and that sold on the export market.

The compliance costs for the scenario are grouped into four major categories which include (1) phosphate mining and land reclamation, (2) phosphogypsum management, (3) process water management, and (4) finished product processing. A discussion of each of these cost categories follows.

5.1.1 *Phosphate Mining and Land Reclamation*

In many locations, particularly outside of the United States, reclamation of mined-out phosphate lands is not widely practiced. In the United States about 75,000 ha of land has been disturbed over the years by phosphate mining in Florida, Tennessee, North Carolina, and the western states, particularly Idaho and Wyoming [42].

In the United States, reclamation of mined-out areas has been practiced since the mid-1970s, generally on an as-mined basis. In Florida all lands mined since July 1, 1975, must be reclaimed. However, much of the approximately 35,000 ha of land mined prior to the mid-1970s, mostly in Florida, has not been reclaimed.

As indicated earlier, the cost of reclamation, such as practiced in Florida, U.S.A., varies widely depending upon the site and desired end use of the land (from about US $5,000/ha to US $25,000/ha). For the purpose of this discussion, an incremental compliance cost of US $4/tonne P_2O_5 is assumed as a global average taking into account existing mined-out sites in Africa, the Middle East, and elsewhere that may require reclamation. However, in the United States, a reclamation cost of about US $1/tonne P_2O_5 to US $2/tonne P_2O_5 seems more appropriate, and this cost, for the most part, is already included in the cost of production and therefore should not be viewed as an additional cost.

Additionally, it is important to note that changes in land use priorities can have a significant effect on the cost of phosphate mining. For example, national and local regulations dealing with encroachment of mining operations on property boundaries, streams, and other land features can significantly decrease the minable reserve base and thus adversely affect the overall economics of the mining operation. Thus, of the reserves stated in Table 3, the quantity that could actually be mined may be significantly less than indicated. Because the additional costs that may be attributed to land use priorities are quite variable from one location to another, it is not possible to assign a meaningful value for the purposes of this discussion.

5.1.2 *Phosphogypsum Management*

5.1.2.1 Active Stacks and Containment Sites—In the worst case, some phosphogypsum could be defined as a hazardous waste according to certain U.S. criteria. The new phosphogypsum disposal site for such a material would resemble a pond much like those used for the storage and disposal of phosphatic clay waste from the phosphate ore beneficiation process; the traditional elevated stack would not be allowed and, of course, a much greater land area would be required. The impoundment-type configuration would be designed to facilitate future closing and capping in accordance with a U.S. hazardous waste regulatory scenario; such a closure scenario could not be practically accomplished with an elevated stack. The disposal sites would have to

be constructed to facilitate collection and total containment of contaminated process water and leachate. Such containment would require that the phosphogypsum disposal site meet specific design and management criteria, including the installation of two layers of an impermeable synthetic liner in addition to specific criteria for soil preparation and process water removal and containment.

In the July 1990 Report to Congress, the U.S.-EPA estimated that phosphogypsum produced by 11 of the 21 U.S. phosphoric-acid production facilities could be classified as a hazardous waste primarily because of leachate toxicity characteristics [21]. U.S.-EPA further estimated that an investment of about US $3.64 billion would be required for the construction of the 11 phosphogypsum disposal sites according to the above criteria [21]. Subsequent to the July 1990 Report to Congress, the U.S.-EPA now believes that phosphogypsum produced by all 21 facilities would be affected by a "hazardous waste" designation [68].

Using the US $3.64 billion as a base and assuming that the 11 affected production facilities produce a total of 6 million tonnes of P_2O_5 annually in the form of wet-process phosphoric acid, the estimated incremental compliance cost per tonne of P_2O_5 for capital charges alone would be about US $90 according to U.S.-EPA estimates, or about US $54 if the cost is prorated across the entire industry to reflect the average impact on the U.S. production cost.

For the same 11 affected facilities, U.S.-EPA estimates indicate a total annual cost of about US $685 million, including operating and capital charges [21]. Again, assuming an annual production of 6 million tonnes of P_2O_5, a cost of about US $114/tonne P_2O_5 is indicated (US $90/tonne capital plus US $24/tonne operating). If this cost (capital and operating) is prorated across the entire industry, the average cost per tonne of P_2O_5 would be about US $68. Subsequent to the U.S.-EPA July 1990 Report to Congress, the estimated cost for this hazardous waste regulatory scenario was adjusted downward in the order of 50% by the U.S.-EPA.

According to U.S.-EPA, some U.S. phosphoric acid production facilities would fall under less costly phosphogypsum management practices according to an alternative "special waste" classification being evaluated by the U.S.-EPA. In these cases, conventional stacking would be allowed; also, the need for impermeable liners and other operational or post-operational practices would be determined on a plant-by-plant basis. The cost for managing the phosphogypsum according to the special waste criteria is estimated by U.S.-EPA at about US $28 to US $36/tonne P_2O_5 depending upon the site-specific management criteria [21]. As with the more rigorous criteria, capital charges account for the majority (about 80%) of this cost.

Using the U.S.-EPA cost estimates as described in the July 1990 Report to Congress and assuming that 60% of the U.S. phosphogypsum fell under the most costly U.S.-EPA hazardous waste criteria and the remainder under the less rigorous special waste criteria, the industry average incremental compliance cost for phosphogypsum management would amount to about US $80/tonne P_2O_5 produced as wet-process phosphoric acid. Of course, this industry average value could be considerably less depending upon the regulatory criteria that are ultimately adopted in view of the May 1991 ruling of the U.S.-EPA Administrator and the regulatory guidelines that may emerge as a result of regulation under the TSCA.

To help place these estimated on-site waste management costs into perspective, it is interesting to note (though academic) that tipping fees for hazardous waste landfills in the United States average US $192/tonne of disposed material not including transportation and state/local taxes [40,46]. For ordinary residential waste (garbage) or "special waste" that meets the residential waste criteria, the landfill cost averages about US $30/tonne of material not including transportation and taxes.

5.1.2.2 Closed Stacks—Compliance with certain phosphogypsum stack closure scenarios being analyzed would call for the closing of about 30 active stacks and 34 inactive stacks in the United States. The cost of closing these stacks is estimated at US $1.3 billion (average of about US $20 million/stack), not including the cost for long-term monitoring and maintenance [3]. Again, using 10 million tonnes of phosphoric acid P_2O_5 production/year as a base and a 20-year capital recovery period at an annual interest rate of 14%, this closure cost would amount to an incremental compliance cost for capital charges alone of about US $20/tonne phosphoric acid P_2O_5 produced by the entire U.S. industry over a 20-year period. Extrapolation of one recent actual closure cost experience [18] and a reported current estimate by a major U.S. producer, however, indicate that the cost of stack closure is quite variable and may be significantly less than the average value of US $20 million/stack. Values in the range of about US $5.5 to US $18 million/stack are indicated.

5.1.3 *Process Water Management*

As previously discussed, the recirculated process water associated with the production of wet-process phosphoric acid represents a major potential environmental cost if such water requires treatment with lime to adjust the pH to a minimum value of 3.5. Estimates made by the U.S.-EPA for the U.S. wet-process phosphoric acid industry indicate an incremental compliance cost for process water treatment and management in the order of US \$22/tonne P_2O_5 produced [21].

Detailed estimates, however, made by an engineering firm on behalf of TFI indicate a much higher additional cost for compliance: about US \$70/tonne P_2O_5 as shown in Table 10 [36]. The large difference between the U.S.-EPA estimates and the TFI-commissioned engineering estimates is attributed to differences in interpretation of the significance of a number of operational cost factors: for example, because some process water is normally returned to the phosphate rock digester, treatment of this water with lime would result in a loss of acidity in the digestion/reaction section that would have to be replaced with additional sulfuric acid; the level of dissolved calcium would also be higher, thus requiring more sulfuric acid; because of lower filtration rates, a lower plant capacity is expected; and because of increased chemical scaling (fouling) of process equipment, lower capacity utilization is also expected [36].

It is important to note that treatment of recirculated process water with lime to maintain the prescribed pH is not commercially practiced. Therefore, such a practice may incur other costs that have not been identified, for example, the extra cost of phosphogypsum disposal caused by the adverse impact that the treated water may have upon the phosphogypsum stacking and drainage (dewatering) characteristics as reported by Ardaman [4]. Alteration of the phosphogypsum properties could possibly preclude conventional stacking as currently practiced. This, or course, could have a significant impact on the cost of phosphogypsum management.

5.1.4 *Finished Product Processing*

Because this portion of the overall phosphate manufacturing complex is largely independent from the phosphoric acid process loop, no significant additional cost attributed to environmental compliance is likely to be incurred in these units.

5.1.5 *Summary of Incremental Cost of Environmental Compliance*

According to the foregoing discussion, the following estimated range of incremental costs for environmental compliance is indicated for the major processing components of the industry. The total cost, of course, will depend upon the number of components that are ultimately included in the regulatory criteria.

Compliance Component	Estimated Incremental Compliance Cost US \$/tonne P_2O_5 as Wet-Process Phosphoric Acid
Phosphate mining and land reclamation[a]	US \$1-\$5
Phosphogypsum management	
Active stacks	US \$6-\$80
Closed stacks	US \$5-\$20
Process water management	US \$20-\$70
Finished product processing	No change

a. Applicable to all phosphate fertilizers; all other costs directly applicable to the production of wet-process phosphoric acid only.

Subsequent to the July 1990 Report to Congress, the regulatory scenarios used to determine some of the above compliance costs were re-examined by the U.S.-EPA and a revised estimated incremental compliance cost in the range of US \$28 to US \$87/short ton of wet-process phosphoric acid P_2O_5 was indicated depending upon the regulatory scenario [67].

The large variability in estimated compliance costs for the indicated components is due to a number of site-specific technical and regulatory factors, variations in the assumed capital recovery period, and the lack of a broad base of actual cost experience relative to the scenario examined.

According to an engineering study performed for TFI, the U.S. industry average cost of production for merchant-grade wet-process phosphoric acid (52%-54% P_2O_5 and 1% or less suspended solids) in 1989 was US \$308/tonne P_2O_5 f.o.b. plant site; the average cost of production for acid having less than merchant-grade specifications was about US \$250/tonne P_2O_5 [36]. This lower value does not include certain concentration and clarification costs nor does it include interest and sales and administration charges that are normally associated with the marketing of a merchant-grade product.

From this it can be seen that in current dollars the indicated environmental compliance costs could increase the f.o.b. cost of merchant-grade phosphoric acid P_2O_5 anywhere from about 11% (US \$308 + US \$34) to about 57% (US \$308 + US \$175), depending upon the level of compliance cost incurred. For the lower grade acid normally used within the complex for the

production of TSP and DAP, the cost per tonne of P_2O_5 would be increased in the order of about 14% (US $250 + US $34) to about 70% (US $250 + US $175). The revised U.S.-EPA estimates indicate a cost increase for phosphoric acid P_2O_5 of anywhere from 12% to 38% depending upon the compliance criteria used [67].

On the basis of this range for the incremental environmental compliance cost, the f.o.b. factory-gate cost range is indicated below for the major finished phosphate products produced by the U.S. industry in existing facilities.

It is quite likely that the total cost per tonne of P_2O_5 would be slightly higher than indicated to take into account the increased value of intermediate and finished product inventories and, consequently, higher levels of required working capital. There is also the issue of the cost of long-term liability for the waste disposal sites that may continue after the useful life of the plant has expired.

Product	Current Cost, f.o.b. Factory[a]	Incremental Environmental Compliance Cost Range[b]	Estimated Total Cost Range, Including Incremental Compliance Cost, f.o.b. Factory	
	(US $/tonne product)	(US $/tonne product)	(US $/tonne product)	(US $/tonne P_2O_5)
Triple superphosphate (TSP), 46% P_2O_5	122	12-57	134-179	291-389
Monoammonium phosphate (MAP), 11% N, 52% P_2O_5	168	18-91	186-259	294-434[c]
Diammonium phosphate (DAP), 18% N, 46% P_2O_5	162	16-81	178-243	270-410[c]

a. Derived from 1989 U.S. industry survey data compiled by The Fertilizer Institute.
b. Based on P_2O_5 content derived from phosphate concentrate and wet-process phosphoric acid.
c. Adjusted to reflect credit for contained nitrogen valued at US $300/tonne N.

6. PHOSPHATE FERTILIZER PRODUCT ALTERNATIVES FOR MITIGATING ENVIRONMENTAL IMPACT AND THE COST OF COMPLIANCE

6.1 Phosphate Product Choices

Aside from the minor phosphate fertilizer products, such as basic slag and bonemeal, the most likely commercial phosphate product choices are listed below:

Product	Approximate Current Contribution to Total P_2O_5 Production
	(%)
Direct application phosphate rock	4
Single superphosphate (SSP) and enriched superphosphate	17
Partially acidulated phosphate rock (PAPR)	nil
Triple superphosphate (TSP)	13
Ammonium phosphate (DAP or MAP)	39
Odda- and mixed acid-type nitrophosphates	20
Other compound (NPK) products derived from various phosphate sources including thermophosphates	7
TOTAL	100

The relative agronomic, technical, and environmental merits of each of these basic phosphate sources have already been discussed. The practical commercial features of each product choice are briefly summarized.

6.1.1 *Direct Application Phosphate Rock*

Only a small amount of the world's commercial phosphate rock is sufficiently reactive to make it suitable for widespread agronomic use as a direct application product. Also, because the agronomic effectiveness of direct application phosphate rock depends heavily upon the occurrence of acid soils with low phosphorus levels, its use is often most appropriate in locations that, unfortunately, are generally located long distances from the major commercial sources of reactive rock that occur in North Carolina (U.S.A.) and Tunisia in North Africa. Therefore, except for special cases where the phosphate rock is sufficiently reactive and located close to the consumption area, direct application phosphate rock is not considered a major alternative source of fertilizer phosphorus.

6.1.2 *Single Superphosphate (SSP) and Enriched Superphosphate*

Although an excellent source of agronomic phosphorus, sulfur, and calcium, SSP is generally too costly on a delivered P_2O_5 basis when compared with TSP or DAP. If, however, the sulfur value of SSP could be reflected in its nutrient content and selling price, then it would be quite competitive with the more concentrated sources of P_2O_5, such as TSP or DAP, if transport costs are not excessive. Enrichment of SSP with phosphoric acid and ammonia to a grade such as 5-25-0 may offer a practical means for increasing the total nutrient content and agronomic performance of the basic SSP product where a low dose of nitrogen may be needed. Also, the addition of ammonia to SSP improves its physical properties and compatibility with urea, an important feature if it is used for blending NPK grades. Nevertheless, the widespread use of SSP-type products is expected to continue to be limited by the economics of transport and distribution.

6.1.3 *Partially Acidulated Phosphate Rock (PAPR)*

The PAPR products are characterized as agronomically intermediate between direct application phosphate rock and its more soluble counterparts, SSP and TSP. As with direct application phosphate rock, the agronomic effectiveness of PAPR depends upon the properties of the phosphate rock on one hand and the characteristics of the soil and crop on the other. Because of these constraints, it is unlikely that PAPR can be viewed as an alternative to the more soluble phosphate products if, in fact, such solubility is agronomically required.

6.1.4 *Triple Superphosphate (TSP)*

Triple superphosphate offers many of the advantages of DAP while depending less on wet-process phosphoric acid; thus, it is a better choice from an environmental viewpoint provided the fluorides evolved from the process are properly dealt with. Also, it is important to note that a TSP unit often complements a merchant-grade wet-process phosphoric acid/DAP complex because the sludge-type phosphoric acid produced during the clarification of merchant-grade phosphoric acid is often suitable for the production of TSP.

6.1.5 *Ammonium Phosphate (DAP or MAP)*

These products currently account for the largest single share of world phosphate fertilizer production, about 39% of the total P_2O_5. Although currently the most economic phosphate fertilizer to produce and transport, especially if one considers the nitrogen content, the ammonium phosphate products have the potential for the most severe environmental impact at the production site because of their total dependence on wet-process phosphoric acid as the source of P_2O_5. However, because of the high nutrient content, good physical properties, and good agronomic performance under a wide variety of conditions, it will be difficult to replace, on a large scale, ammonium phosphates with other phosphate products.

6.1.6 *Odda-Type Nitrophosphates*

This phosphate production technology has the least impact on the environment because phosphogypsum and its associated process water are not produced. This technology does, however, require nitric acid, and therefore, the impact of nitrogen oxide (NO_x) emissions upon the environment must be considered and controlled. The main disadvantage of this technology is that a relatively large amount of nitrogen in the nitrate form is produced. If, for example, 50% of world's current P_2O_5 consumption was supplied with Odda-type nitrophosphate products, about 38 million tonnes of ammonium-nitrate type nitrogen would be produced. The international marketing of such a large amount of nitrate-containing product, which is agronomically inappropriate for some crops, e.g., flooded rice, would be difficult, considering that total world consumption of nitrogen amounts to about 79 million tonnes, of which urea currently accounts for nearly 40%.

Because of the nitrogen constraint, it appears that the Odda-type nitrophosphate plants can most appropriately supply local and regional markets where the 2:1 $N:P_2O_5$ nutrient ratio and the nitrate form of nitrogen are preferred. The plants in Europe, India, Pakistan, and China, for example, meet these criteria. Also, the recently announced decision by a major European phosphate fertilizer producer to close its phosphoric acid plant at Antwerp, Belgium, and expand its Odda nitrophosphate-type facility illustrates the advantage offered by the Odda process when the costs associated with the disposal of phosphogypsum and contaminated process water become unacceptable [6].

6.1.7 *Mixed Acid-Type Nitrophosphates (Phosphonitric Products)*

This technology, also developed in Europe, is very flexible and well suited for local or regional locations where a number of $N:P_2O_5$ nutrient ratios are required. Also, because the technology is less capital intensive and less complex than the more fully integrated Odda-type process, it is better suited for those developing countries that often depend heavily upon imported raw materials, including ammonia and phosphoric acid. Today, however, some of these import-dependent countries are closing their basic production units and converting to blending of imported granular materials. This approach often proves to be more cost effective especially if the level of government production subsidies is decreased or eliminated.

6.1.8 *Compound NPK Products*

Compound NPK products, including nitrophosphate- and thermophosphate-type products but not including DAP and MAP, currently account for about 35% of world P_2O_5 consumption (Figure 4). For the most part, with the exception of the Odda-type nitrophosphate products and the thermophosphates, these compound products derive their P_2O_5 from SSP, TSP, or directly from wet-process phosphoric acid. Worldwide, about 275 plants are currently producing compound NPK

products, not including the major producers of DAP and MAP [50]. The combined production of these 275 compound NPK production units is estimated at about 10-12 million tonnes of P_2O_5. Growth in compound NPK production capacity has stagnated, and blending is expected to replace some of the capacity lost through plant closures/industry rationalization.

6.2 Comparative Cost of Phosphate Products Including Estimated Incremental Cost of Environmental Compliance

As can be seen from the foregoing discussion and estimates, the incremental cost of environmental compliance is roughly proportional to the amount of P_2O_5 in the fertilizer product that is derived from wet-process phosphoric acid. In addition to the costs directly related to wet-process phosphoric acid, an average incremental cost equivalent to US $4/tonne P_2O_5 is also estimated for the reclaiming of existing and future mine sites to make these sites conform to existing or proposed standards. There is a great deal of variability in the cost of reclamation, and the US $4/tonne P_2O_5 global value is only indicative.

The most common phosphate fertilizer product choices are listed as follows, according to their increasing dependence upon wet-process phosphoric acid and, therefore, increasing incremental cost for environmental compliance at the factory gate:

6.2.1 *Estimated Impact of Product Choices on the Delivered Cost of Phosphate Fertilizer*

To arrive at an estimate of the impact that environmental compliance costs at the production site would have on the farm-level cost of phosphate fertilizer, the current product composition and logistics of the world phosphate industry were examined on a regional basis as described in Chapter 4. The data in Chapter 4 were then used to determine the delivered cost of P_2O_5 to the farm level on a regional basis for several products according to two scenarios as shown in Table 12. The Case 1 scenario (base case) reflects the estimated farm-level cost of P_2O_5 assuming production in a new facility according to current commercial standards. The Case 2 scenario assumes the Case 1 production costs plus an additional (incremental) cost for environmental compliance as described in section 6.2. The upper values for environmental compliance were used to describe a maximum cost scenario.

The estimated and incremental environmental compliance costs for phosphogypsum disposal described for the United States were adjusted downward by US $20/tonne P_2O_5 for non-U.S. phosphoric acid producers. This was done to correct for the estimated maximum cost of closing inactive phosphogypsum stacks, which is more likely to be necessary in the United States than elsewhere.

Product[a]	P_2O_5 Derived From Wet-Process Phosphoric Acid	Estimated Range of Incremental Cost of Environmental Compliance	
	(% of total)	(US $/tonne product)	(US $/tonne P_2O_5)
Direct application phosphate rock, 30% P_2O_5	0	1.2	4.0
Single superphosphate, SSP 20% P_2O_5, 10% S	0	0.8	4.0
Partially acidulated phosphate rock, (PAPR—sulfuric acid based), 22% P_2O_5, 6% S	0	0.9	4.0
Nitrophosphate (Odda process), 26% N, 13% P_2O_5	0	0.5	4.0
Nitrophosphate (mixed acid process), 20% N, 20% P_2O_5	50[b]	3.8-18	19 -90
Enriched superphosphate, 30% P_2O_5, 5% S	50[b]	5.7-27	19 -90
Partially acidulated phosphate rock (PAPR—phosphoric acid based), 40% P_2O_5	50[b]	7.6-36	19 -90
Triple superphosphate (TSP), 46% P_2O_5	70[b]	12 -57	25 -124
Diammonium phosphate (DAP), 18% N, 46% P_2O_5	100	16 -81	34 -175
Monoammonium phosphate (MAP), 11% N, 52% P_2O_5	100	18 -91	34 -175

a. Indicated P_2O_5 content of direct application phosphate rock and the PAPR products is total; P_2O_5 in other products is assumed to be available according to normal commercial test methods.

b. Quantity of wet-process phosphoric acid may vary slightly depending upon properties of phosphate rock and wet-process phosphoric acid.

Table 12. Effect of the Cost of Environmental Compliance on the Farm-Level Cost of P_2O_5 From Selected Products

Region/Country[a]	Ammonium Phosphate (DAP)			Triple Superphosphates (TSP)			Single Superphosphate (SSP)			Other Phosphate Products (NPKs)			Direct Application Phosphate Rock		
	Case 1[b]	Case 2[c]	Difference[d]	Case 1[b]	Case 2[c]	Difference[d]	Case 1[b]	Case 2[c]	Difference[d]	Case 1[b]	Case 2[c]	Difference[d]	Case 1[b]	Case 2[c]	Difference[d]
	(US $/t P_2O_5)														
Western Europe	553	720	167	663	789	126	742	746	4	549	659	110	425	429	4
Eastern Europe	573	736	163	645	771	126	707	711	4	585	655	70	No reported market		
Former Soviet Union	507	668	161	596	722	126	631	635	4	452	489	37	No reported market		
North America	469	651	182	552	688	136	596	600	4	458	555	97	No reported market		
Central America	564	732	168	649	775	126	736	740	4	607	708	101	No reported market		
South America	527	698	171	605	732	127	657	661	4	605	707	102	350	354	4
North Africa	498	659	161	570	696	126	621	625	4	541	636	95	No reported market		
Sub-Saharan Africa	687	853	166	761	887	126	912	916	4	929	1,043	114	No reported market		
South Africa	534	696	162	No reported market			658	662	4	632	768	136	No reported market		
West Asia	551	726	175	600	726	126	657	661	4	599	692	93	326	330	4
South Asia	597	764	167	657	784	127	726	730	4	692	822	130	414	418	4
East Asia (excluding China)	598	770	172	697	823	126	748	752	4	601	661	60	436	440	4
China	573	751	178	620	746	126	623	627	4	400	404	4	312	316	4
Oceania	601	772	171	682	809	127	765	769	4	503	512	9	395	399	4
World	551	720	169	630	757	127	682	686	4	573	656	83	372	376	4

a. Refer to Appendix B for regional classification of countries.
b. Case 1 (base case) assumes a new plant with full capital charges as described by Schultz and Le [52].
c. Case 2 values include the base case (Case 1) values plus estimated incremental costs due to environmental compliance as described in the text. Refer to Table 13 for summary of estimated physical distribution and marketing costs.
d. Difference is attributed to the estimated maximum cost of environmental compliance. Estimated minimum incremental environmental cost is approximately 20% of the indicated maximum values. Values are independent of base case investment requirements (capital charges) so they may be applied to current production costs in existing facilities to give a reasonable approximation of the cost of compliance.

The cost of international and domestic transport and marketing was also estimated (Table 13). Furthermore, because some phosphate products contain nitrogen and/or sulfur, these nutrients were credited on a farm-level cost basis of US $520/tonne for nitrogen and US $135/tonne for sulfur to arrive at a net delivered cost for P_2O_5 at the farm level. For compound NPK products, all calculations were made on a net P_2O_5 basis to avoid the complexity of determining credits for other nutrients commonly contained in NPKs.

As shown in Table 12, the most extreme estimated incremental cost of environmental compliance (world weighted-average basis) at the farm level varies from US $4/tonne P_2O_5 (direct application phosphate rock and SSP) to US $169/tonne P_2O_5 (DAP). However, the net cost of P_2O_5 delivered at the farm level, including the environmental compliance cost, varies from US $376/tonne P_2O_5 for direct application phosphate rock to US $720/tonne P_2O_5 for DAP and US $757/tonne P_2O_5 for TSP. Again, the reader is reminded that these costs not only reflect the expected highest estimated cost of environmental compliance but also the higher cost of production in new facilities, which is caused by higher capital charges than currently experienced by the established industry. These data are summarized in Table 14 along with the estimated current delivered cost of P_2O_5 derived from DAP and TSP, based on 1990 average international f.o.b. prices (shown for comparison). The data in Table 14 also describe the impact that the large variation in estimated environmental compliance costs may have upon the delivered cost of phosphate fertilizer.

The data also clearly show the favorable cost structure for existing production facilities compared with new units that would incur a much higher level of capital charges than experienced with the existing units. The favorable cost profile for the existing industry remains intact compared with new units even when the incremental environmental compliance costs are considered.

6.2.1.1 Relating Delivered Cost of Phosphate Fertilizer to Agronomic (Solubility) Needs—The above analysis quite clearly shows that DAP, even with a relatively high estimated cost for environmental compliance, ranks very favorably among the phosphate product choices from the point of view of delivered cost. Although at the highest compliance cost SSP and some NPKs may effectively deliver P_2O_5 to the farm level at a net cost slightly below that of DAP (in the order of 5%-10%), it would not be practical or cost effective in most cases to assume that the total P_2O_5 requirements could be effectively supplied in the form of SSP or NPKs that usually contain only about 15%-20% P_2O_5.

It is interesting to note that TSP, with an estimated environmental compliance cost of about 70% that of DAP, still remains less attractive on a delivered P_2O_5 basis than DAP. This, of course, is due to the extra value placed on DAP (US $94/tonne DAP) for its nitrogen content.

Direct application phosphate rock is, of course, the least-cost form of P_2O_5. Its delivered cost (P_2O_5 basis) at the farm level is about 52% that of P_2O_5 derived from DAP, according to the assumptions used for this evaluation. As already noted, the widespread use of direct application phosphate rock as a source of P_2O_5 is severely limited for agronomic reasons as well as by the lack of general availability of suitably reactive material. Therefore, it should not be viewed as an alternative product without qualification.

The overall economics (production and use) of PAPR, produced from either sulfuric acid or phosphoric acid, fall between those of direct application phosphate rock and conventional low-P_2O_5 products such as SSP and many NPKs. Therefore, it is unlikely that such products offer a significant alternative to DAP and TSP on a global basis. In certain very specific locations, however, the PAPR family of products may be appropriate provided the cost of production and physical distribution can be minimized.

As discussed in Chapter 2, the agronomic suitability of phosphate fertilizer products containing lower levels of water-soluble P_2O_5, for example, 40%-60%, may offer significant economic advantages other than those related directly to mitigating the cost of environmental compliance. Some of these advantages are as follows:

1. The use of lower grade phosphate rock to produce conventional products, such as DAP, TSP, and SSP, containing lower levels of water-soluble P_2O_5, would extend the useful life of existing mines and production facilities.
2. Less soluble products would help to expand the regional and global phosphate resource base to include phosphate ores containing higher levels of impurities.
3. Less soluble products would tend to decrease the environmental impact at the production site because less intensive beneficiation would be required.
4. Under some soil/crop/climatic conditions, the use of less soluble products would improve the agronomic performance of the applied phosphate fertilizer. This is especially relevant in soils that are relatively acidic and that have a high phosphorus fixation capacity.

Table 13. Estimated Physical Distribution and Marketing Costs for Phosphate Fertilizer Materials[a]

International Transport Cost

Origin (Region/Country)	Destination (Region/Country)[b]													
	Western Europe	Eastern Europe	Former Soviet Union	North America	Central America	South America	North Africa	Sub-Saharan Africa	South Africa	West Asia	South Asia	East Asia	China	Oceania
	(US $/t product)													
Western Europe	x	15	20	25	25	30	12	40	40	15	30	35	35	35
Eastern Europe	15	x	15	25	25	30	13	40	40	15	30	35	35	35
Former Soviet Union	25	15	x	27	27	32	14	42	42	12	32	37	37	37
North America	25	25	27	x	15	20	30	35	35	32	44	36	36	35
Central America	25	25	27	15	x	15	30	35	35	32	44	42	36	35
South America	30	30	32	20	15	x	35	35	30	37	45	42	36	47
North Africa	25	25	27	30	30	30	x	40	40	12	35	42	47	35
Sub-Saharan Africa	40	40	42	35	35	35	40	x	25	40	30	42	38	28
South Africa	40	40	42	35	35	30	40	25	x	40	25	28	28	30
West Asia	15	15	17	40	40	40	12	40	40	x	22	28	33	30
South Asia	30	30	32	44	44	45	35	30	25	22	x	15	18	22
East Asia	35	35	37	42	42	42	42	38	28	28	15	x	15	20
China	35	35	37	36	36	36	47	38	28	33	18	15	x	27
Oceania	35	35	37	35	35	35	47	35	28	30	22	20	27	x

Domestic (Internal) Transport and Marketing Costs

Region/Country	Transport	Marketing	Total
	(US $/t product)		
Sub-Saharan Africa	50	30	80
All other regions/countries	15		1530

a. Estimated costs are indicative only and are assumed to cover all costs of moving (including handling and in-transit storage) fertilizer materials from their source, through processing, and on to the farm level.
b. Refer to Appendix B for regional classification of countries.

Table 14. Estimated World Average Delivered Cost of P_2O_5 at the Farm Level Including Incremental Cost of Environmental Compliance—New and Existing Production Facilities[a]

Product	Incremental Cost of Environmental Compliance[c]	New Production Facilities: Delivered Cost at Farm Level	Existing Production Facilities: Delivered Cost at Farm Level Using Average 1990 f.o.b. Prices[b]: With Incremental Cost of Environmental Compliance	Existing Production Facilities: Delivered Cost at Farm Level Using Average 1990 f.o.b. Prices[b]: Without Incremental Cost of Environmental Compliance
	(US $/t P_2O_5)			
Direct application phosphate rock	4	376	-	-
Compound NPKs[d]	28-83	601-656	-	-
SSP	4	686	-	-
DAP	32-169	583-720	355-492	323
TSP	26-127	656-757	459-560	433

a. Refer to Table 12 for regional/country cost data.
b. Based on average 1990 U.S. Gulf Coast f.o.b. prices plus US $70/t product to cover transportation, bagging, and marketing costs. DAP is given credit for its nitrogen content at US $520/t nitrogen delivered at the farm level.
c. Indicated average global range depending upon compliance criteria.
d. NPKs assumed to contain an average of 15% P_2O_5.

6.2.2 *Impact of Increased Fertilizer Cost*

From the previous discussion, it can be concluded that any significant change in the overall phosphate fertilizer product mix is unlikely even if the indicated incremental costs for environmental compliance for the phosphoric acid-based products were uniformly applied on a global basis. However, the increased costs would most certainly have an adverse effect on demand and consumption patterns. The expected regional impact, using the maximum estimated incremental environmental compliance cost at the farm-gate, is summarized in Table 12. In North America the cost increase would be highest in both absolute and percentage terms because of the high proportion of phosphoric acid-based products used. China, Oceania, and Eastern Europe, all regions with high proportions of SSP use in the current product mix, would be least affected. However, the absolute farm-gate cost for P_2O_5 in developing countries, except China, would increase by $80 to $130/tonne to over $700/tonne P_2O_5 and up to about $1,000/tonne P_2O_5 in sub-Saharan Africa.

There is little doubt that under this estimated maximum cost scenario the demand for phosphate fertilizer would decrease in most regions and the impact would be particularly severe in the developing countries. In Western Europe, the combination of an estimated 19% incremental cost increase with high average application rates could increase average phosphate fertilizer costs by more than $7/ha, twice the increase of any other region. However, the impact on the benefit/cost ratio attributed to phosphate fertilizer use would be much less for European farmers than for farmers in developing countries where fertilizer costs represent a much higher proportion of the total crop production costs. The likely impact of increased fertilizer costs in sub-Saharan Africa with its already very low use of phosphate fertilizer would be severe; this would undoubtedly decrease opportunities for increased food production in this region.

6.3 Barriers to Change and Initiatives Required to Bring About Change

As indicated in the foregoing discussion, the phosphate fertilizer industry will face a significant increase in the cost of producing certain phosphate fertilizers if compliance with some of the proposed environmental initiatives is widely mandated. The phosphate fertilizer products that depend heaviest upon wet-process phosphoric acid as the source of P_2O_5 will be affected the most, as discussed and as shown in Table 12. A number of barriers will need to be overcome to bring about change and help mitigate the expected impact that certain environmental initiatives may have upon the phosphate fertilizer production industry, the farmer, and society in general. The following observations address some of the most significant barriers that have been identified.

6.3.1 *Identifying and Overcoming the Barriers to Change*

An examination of the alternatives that may be available for mitigating the impact of an increased level of environmental compliance in the phosphate fertilizer production and use sectors indicates the following barriers (constraints) to achieving widespread implementation:

- Lack of definition of acceptable environmental standards.
- Lack of global environmental compliance standards.
- Cost required to implement available technology.
- Major investments required to change product mix.
- Limited availability of foreign exchange.
- Marginal competitive status within the phosphate fertilizer industry.
- Disturbance of commercial equilibrium.
- Lack of significant farm-level cost differences.
- Restrictive fertilizer product legislation.
- Difficulty in changing farmers' practices.

A discussion of these constraints follows.

6.3.1.1 Lack of Definition of Acceptable Environmental Standards—There is currently no universal definition or criteria for objectively judging the "environmental acceptability" of a fertilizer production or use practice. The criteria for an "acceptable standard" may vary widely depending upon climatic, geological, and other technical and nontechnical factors including population density and public pressures. Forcefully expressed public concern can often result in environmental regulations that lack a sound technical/economic basis.

Currently, in many countries, industry standards are being debated and negotiated at the national and local level between environmental regulatory agencies, public action groups, and fertilizer industry representatives. Although it is unlikely that a single set of standards for universal application in the industry can, or should, be established, it seems desirable for the global industry to agree upon scientifically established minimum environmental standards appropriate to given locations. It is therefore appropriate that international and national industry agencies, together with national environmental regulatory agencies, convene to establish and agree upon minimal standards for environmental compliance in the phosphate industry. Additional compliance standards for national industries, where deemed necessary or desirable, could be resolved on a national or local level.

6.3.1.2 Lack of Global Environmental Compliance Standards—An increase in the farm-level cost of P_2O_5 can be influenced directly or indirectly by environmentally related cost factors. Therefore, unless environmental compliance is viewed as a global responsibility, there can be a great disparity in production costs and consequently an unhealthy competitive environment caused by unilateral environmental legislation and enforcement. The net result may be supply/demand-driven farm-level cost increases and a declining farm-level benefit/cost ratio attributed to fertilizer use without mitigating the environmental impact of the nonregulated production units.

Without a global initiative for environmental compliance, or at least an environmental policy agreed upon by the leading producers of phosphate fertilizers, it is doubtful whether the cost of an increased level of environmental compliance could be sustained.

On the contrary, it should also be noted that an increased level of mandated environmental compliance will deter economic development, especially in the resource-poor developing nations.

6.3.1.3 Cost Required to Implement Available Technology—The lack of technology is perhaps the least significant barrier to change. Today's modern phosphate fertilizer industry has evolved over a period of nearly 150 years. During this time, technological progress together with strong local and international competition for market share has resulted in a very efficient industry, especially with regard to optimizing production costs, including the recovery of effluents and their conversion into marketable byproducts.

On the basis of the industry's demonstrated performance, it is clear that, given the appropriate economic incentives, the industry, in general, is not significantly constrained by the lack of knowledge and available technology. The widespread implementation of the available technology required to mitigate certain environmental concerns is, however, severely constrained by cost-related market factors.

If, for instance, the environmental standards described in this paper were adopted globally, the annual total industry cost for compliance could be in the order of $4 billion. This raises questions concerning the social benefit/cost ratio of environmental protection. Because of the industry structure, environmental benefits will accrue to a limited number of countries where strict compliance is observed, but the costs will be incurred globally. A growing body of opinion, however, recognizes that environmental stewardship should be approached on a global basis and therefore its costs should be shared globally.

Lack of profitability in the private sector, and inertia in the public sector in many countries, will preclude or delay enforcement of any agreed-upon minimum standards. It is therefore appropriate that acceptance of minimum industry standards should be coupled with international agreement on an implementation timetable for compliance. With the concentration of production in

only a few countries and the preponderance of public-sector ownership of the production resources, a significant level of international cooperation may be an achievable goal.

6.3.1.4 Major Investments Required to Change Product Mix—While it is clear from the foregoing discussion that the farm-level cost of P_2O_5 derived from direct application phosphate rock, SSP, and some NPKs would be least affected by increased environmental compliance costs at the production site, the industry would have to undergo a major restructuring to meet the world's P_2O_5 demand with such products. Not only would such a restructuring require large investments in new and modified production and distribution facilities, but also, as already mentioned, the increased cost of distributing the lower analysis products would offset most of the environmentally related production cost advantages, as described in Table 12.

In some countries, the current viability of existing or proposed SSP, NPK, and direct application phosphate rock production units is questionable because the more concentrated DAP and TSP products offer economic advantages even though they are imported. Given adoption of increased environmental compliance costs for the more concentrated phosphoric acid-based products, the viability of production units that do not depend upon phosphoric acid will be improved. Under certain conditions, such plants will be more cost effective in supplying local markets when compared with DAP or TSP. This would provide increased opportunities for exploiting indigenous phosphate resources for serving selected local markets.

6.3.1.5 Limited Availability of Foreign Exchange—Compliance with many of the proposed environmental standards will require large investments at the production facilities and thus increase the cost of phosphate fertilizer at all levels. In many cases, the foreign exchange required to finance the necessary investments and/or fertilizer raw material and finished product imports is expected to be lacking. This constraint will be especially critical in those resource-poor countries that depend heavily upon imported raw materials and finished phosphate fertilizers.

6.3.1.6 Marginal Competitive Status Within the Phosphate Fertilizer Industry—The generally depressed state of the phosphate fertilizer industry, with its overcapacity, high capital investment, low returns, and intense competition among the major phosphate-surplus countries, is not conducive to increases in investments and production costs related to environmental compliance. This is not to say that the industry is ignoring its social responsibilities; however, it does acknowledge that commercial realities dictate that least-cost approaches be taken and, thus, the value of many of the proposed environmental initiatives continue to be questioned.

Multilateral enforcement of agreed-upon compliance standards would tend to equalize the increased cost of production among producers. These increased costs would be reflected in increased product prices. This, in turn, would provide the economic incentives required for compliance. Such an approach would, of course, disproportionately increase the burden on the developing country farmer who often can ill afford an increased cost of inputs.

6.3.1.7 Disturbance of Commercial Equilibrium—As described in Chapter 4, the phosphate fertilizer industry is highly integrated at all levels of raw- and intermediate-material supply, production, and marketing. It is especially important to recognize also the role played by fertilizer raw materials, intermediates, and products as a means for payment in international trade for food and other nonfertilizer commodities.

Although very dynamic in the short term, the commercial sector constantly seeks to achieve some sort of "equilibrium" based on local and international supply/demand-driven economic forces.

The difficulty of introducing a major change in the global phosphate fertilizer product mix and its associated raw- and intermediate- material requirements constitutes a major constraint to change. Change is also perhaps more difficult to obtain in the phosphate sector than in the nitrogen and potassium (potash) sectors because phosphate products have more product distinction relative to their solubility and perceived agronomic effectiveness. The optimum phosphate product mix is also closely tied to the cost and availability of ammonia, sulfur, and energy.

The reliance of the majority of the developing countries on imported phosphate raw materials and/or finished products to sustain domestic food production requires an uninterrupted supply of phosphate materials on the international market. Only under conditions where all major international suppliers meet similar competitive standards can the current levels of supply be maintained or increased.

6.3.1.8 Lack of Significant Farm-Level Cost Differences—Even though the indicated incremental cost of environmental compliance is the highest for DAP and TSP, the farm-level delivered cost of P_2O_5 derived from these products is still very competitive with SSP and compound NPKs. The favorable factory-

gate cost advantage of those products less dependent on wet-process phosphoric acid—for example, some NPKs and, of course, SSP, which is totally independent of phosphoric acid—is eroded as the less concentrated products are moved through the distribution system.

The farm-level cost differential between low- and high-analysis phosphate fertilizers will decline as the incremental cost of environmental compliance is added to the high-analysis phosphoric acid-based products. This will increase the break-even distribution distance from any given source of supply for the lower analysis products. Many developing countries still adhere to uniform delivered pricing policies for fertilizers regardless of distance from supply. While helping to ensure widespread use of fertilizer and improvement of soil fertility, this uniformity in pricing distorts the real farm-gate cost and inhibits the marketing of low-analysis products in markets located close to the source of supply. The natural market areas for low-analysis products such as SSP and some NPKs will be increased if pricing policies reflect the true cost of distribution.

6.3.1.9 Restrictive Fertilizer Product Legislation—National and local legislation relative to fertilizer product specifications, including product type, nutrient sources, solubility, and particle-size characteristics, constitutes a major constraint to changing the current fertilizer product mix in many locations. Legislation designed to encourage or protect local or regional production and marketing initiatives can result in product mixes that may actually be detrimental to meeting the agronomic needs of the crop in addition to having an adverse impact on the environment at the level of production and use.

To encourage, where economically appropriate, changes in product mix towards less soluble phosphate forms (less dependency upon phosphoric acid), there is a need to amend fertilizer legislation in many countries so that all agronomically suitable sources of phosphate can be used by farmers without penalty. Many developing countries providing production or end-user subsidies for phosphate fertilizers restrict eligibility for such subsidies by specifying the product type, nutrient source, and water-soluble P_2O_5 content. Unless such restrictions are removed, the use of less water-soluble products, even though they may be agronomically effective and less costly, will be constrained.

6.3.1.10 Difficulty in Changing Farmers' Practices—In addition to the cost-related constraints affecting manufacturing and distribution, farm-level fertilizer use practices must also be considered. In most developing countries, effective farm-level extension programs are woefully lacking. Thus, when considering a change from one fertilizer product type or use practice to another, it is most important to evaluate the results of such change in the context of farm-level benefit/cost criteria under actual farming conditions. Because reliable benefit/cost data are often lacking, it is difficult to develop a convincing case for using any type of fertilizer let alone changing or tailoring the product type to reflect a more environmentally optimum mix of products.

An environmentally sustainable phosphate industry can only be achieved at an additional cost. This cost will undoubtedly be initially borne by the farmer, but it will ultimately be transferred to the consumer of agricultural products if fertilizer use and crop production are to be maintained or increased. In developed economies this does not pose a major problem; however, in the developing countries, characterized by resource-poor farmers and large and poor urban populations, considerable problems arise. In those developing countries where farm prices have been kept below international parity prices, there is a need for progressive increases in farm prices to achieve parity in order to provide sufficient benefit/cost ratio incentives for farmers and thus ensure and promote the use of the more costly, but more environmentally benign, fertilizers. Unless developing countries with low-cost food policies increase crop prices to maintain farmer benefits, food crop production will decline, adding to the problem of food security.

Partial resolution for the problem of increased phosphate fertilizer costs at the farm level lies in improving phosphate fertilizer use efficiency. It is therefore essential that a high priority be given to programs that will assist developing countries in improving use efficiency of phosphate fertilizers through improved application methods and the use of integrated nutrient management systems.

7. SUMMARY OF THE ISSUES

The foregoing analysis of the global phosphate fertilizer sector suggests the need to resolve the following issues with respect to addressing the environmental pressures on the one hand and maintaining agricultural productivity on the other.

- Phosphate fertilizer is essential to crop production. The removal of phosphate from the soil in the form of harvested crops, which are marketed elsewhere, minimizes the level of phosphate recycling that can be accomplished by the return of crop residues and animal manure. Thus, the supply of phosphate

fertilizers in an environmentally sustainable manner must be assured.

- The current phosphate fertilizer product mix, in which about 70% of the total P_2O_5 is derived from wet-process phosphoric acid, is the most cost effective at the farm level. From an agronomic point of view, these highly water-soluble phosphate fertilizers are not required for most crop production; however, because they are so concentrated they continue to provide the most cost effective source of P_2O_5 at the farm level even if the current cost of phosphoric acid is increased by as much as 50% to cover the estimated added cost of complying with the most rigorous environmental regulatory scenarios described in this paper.
- Products that are less dependent upon wet-process phosphoric acid (nitrophosphate-based NPKs and SSP, for example) have a more favorable cost per unit of P_2O_5 at the factory gate. However, because of their lower nutrient concentration and, in some cases, their unfavorable companion nutrient content (for example, nitrate nitrogen for flooded rice), they become less competitive with the ammonium phosphate and TSP products in the overall marketing system.
- In some cases, products that require little or no phosphoric acid, for example, direct application phosphate rock, PAPR, and SSP, have an environmental and economic advantage. When this occurs and the agronomic needs are met, then the feasibility of producing, or even importing, such products for local consumption is enhanced.
- The global phosphate fertilizer production industry is faced with an increasing level of environmental concerns that are gradually being formulated into legislation at local and national levels. A convincing scientific rationale for some of the environmental concerns and legislative initiatives is sometimes lacking or overlooked in the public debate. At present there is no clear definition of what constitutes "environmental acceptability" or "environmental sustainability" in the phosphate fertilizer production sector. There is an urgent need for a more clear definition of both terms as they are applied to the production sector.
- Wet-process phosphoric acid currently accounts for about 70% of world P_2O_5 consumption in the form of DAP/MAP, TSP, and NPKs. The cost-effective production of wet-process phosphoric acid by certain producers will be threatened if the cost of treatment and disposal of process wastes, primarily phosphogypsum and contaminated process water, is unilaterally escalated as a result of certain environmental-compliance legislation currently under study. This suggests the need for scientifically based, multilateral compliance legislation that is applied uniformly. This approach, however, runs the risk of deterring economic growth, especially in resource-poor developing countries.
- Unilateral legislation and enforcement of environmental initiatives at the national and local levels will restrict competition in national and international markets. This will result in windfall profits for noncompliant producers and an increase in the farm-level price of phosphate fertilizers without achieving the global objective of environmental sustainability.
- Despite the lack of total agreement on the scientific rationale, it is quite apparent that the phosphate fertilizer producers will face increased costs as they strive to comply with a number of new environmental legislative initiatives that are likely to be implemented in the near term on a widespread basis. These increased costs of production will result in a significant increase in the farm-level cost of fertilizer. While the impact of increased costs can be more easily borne in the developed countries, it could be a major constraint to productivity in many of the resource-poor countries of the world where fertilizer use is already small and the need for increased local food production is paramount. Thus, methods need to be formulated to help finance the increased costs attributed to achieving greater environmental sustainability in the phosphate fertilizer production sector without adversely affecting international trade and economic development.
- A more quantitative analysis is needed to determine the impact that an increase in the cost of phosphate fertilizers at the factory gate and the farm gate would have upon the farm-level benefit/cost ratio and, therefore, phosphate fertilizer demand and crop production.
- Achievement of environmental sustainability in the phosphate fertilizer production sector, as defined by public opinion more so than scientific criteria, will require the widespread deployment of the practical and intellectual resources of the global industrial and agricultural communities.

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APPENDIX A

Regional Production, Consumption, and
Trade Data for Sulfur, Phosphate Concentrate,
Wet-Process Phosphoric Acid, and Finished Phosphate Products

Table A-1. Production and Trade of Sulfur in All Forms (1988)[a]

Origin (Region/Country)	Domestic Production	Domestic Consumption	Exports	Export Recipient (Region/Country): Western Europe	Eastern Europe	Former Soviet Union	North America	Central America	South America	North Africa	Sub-Saharan Africa	South Africa	West Asia	South Asia	East Asia	China	Oceania
	(thousand t sulfur)																
Western Europe	8,360	6,848	1,512	1,229	6					224	30		21				
Eastern Europe	6,405	2,488	3,917	1,032	978	748			430	601			36		95		
Former Soviet Union	11,081	10,771	310	10	265										35		
North America	17,744	9,102	8,642	749			915	538	1,069	2,529	154	501	259	204	1,049	20	656
Central America	2,366	634	1,732		74		1,077		18	496	6		61				
South America	825	775	50						50								
North Africa	184	184	0														
Sub-Saharan Africa	91	91	0														
South Africa	813	813	0														
West Asia	4,019	939	3,080	344	18	60		77	2	827	62		328	1,309	53		
South Asia	26	26	0														
East Asia	3,439	3,275	164												164		
China	4,863	4,863	0														
Oceania	286	286	0														
Subtotal	60,502	41,095	19,407	3,364	1,341	808	1,992	615	1,569	4,677	252	501	705	1,513	1,396	20	656
Domestic Deliveries				6,848	2,488	10,771	9,102	634	775	184	91	813	939	26	3,275	4,863	286
Total Supply (60.50 million t)				10,212	3,829	11,579	11,094	1,249	2,344	4,861	343	1,314	1,644	1,539	4,671	4,883	942
Regional Dependency on Imports (%)				33	35	7	18	49	67	96	74	38	43	98	30	0	70

a. Deliveries (domestic consumption plus exports) may not match domestic production due to changes in inventories.

Source: Derived from published statistical data and IFDC data file.

Table A-2. Production and Trade of Phosphate Rock Concentrate (1988)[a]

Origin (Region/Country)	Domestic Production	Domestic Consumption	Exports	Export Recipient (Region/Country): Western Europe	Eastern Europe	Former Soviet Union	North America	Central America	South America	North Africa	Sub-Saharan Africa	South Africa	West Asia	South Asia	East Asia	China	Oceania
	(thousand t P_2O_5)																
Western Europe	253	206	47	47													
Eastern Europe																	
Former Soviet Union	12,010	11,004	992	360	630			2									
North America	14,327	12,672	2,853	1,043	173		375	187	2					123	812		138
Central America	201	193															
South America	1,718	1,599															
North Africa	10,394	5,361	5,213	2,601	1,186		245	363	62				60	126	325	85	160
Sub-Saharan Africa	2,132	247	1,710	636	184		310		17		1		47	164	303		49
South Africa	1,102	836	480	480													
West Asia	4,057	1,184	3,135	899	871	7			11				295	452	541	15	44
South Asia	213	208															
East Asia	293	293															
China	4,050	4,150															
Oceania	594	2	593												38		555
Subtotal	51,344	37,955	15,023	6,066	3,044	7	930	552	92	0	1	0	402	865	2,019	100	946
Domestic Deliveries				206	0	11,004	12,672	193	1,599	5,361	247	836	1,184	208	293	4,150	2
Total Supply (52.98 million t)				6,272	3,044	11,011	13,602	745	1,691	5,361	248	836	1,586	1,073	2,312	4,250	948
Regional Dependency on Imports (%)				97	100	0	7	74	5	0	0	0	25	81	87	2	100

a. Deliveries (domestic consumption plus exports) may not match domestic production due to changes in inventories.

Source: Derived from U.S. Bureau of Mines and IFDC statistical data.

Table A-3. Production and Trade of Wet-Process Phosphoric Acid (1988)[a]

Origin (Region/Country)	Domestic Production	Domestic Consumption	Exports	Export Recipient (Region/Country): Western Europe	Eastern Europe	Former Soviet Union	North America	Central America	South America	North Africa	Sub-Saharan Africa	South Africa	West Asia	South Asia	East Asia	China	Oceania
	(thousand t P_2O_5)																
Western Europe	3,116	2,343	773	501	71	147	2		3				9	21	17		
Eastern Europe	1,316	1,316															
Former Soviet Union	4,990	4,990															
North America	10,507	9,632	875	2		639			66					120	30		17
Central America	474	474															
South America	763	763															
North Africa	3,898	1,668	2,230	436	44				117		31		222	1,232	122		28
Sub-Saharan Africa	189	41	148											148			
South Africa	576	323	253	73					81				99				
West Asia	1,019	924	95	76									19				
South Asia	376	376															
East Asia	1,261	1,207	54											18	36		
China	50	50															
Oceania	108	108															
Subtotal	28,643	24,215	4,428	1,088	115	786	2	0	267	0	31	0	349	1,539	205	0	45
Domestic Deliveries				2,343	1,316	4,990	9,632	474	763	1,668	41	323	924	376	1,207	50	108
Total Supply (28.64 million t)				3,431	1,431	5,776	9,634	474	1,030	1,668	72	323	1,273	1,915	1,412	50	153
Total Consumption (27.98 million t)				3,434	1,430	5,220	9,539	474	1,031	1,668	72	323	1,267	1,901	1,412	50	153
Nonfertilizer Use (1.90 million t)				640	48	200	546	15	160	0	0	13	17	31	200	15	14
Fertilizer Use (26.08 million t)				2,794	1,382	5,020	8,993	459	871	1,668	72	310	1,250	1,870	1,212	35	139
Phosphoric Acid Expressed as % of Total Regional Fertilizer P_2O_5 Production[b]				64.2	48.9	54.4	89.9	113.1	57.8	85.4	66.7	80.7	85.0	76.2	56.2	1.0	13.6
Regional Dependency on Phosphoric Acid Imports (%)				31.7	8.0	13.6	0.0	0.0	25.9	0.0	43.1	0.0	27.4	80.4	14.5	0.0	29.4
Regional Dependancy on Inter-Regional Phosphoric Acid Imports (%)				17.1	8.0	13.6	0.0	0.0	25.9	0.0	43.1	0.0	25.9	80.4	12.0	0.0	29.4

a. Deliveries (domestic consumption plus exports) may not match domestic production due to changes in inventories.
b. Value in excess of 100% due to variations in reporting data.

Source: Derived from British Sulphur Corporation Ltd. and other published statistical data.

Table A-4. Production and Trade of Ammonium Phosphates (DAP/MAP) (1988)[a]

Origin (Region/Country)	Domestic Production	Domestic Consumption	Exports	Export Recipient (Region/Country): Western Europe	Eastern Europe	Former Soviet Union	North America	Central America	South America	North Africa	Sub-Saharan Africa	South Africa	West Asia	South Asia	East Asia	China	Oceania
	(thousand t P_2O_5)																
Western Europe	38	38	112	9			8				21			26	48		
Eastern Europe	210	177	33		33												
Former Soviet Union	3,365	3,365	0		0												
North America	8,680	5,570	3,110	277	26		225	82	311		30		425	533	269	845	87
Central America	186	167	19					19									
South America	364	347	17						17								
North Africa	909	149	760	445	85			6		12	17		47			135	13
Sub-Saharan Africa	63	45	18	18													
South Africa	95	19	76	58									18				
West Asia	458	0	458	107	32		24	4			40		129	98	24		
South Asia	1,445	1,445	0														
East Asia	323	112	211										30		51	130	
China	0	0	0														
Oceania	99	99	0														
Subtotal	16,235	11,533	4,814	914	176	0	257	111	328	12	108	0	649	657	392	1,110	100
Domestic Deliveries				38	177	3,365	5,570	167	347	149	45	19	0	1,445	112	0	99
Total Supply (14.64 million t)				952	353	3,365	5,827[b]	278	675	161	153	19	649	2,102	504	1,110	199
Total Consumption (11.57 million t)				584	258	3,272	3,424	237	601	61	111	28	634	2,085	364	1,110	222
DAP/MAP Expressed as % of Total Regional P_2O_5 Production[c]				0.9	0.0	36.4	86.8	45.8	24.1	46.5	58.3	24.7	31.1	58.9	15.0	0.0	9.7
DAP/MAP Expressed as % of Total Regional P_2O_5 Consumption[c]				11.4	9.6	38.2	78.6	39.4	28.3	13.8	32.4	8.8	44.5	61.0	15.9	22.5	18.9

a. Deliveries (domestic consumption plus exports) may not match domestic production due to changes in inventories.
b. Assumed to include increased stocks destined for export.
c. DAP/MAP account for 39.1% of world total P_2O_5 production and 30.6% of total P_2O_5 consumption.

Source: Derived from published British Sulphur Corporation Ltd., FAO statistical data, and IFDC data file.

Table A-5. Production and Trade of Triple Superphosphate (TSP) (1988)[a]

Origin (Region/Country)	Domestic Production	Domestic Consumption	Exports	Export Recipient (Region/Country): Western Europe	Eastern Europe	Former Soviet Union	North America	Central America	South America	North Africa	Sub-Saharan Africa	South Africa	West Asia	South Asia	East Asia	China	Oceania
	(thousand t P_2O_5)																
Western Europe	469	293	176	101	10				12		11		23	19			
Eastern Europe	430	354	76			76											
Former Soviet Union	840	840	0														
North America	886	431	455		7		68	10	157					153	31		29
Central America	100	100	0														
South America	402	395	7						7								
North Africa	850	155	695	236	65	79	48	5	11	1	9		81	77		78	5
Sub-Saharan Africa	28	24	4	3							1						
South Africa	0	0	0														
West Asia	720	220	500	95	109	134		5	7	4	10		123	13			
South Asia	66	66	0														
East Asia	582	570	12												12		
China	80	80	0														
Oceania	54	54	0														
Subtotal	5,507	3,582	1,925	435	191	289	116	20	194	5	31	0	227	262	43	78	34
Domestic Deliveries				293	354	840	431	100	395	155	24	0	220	66	570	80	54
Total Supply (5.48 million t)				728	545	1,129	547	120	589	160	55	0	447	328	613	158	88
Total Consumption (4.87 million t)				603	477	840	545	116	592	143	14	0	332	279	612	158	68
TSP Expressed as % of Total Regional P_2O_5 Production[b]				10.8	0.0	9.1	8.9	24.6	26.7	43.5	25.9	0.0	48.9	2.7	27.0	2.2	5.3
TSP expressed as % of Total Regional P_2O_5 Consumption[b]				11.7	17.8	9.8	12.5	19.3	27.9	32.4	4.1	0.0	23.3	8.2	26.7	3.2	5.8

a. Deliveries (domestic consumption plus exports) may not match domestic production due to changes in inventories.
b. TSP accounts for 13.3% of total world P_2O_5 production and 12.9% of total P_2O_5 consumption.

Source: Derived from published FAO statistical data and IFDC data file.

Table A-6. Production and Trade of Single Superphosphate (SSP) (1988)[a]

Origin (Region/Country)	Domestic Production	Domestic Consumption	Exports	Export Recipient (Region/Country): Western Europe	Eastern Europe	Former Soviet Union	North America	Central America	South America	North Africa	Sub-Saharan Africa	South Africa	West Asia	South Asia	East Asia	China	Oceania
	(Thousand t P_2O_5)																
Western Europe	442	424	18	18													
Eastern Europe	1,008	999	9		9												
Former Soviet Union	1,035	937	98		36			53	9								
North America	72	68	4				4										
Central America	53	53	0														
South America	423	423	0														
North Africa	168	168	0														
Sub-Saharan Africa	15	15	0														
South Africa	40	40	0														
West Asia	20	11	9								2		7				
South Asia	496	496	0														
East Asia	310	310	0														
China	2,220	2,220	0														
Oceania	781	770	11														11
Subtotal	7,083	6,934	149	18	45	0	4	53	9	0	2	0	7	0	0	0	11
Domestic Deliveries				424	999	937	68	53	423	168	15	40	11	496	310	2,220	770
Total Supply (7.08 million t)				442	1,044	937	72	106	432	168	17	40	18	496	310	2,220	781
Total Consumption (6.44 million t)				333	879	700	70[b]	105	427	168	5	40	4	545	236	2,220	777
SSP Expressed as % of Total Regional P_2O_5 Production[c]				10.2	0.0	11.2	0.7	13.1	28.1	8.6	13.9	10.4	1.4	20.2	14.4	61.5	76.2
SSP expressed as % of Total Regional P_2O_5 Consumption[c]				6.5	32.7	8.2	1.6	17.5	20.1	38.0	1.5	12.6	0.3	15.9	10.3	44.9	66.1

a. Deliveries (domestic consumption plus exports) may not match domestic production due to changes in inventories.
b. The majority of this consumption is used to produce granular NPKs.
c. SSP accounts for 17% of total world P_2O_5 production and consumption.

Source: Derived from published FAO statistical data and IFDC data file.

Table A-7. Production and Trade of NPK Fertilizers (1988)[a,b]

Origin (Region/Country)	Domestic Production	Domestic Consumption	Exports	Export Recipient (Region/Country): Western Europe	Eastern Europe	Former Soviet Union	North America	Central America	South America	North Africa	Sub-Saharan Africa	South Africa	West Asia	South Asia	East Asia	China	Oceania
	(thousand t P_2O_5)																
Western Europe	2,953	1,380	1,573	1,009				35	115		167		127	46	70		4
Eastern Europe	735	310	425	233	70								122				
Former Soviet Union	1,855	1,810	45		45												
North America	288	264	24					24									
Central America	65	61	4					4									
South America	199	199	0														
North Africa	27	27	0														
Sub-Saharan Africa	2	0	3								3						
South Africa	224	224	0														
West Asia	262	208	54	47						4			3				
South Asia	411	411	0														
East Asia	798	629	169											55	114	0	
China	307	307	0														
Oceania	91	91	0														
Subtotal	8,217	5,921	2,297	1,289	115	0	0	63	115	4	170	0	252	101	184	0	4
Domestic Deliveries				1,380	310	1,810	264	61	199	27	0	224	208	411	629	307	91
Total Supply (8.22 million t)				2,669	425	1,810	264	124	314	31	170	224	460	512	813	307	95
Total Consumption (10.88 million t)				3,313	665	1,632	264[c]	133	383	71	213	224	455	465	904	334	80
NPKs Expressed as % of Total Regional P_2O_5 Production[d]				67.8	0.0	20.1	2.9	16.0	13.2	1.4	1.9	58.3	17.8	16.8	37.0	8.5	8.9
NPKs Expressed as % of Total Regional P_2O_5 Consumption[d]				64.6	24.8	19.1	6.1	22.1	18.0	16.1	62.1	70.7	32.0	13.6	39.5	6.8	6.8

a. Deliveries (domestic consumption plus exports) may not match domestic production due to changes in inventories.
b. Does not include physically mixed (bulk blended) products.
c. This value does not include P_2O_5 derived from SSP which is shown separately in Table A-6.
d. NPKs are reported to account for about 20% of total world P_2O_5 production and about 29% of total P_2O_5 consumption. Large difference is due to method of reporting P_2O_5 raw material sources used to produce NPKs.

Source: Derived from published FAO statistical data and IFDC data file.

Table A-8. Production and Trade of Other Phosphate Fertilizers (OPF) (1988)[a,b]

Origin (Region/Country)	Domestic Production	Domestic Consumption	Exports	Export Recipient (Region/Country): Western Europe	Eastern Europe	Former Soviet Union	North America	Central America	South America	North Africa	Sub-Saharan Africa	South Africa	West Asia	South Asia	East Asia	China	Oceania
	(thousand t P_2O_5)																
Western Europe	204	202	2	2													
Eastern Europe	440	440	0														
Former Soviet Union	1,300	1,169	131	8			22									101	
North America	37	37	0														
Central America	0	0	0														
South America	50	50	0														
North Africa	0	0	0														
Sub-Saharan Africa	0	0	0														
South Africa	25	25	0														
West Asia	0	0	0														
South Asia	0	0	0														
East Asia	132	132	0														
China	700	700	0														
Oceania	0	0	0														
Subtotal	2,888	2,755	133	10	0	0	22	0	0	0	0	0	0	0	0	101	0
Domestic Deliveries				202	440	1,169	37	0	50	0	0	25	0	0	132	700	0
Total Supply (4.66 million t)				212	440	1,169	59	0	50	0	0	25	0	0	132	801	0
Total Consumption (2.50 million t)				120	408	902	41	10	383	0	0	25	0	0	132	818	0
OPFs Expressed as % of Total Regional P_2O_5 Production[c]				4.7	0.0	14.1	0.4	0.0	3.3	0.0	0.0	6.5	0.0	0.0	6.1	19.4	0.0
OPFs Expressed as % of Total Regional P_2O_5 Consumption[c]				2.3	15.2	10.5	0.9	1.7	18.0	0.0	0.0	7.9	0.0	0.0	5.8	16.6	0.0

a. Deliveries (domestic consumption plus exports) may not match domestic production due to changes in inventories.
b. OPFs include thermophosphates, fluid fertilizers, bone meal, and miscellaneous other products.
c. OPFs reported to account for 7.0% of total world P_2O_5 production and 6.6% of total P_2O_5 consumption.

Source: Derived from published FAO statistical data and IFDC data file.

Table A-9. Production and Trade of Direct Application Phosphate Rock (DAPR) (1988)[a]

Origin (Region/Country)	Domestic Production	Domestic Consumption	Exports	Export Recipient (Region/Country)[b]: Western Europe	Eastern Europe	Former Soviet Union	North America	Central America	South America	North Africa	Sub-Saharan Africa	South Africa	West Asia	South Asia	East Asia	China	Oceania
	(thousand t P_2O_5)																
Western Europe	90	90	0														
Eastern Europe	0	0	0														
Former Soviet Union	795	795	0														
North America	0	0	31														31
Central America	0	0	0														
South America	66	57	9														
North Africa	0	0	0														
Sub-Saharan Africa	0	0	0														
South Africa	0	0	0														
West Asia	12	0	12														
South Asia	36	36	0														
East Asia	11	11	0														
China	300	300	0														
Oceania	0	0	0														
Subtotal	1,310	1,289	52	4	0	0	0	0	0	0	0	0	0	0	0	0	31
Domestic Deliveries				90	0	795	0	0	57	0	0	0	0	36	11	300	0
Total Supply (1.33 million t)				94	0	795	0	0	57	0	0	0	0	36	11	300	31
Total Consumption (1.33 million t)				28	0	805	0	0	84	0	0	0	12	43	40	300	30
DAPR Expressed as % of Total Regional P_2O_5 Production[c]				2.1	0.0	8.6	0.0	0.0	4.4	0.0	0.0	0.0	0.8	1.5	0.5	8.3	0.0
DAPR Expressed as % of Total Regional P_2O_5 Consumption[c]				0.5	0.0	9.4	0.0	0.0	4.0	0.0	0.0	0.0	0.8	1.3	1.7	6.1	2.6

a. Deliveries (domestic consumption plus exports) may not match domestic production due to changes in inventories.
b. Data on export deliveries not fully reported.
c. DAPR accounts for 3.2% of total world P_2O_5 production and 3.5% of total P_2O_5 consumption.

Source: Derived from published FAO statistical data and IFDC data file.

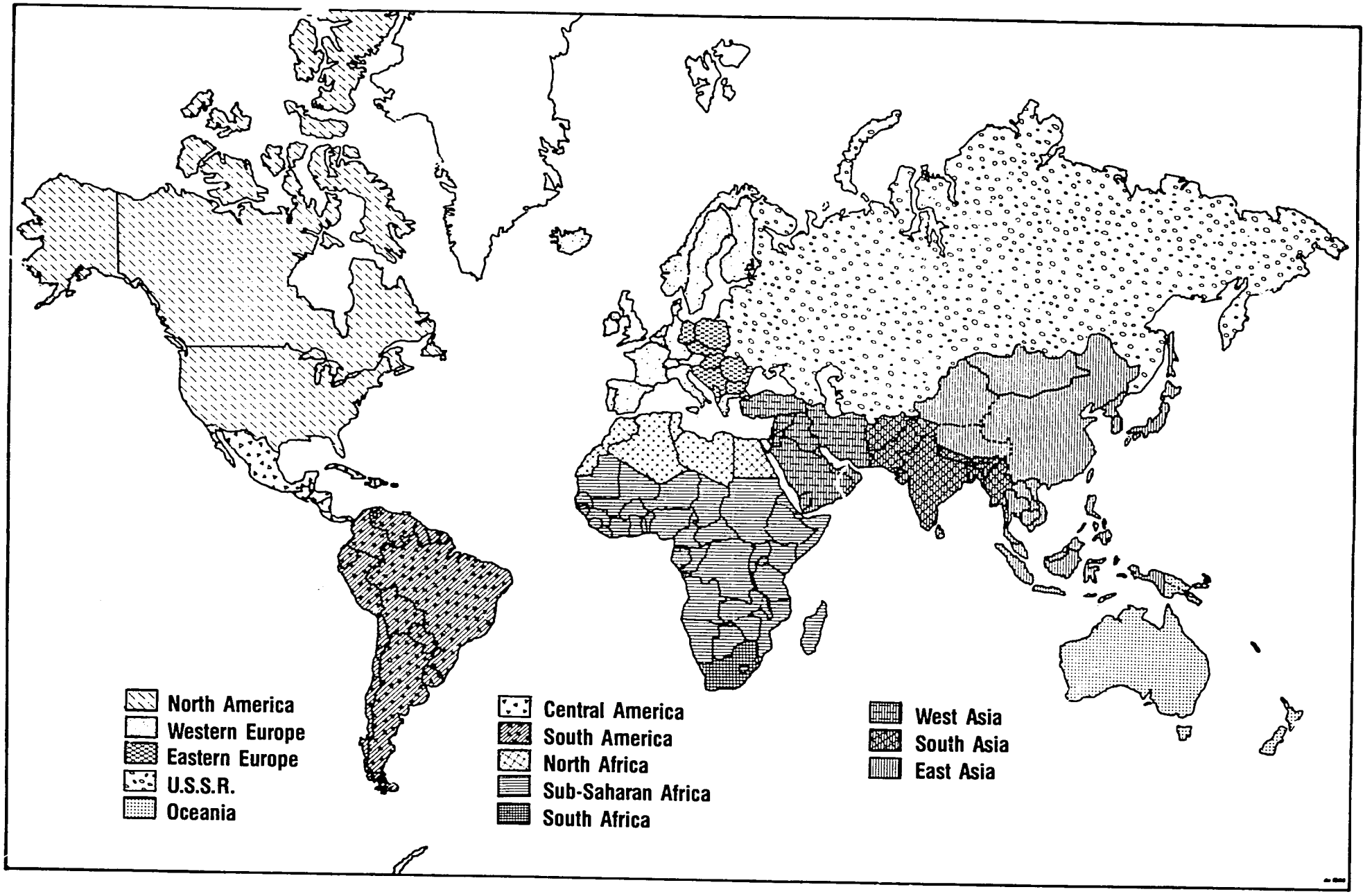
APPENDIX B

Regional Classification of Countries
Regional Map

Regional Classification of Countries

North America	Western Europe	Eastern Europe	U.S.S.R.[b]	Africa		Latin America	Asia	Oceania
Canada	Austria	Albania	U.S.S.R.	*Sub-Saharan Africa*	*South Africa*	*Central America*	*West Asia*	Australia
United States[a]	Belgium-Lux	Bulgaria		Angola	Republic of South Africa	Bahamas	Afghanistan	New Zealand
	Denmark	Czechoslovakia		Benin		Barbados	Bahrain	Papua New Guinea
	Finland	Hungary		Botswana	*North Africa*	Belize	Cyprus	Samoa
	France	Poland		Burkina Faso	Algeria	Bermuda	Iran	Fiji
	Germany DR	Romania		Burundi	Egypt	Costa Rica	Iraq	
	Germany FR	Yugoslavia		Cameroon	Libya	Cuba	Israel	
	Greece			Central African Republic	Morocco	Dominica	Jordan	
	Iceland			Chad	Tunisia	Dominican Republic	Kuwait	
	Ireland			Congo		El Salvador	Lebanon	
	Italy			Cote d'Ivoire		Guadeloupe	Oman	
	Malta			Ethiopia		Guatemala	Qatar	
	Netherlands			Gabon		Haiti	Saudi Arabia	
	Norway			Gambia		Honduras	Syria	
	Portugal			Ghana		Jamaica	Turkey	
	Spain			Guinea Bissau		Martinique	United Arab Emirates	
	Sweden			Guinea		Mexico	Yemen Arab R	
	Switzerland			Kenya		Nicaragua	Yemen Dem	
	United Kingdom			Lesotho		Panama	*South Asia*	
				Liberia		St. Chris, etc.	Bangladesh	
				Madagascar		Saint Lucia	Bhutan	
				Malawi		St. Vincent	India	
				Mali		Trinidad, etc.	Nepal	
				Mauritania		Virgin Islands	Pakistan	
				Mauritius		*South America*	Sri Lanka	
				Mozambique		Argentina	*East Asia*	
				Niger		Bolivia	Cambodia	
				Nigeria		Brazil	China	
				Rwanda		Chile	Indonesia	
				Senegal		Colombia	Japan	
				Seychelles		Ecuador	Laos	
				Sierra Leone		French Guiana	Malaysia	
				Somalia		Guyana	Mongolia	
				Sudan		Paraguay	Myanmar	
				Swaziland		Peru	Korea, DPR	
				Tanzania		Suriname	Korea, Republic	
				Togo		Uruguay	Philippines	
				Uganda		Venezuela	Singapore	
				Zaire			Taiwan	
				Zambia			Thailand	
				Zimbabwe			Viet Nam	

Developed Countries - Includes North America, Western Europe, Eastern Europe, U.S.S.R., Japan, Israel, South Africa, Australia, and New Zealand.
Developing Countries - Includes Latin America, Asia (except Japan and Israel), Africa (except South Africa), and Oceania (except Australia and New Zealand).
a. Includes Puerto Rico.
a. Refers to the former Soviet Union.



Regional Map