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Water Solubility of Phosphate Fertilizers: Agronomic Aspects- A Literature Review

IFDC International Fertilizer Development Center

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Foreword

Phosphate fertilizer solubility requirements have a major impact upon the choice of manufacturing technology used to process phosphate-bearing minerals into useful fertilizer products. Currently, about 95% of all phosphate rock (concentrate) is processed to increase its solubility. To achieve this objective, phosphoric acid is the major intermediate product produced from the concentrate. The phosphoric acid is further processed into a number of finished products that usually exhibit a high level of water solubility, typically in the range of 80%-90%. About 70% of all phosphate fertilizers are produced using variations of this phosphoric acid-based technique.

Calcium is the most significant impurity in the phosphate ore; in the phosphoric acid process, it is removed as hydrated calcium sulfate commonly referred to as phosphogypsum. About 5 tons of phosphogypsum is produced for each ton of P_2O_5 produced in the form of phosphoric acid. The procedures used for managing this large amount of phosphogypsum together with its associated process water are not only costly but also the subject of a number of environmental concerns.

The phosphoric acid-based products are effective from an agronomic viewpoint and, because they are very concentrated with respect to nutrient content, are usually more cost-effective at the farm level than less soluble products that are less dependent upon phosphoric acid.

This review, with commentary, was prepared to examine the agronomic merits of phosphate water solubility and attempt to answer the question—How much is enough? As such, it provides further agronomic support to a complementary IFDC publication entitled *Phosphate Fertilizers and the Environment--A Discussion Paper.*

James J. Schultz
International Fertilizer Development Center

Preface

The purpose of this paper is to assess the agronomic aspects of the water solubility of solid phosphate fertilizers. Included is a discussion of the more important soil, crop, fertilizer management, and climatic factors that affect plant response to the level of water solubility of applied phosphate fertilizers. It should be recognized that, in view of the interacting variables involved, predicting the agronomic need for water-soluble phosphorus for a given crop/soil/climatic situation is, at best, a subjective judgment, unless extensive field experiments have been done in each particular environment/farming system.

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Water Solubility of Phosphate Fertilizers: Agronomic Aspects—A Literature Review

Introduction

Phosphorus Solubility in Fertilizers

Water-soluble phosphorus in fertilizers, i.e., the portion that is soluble in water, can be expressed as a percentage of either the "available" (as defined below) or the total phosphorus content. In this paper, water-soluble phosphorus is expressed as a percentage of the total phosphorus content; however, in some of the literature cited in this review, water-soluble phosphorus is expressed as a percentage of the available phosphorus. For most commercially processed phosphates, the difference is not great. Only where there is a substantial amount of insoluble phosphate will the difference be significant.

"Available" phosphorus is often defined as the proportion of the total phosphorus in the fertilizer that is potentially available to the crop. This is estimated using various extractants. In the United States, available phosphorus is determined by using a neutral ammonium citrate solution to extract the residue from the water-soluble phosphorus determination (AOAC, 1984). This is often referred to as citrate-soluble phosphorus and will be so expressed for the purpose of this discussion. In other countries, solutions of citric or formic acid are used. These methods, at best, give approximations of the phosphorus that can be used by the crop. Yet, an orderly fertilizer marketing system requires some guarantee of quality in the product; thus, such solubility criteria are useful for commercial purposes.

It should be recognized that the proportions of citrate-soluble and citrate-insoluble phosphorus can vary in the non-water-soluble fraction of the phosphate in fertilizer. It is assumed that most chemically processed phosphates such as ammonium phosphates have a relatively low content of citrate-insoluble phosphorus; however, phosphate rock and partially acidulated phosphate rock have a much higher proportion of phosphorus in citrate-insoluble form. In those situations where phosphate rock for direct application or partially acidulated phosphate rock is of value, water-soluble phosphorus is not generally an overriding issue. In this review, where the level of water solubility is important, the water-insoluble phosphate is regarded as being low in citrate-insoluble phosphate and high in citrate-soluble phosphate.

Some phosphate rocks contain significant amounts of impurities that lower the water-soluble phosphorus content in the processed product, whether it be superphosphate or monoammonium phosphate. Sikora et al. (1989) and Mullins and Sikora (1990) found that such decreases in water solubility were not great enough to affect agronomic performance. However, most of the water-solubility levels tested in these studies were in the range of 80% to 100% of the available phosphorus.

The nature of the water-insoluble fraction in the fertilizer becomes more important as the percentage of water-soluble phosphorus declines. Govil and Prasad (1972) found that sorghum yield response to phosphorus declined when the water solubility was below 50% in triple superphosphate/dicalcium phosphate mixtures and below 75% in triple superphosphate/phosphate rock mixtures. The difference in these cases can be explained in terms of the nature of the water-insoluble fraction. Dicalcium phosphate has a higher citrate-soluble fraction and greater phosphorus availability compared with phosphate rock.

Those phosphates that are of low water solubility but of varying citrate solubility, such as phosphate rock and partially acidulated phosphate rock, dissolve quite slowly in soil. Dissolution occurs in very thin surface "layers" around the fertilizer particle; movement of phosphorus away from the particle site is also minimal in such cases.

Phosphorus Solubility in the Soil

Single superphosphate (SSP) and tripie superphosphate (TSP) contain water-soluble monocalcium phosphate; ammonium phosphates contain water-soluble mono- and diammonium phosphates (MAP and DAP). When applied to the soil, these water-soluble phosphates react with soil components to form reaction products of lower water solubility. This process, called phosphorus fixation or retention, has been studied quite thoroughly over the years.

With water-soluble phosphates, the initial reactions between the fertilizer solution and the soil occur quite rapidly; further reactions occur over a much longer period of time. The nature of the reaction products varies according to the soil pH (acidity or alkalinity). In acid soils, complex iron and aluminum phosphates predominate; in calcareous soils, first dicalcium phosphate forms, and later octacalcium phosphate. In each case, the solubility of the reaction products formed is significantly lower than that of the water-soluble phosphate applied in the fertilizer. Correspondingly, the concentration of phosphorus in the soil solution declines as reaction products of lower solubility form.

Even with the use of water-soluble phosphatic fertilizers, phosphorus is rapidly converted to forms of low solubility in many soils, and is regarded as being quite immobile. Young et al. (1985) stated that phosphorus moves only 2-3 cm from a fertilizer particle. This has two important consequences. First, phosphatic fertilizers need to be distributed throughout the soil volume exploited by the majority of the root system. Second, in many soils phosphorus derived from fertilizers is retained in the cultivated soil layer. Results (Johnston, 1976; Johnston and Poulton, 1992) showed that after more than 125 years of annual applications of superphosphate applying 33 kg P/ha to a silty clay loam low in organic matter and growing arable crops, there was little P enrichment of soil below 30 cm. However, P had leached below this depth where superphosphate had been applied to permanent grassland. Where farmyard manure had been applied, subsoils had also been enriched with P (Table 1). Apparently, the movement of P was linked with organic matter. Concentrations of P in 0.01 M $CaCl_2$ extracts of soils were much larger from highly organic soils than from soils low in organic matter. The phosphorus in these extracts was probably in organic compounds of low molecular weight, and it may well be that these are readily leached from soil (Johnston and Poulton, 1992). An important exception to this generalization is the downward movement of P on very sandy soils, but even in this case P may be retained in clay-enriched subsoils.

Only about 10% to 20% of applied phosphorus is taken up by the first crop.

Table 1. Total Phosphorus (mg/kg) in Soil at Different Depths Where Superphosphate or Farmyard Manure Was Applied to Surface Soils at pH 6.5

	Soil Type and P Treatment[a]				
	Silty Clay Loam				
	Arable Crops			Permanent Grassland	
Soil Depth (cm)	None	SP	FYM	None	SP
0-23	780	1,295	1,375	575	1,425
23-30	465	525	650	555	785
30-46	415	450	525	500	600
Below 46	400	395	440	-	-

a. SP = superphosphate, FYM = farmyard manure.

The remainder contributes to building up soil reserves. In most soils, these reserves provide significant amounts of phosphorus to the crop in spite of the loss in water solubility that takes place in the soil after application.

Currently there is no universally reliable method to estimate the size of these soil phosphorus reserves. Many different chemical extractants have been used in an attempt to obtain an indication of their magnitude. The principle adopted is to relate an amount of extracted phosphorus to the crop response to freshly applied phosphate fertilizer. Because so many extractants are used, the term "readily soluble phosphorus" will be used here for this category of soil phosphorus.

Phosphorus added to soil in the form of fertilizers or as organic manures appears to be held in soil as phosphate ions on sites with varying bonding energies. Reagents to determine readily soluble phosphorus remove phosphate from sites with low bonding energies. However, phosphate held on sites with high bonding energies will become available to crops in the long term.

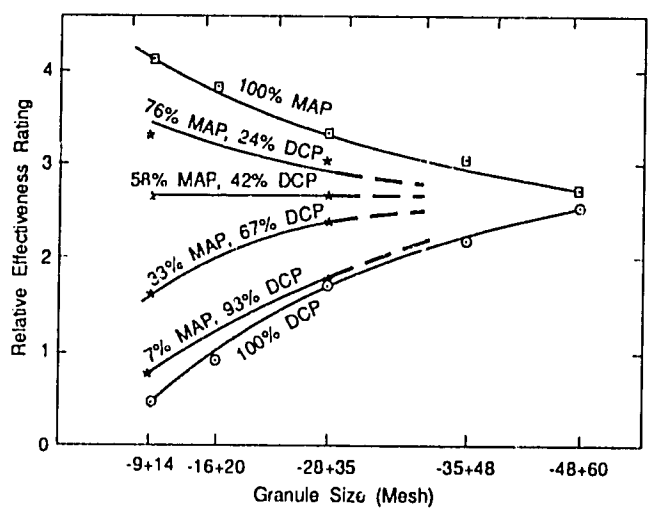
Agronomic Factors Relating to Water Solubility

The agronomic effects of phosphorus water solubility in fertilizers cannot be properly understood without considering several related factors; this topic has attracted much attention over the years. Most of the data available in developed countries were obtained from research conducted before the levels of residual soil phosphorus increased. Therefore, these earlier data must be interpreted in light of the present level of soil fertility.

Particle Size

Research has shown rather clearly that the effects of water solubility on crop growth are closely related to the particle size of the phosphate fertilizer. In acid soils, the effectiveness of water-soluble phosphorus is enhanced by use of larger particles to limit the contact with the soil and thereby delay the formation of reaction products of decreased solubility. The interaction between water solubility and particle size is illustrated in Figure 1, which shows the relative crop response to water-soluble and water-insoluble phosphates of varying particle size. The benefit of water solubility declines as particle size decreases. However, with water-insoluble phosphates, effectiveness increases as particle size decreases. This applies to phosphate rock as well; Khasawneh and Doll (1978) showed that fineness of grinding increased the effectiveness of phosphate rock down to 100 mesh. Grinding to finer particle size was not justified.

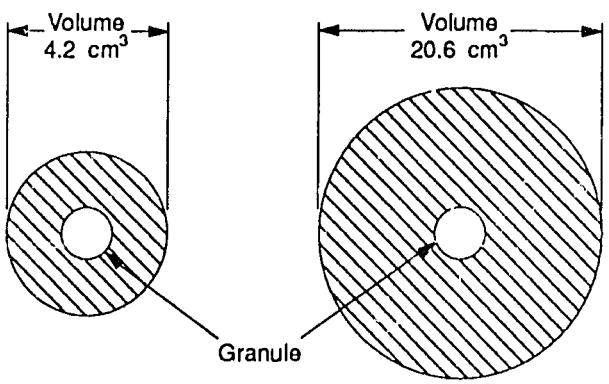
Within a given particle size of granular fertilizer, the water solubility level affects the



Source: Bouldin et al. (1960).

Figure 1. Relative effectiveness of phosphate fertilizers for two successive crops of oats grown in greenhouse pots, as affected by water solubility and granule size. Water-soluble monammonium phosphate, MAP; water-insoluble anhydrous dicalcium phosphate, DCP.

volume of soil into which fertilizer phosphorus moves upon dissolution; i.e., the higher the level of water-soluble phosphorus, the greater the volume of soil affected around the particle and the greater the chance that plant roots will encounter such high-phosphorus zones. The volume of soil affected by granular, water-insoluble phosphate particles is much less (Figure 2). The early-growth stimulation caused by water-soluble phosphate is thought to be related to the high concentration of phosphorus near the young seedlings (Khasawneh and Copeland, 1973).



14% Water Solubility 70% Water Solubility

Source: Sample and Taylor (1964).

Figure 2. Volume of soil affected by P diffusing from 6-mm granules containing different levels of water-soluble P.

Fertilizer phosphorus comes in contact with, at most, only about 2% of the soil in the plow layer (15-20 cm depth). Therefore, any practice that enhances the volume of soil affected close to the seedling, thereby increasing the chance of contact by plant roots, is likely to be beneficial, at least in stimulating early growth.

Water solubility is particularly important with regard to the widespread use of granular fertilizers as a means of improving the convenience of handling and precision of application; i.e., the use of granular fertilizers requires a higher level of water solubility. A choice of particle size is not always an option; manufacturing, handling, and application practices often dictate particle size. For more information on particle size effects, see Terman et al. (1964), Barber (1980), and Engelstad and Terman (1980).

Application Method

For obtaining a rapid early-growth response in cooler soils typical of the temperate climates, water-soluble phosphorus is applied in spots or in bands near the seed. Banding stimulates growth by increasing the phosphorus concentration in the soil solution near the plant roots. As mentioned previously, applying water-soluble phosphorus in granular form increases the chances of plant roots encountering phosphorus-enriched soil. The same principle applies to localized placement such as banding; because the band is positioned near the seed row, chances are very good that roots will quickly encounter phosphorus-enriched soil with immediate increases in uptake. Young et al. (1985) pointed out that plants often absorb about 50% of the seasonal need for phosphorus by the time they accumulate 25% of the total seasonal dry matter.

Whether early-growth response persists and is reflected in the final yield is dependent upon the level of soil phosphorus and the length of the growth period of the crop. This will be discussed in more detail later. Where soil phosphorus is rather low, it is usually advisable to broadcast and plow under or otherwise incorporate some phosphate to supplement the band application.

In addition to stimulating early growth, banding also decreases the rate of reaction with the soil as does granulation (large particles). This is especially important in acid soils; in calcareous soils, there is little agronomic advantage to localized placement, regardless of water solubility of phosphorus (Webb et al., 1961).

Ammonium-nitrogen in the band tends to enhance uptake of phosphorus and thus gives some advantage to the use of ammonium phosphates as a starter fertilizer. Diammonium phosphate, however, can injure the seedling by releasing toxic ammonia. Monoammonium phosphate, on the other hand, has been shown to be fairly harmless to young seedlings.

In warmer climates, localized placement would be less likely to produce an early-growth response compared with broadcast application. Rather, localized placement would provide the option of a lower rate of phosphate application. Banding, especially on soils low in phosphorus, often results in greater efficiency of applied phosphorus than does broadcast application. Localized placement is regarded as feeding the crop, whereas broadcast application is regarded as building up soil phosphorus reserves.

Where minimum tillage systems are used, banding of fertilizer phosphorus has been quite effective; however, such subsurface placement is not practical for strictly no-till planting. In such cases, surface application has been shown to be quite effective, except in dry years, provided that the quantity of phosphorus in the bulk of the soil exploited by actively growing roots is sufficient to meet crop needs. Because soil temperatures are often lower due to surface cover of residue, water-soluble phosphorus may be needed for spring planting. If planting is done when the soil is relatively warm, water-soluble phosphorus is not as important. Insoluble forms of phosphate (including phosphate rock) should be broadcast applied, and not banded. This is because maximum contact with the soil is needed to enhance dissolution.

For more information on placement effects, see Randall et al. (1985), Randall and Hoeft (1988), Dibb et al. (1990), and Young et al. (1985).

Soil pH

As mentioned above, water-soluble phosphate fertilizers should be of relatively large particle size for use in acid soils. Particle size is not as critical in calcareous soils. Evidence indicates also that localized placement is less important in calcareous soils. Generally, water-insoluble sources of phosphorus, including phosphate rock, are ineffective on calcareous soils.

Soil phosphorus in most soils is most soluble between pH 6 and 7, decreasing on both sides of this range. If the soil pH is less than 5.5, liming of the soil should be considered. There are other benefits of liming as well; liming acid soils to pH 5.5 eliminates aluminum and manganese toxicity and also supplies calcium.

There are alternatives to liming. For example, plant tolerance to aluminum and manganese toxicities can be enhanced through plant breeding and genetic engineering. Another alternative to liming acid soils is to apply one of the more citrate-soluble phosphate rocks. Phosphate rock can be quite suitable for long-season or perennial crops grown on acid soils. Phosphate rock can be applied as a basal dressing, followed by a soluble phosphate for immediate effect. In some cases, phosphate rock can provide greater residual effect than chemically processed phosphates (De Datta et al., 1990). Phosphate rocks vary in reactivity, and this should be kept in mind when selecting a phosphate rock for application. Another alternative is offered by partially acidulated phosphate rock. These products are manufactured by treating the rock with less than stoichiometric amounts of sulfuric acid or phosphoric acid. A supplementary application of soluble phosphate would not be needed when such a material is used. More detail on partially acidulated phosphate rock is provided by Schultz (1986), Hammond et al. (1986), IFDC (1988), and Chien et al. (1990).

For more information on soil pH effects, see Kamprath and Foy (1985).

Phosphorus Fixation Capacity

The term phosphorus "fixation" is misleading in that it implies complete reversion to insoluble forms. If this occurred in practice, it would be impossible to increase the level of plant-available phosphorus in soil. Based on the assumption of complete reversion, a great deal of research has been conducted over the years to study the nature of phosphorus fixation or retention, including study of the dissolution of the water-soluble phosphate at the particle site. The process of water vapor transport to the site and outward movement by the phosphate in solution continues as long as some of the original fertilizer salt remains. This solution reacts with soil components, and reaction products are formed. The pH of the solution containing monocalcium phosphate, the form of phosphate contained in superphosphate, is very low (pH 1.5). Solutions containing diammonium phosphate temporarily increase the pH of the soil surrounding the particle to about 8.0, whereas solutions containing monoammonium phosphate decrease the pH to about 3.5.

The first reaction product to form with the application of water-soluble monocalcium phosphate is dicalcium phosphate; this reaction occurs at the particle site. As movement proceeds, relatively large quantities of such elements as aluminum, iron, calcium, manganese, and magnesium are dissolved because of the high acidity produced by the hydrolysis of monocalcium phosphate. A large number of reaction products are then formed. However, it is very difficult to isolate these reaction products from soil and identify them. Most of these reaction products contain aluminum and iron in acid soils and calcium in calcareous soils. In the latter case, dicalcium phosphate is the most likely initial reaction product. Further discussion of this topic is provided by Sample et al. (1980) and by Kummer (1986).

Soils vary significantly in phosphorus-fixing capacity. However, the phosphorus-fixing capacities of specific soils are difficult to determine. Estimates of such fixing capacities can be obtained by use of phosphorus-sorption isotherms. Sanchez and Uehara (1980) reported that the time and analytical precision required make this technique impractical for routine soil testing. They also point out that the heavily weathered Oxisols often require initial heavy rates of phosphate to satisfy the high phosphorus-fixing capacity before obtaining satisfactory crop growth. In such cases, phosphate can be regarded as an amendment. These relatively large initial applications can then be supplemented by annual applications as needed. Werner (1978) concluded that on the acid soils of the tropics and subtropics with high phosphorus-fixing potential, phosphate fertilizers soluble in citrate or citric acid can be superior to water-soluble phosphates.

For a further discussion of this subject, see Fox and Li (1986) and Olson and Engelstad (1972).

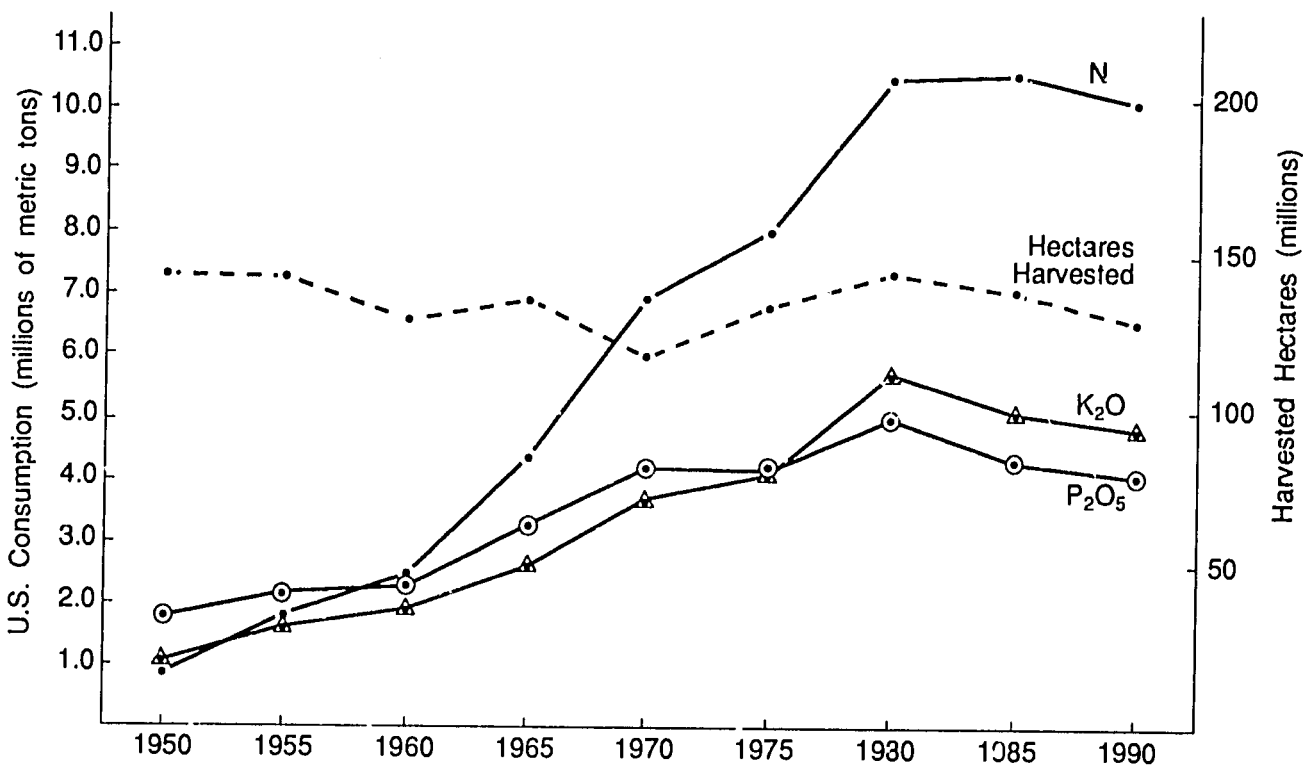
Soil Phosphorus Level

It was mentioned earlier that only about 10% to 20% of applied phosphorus is recovered by the first crop. Much of the above research on phosphorus fixation was conducted on the assumption that the reaction products were quite ineffective as sources of phosphorus. However, yield responses to repeated fresh application of phosphates declined in magnitude over time to the extent that the above assumption was called into question. With further study, the answer became clear; the reaction products were collectively supplying significant quantities of phosphorus to the crop. Furthermore, soil test results were showing these increases in phosphorus level. The term phosphorus fixation is thus a misnomer in that it implies complete inactivation.

With continual application of phosphate fertilizers, many soils in developed countries are now at the point where yield responses to fresh applications of phosphorus are unlikely. However, early-growth responses to water-soluble phosphorus can still be observed on such soils; these responses usually disappear by harvest time for most long-season crops. Figure 3 shows the consumption of fertilizer nitrogen, phosphorus (as P_2O_5), and potassium (as K_2O) over the period 1950 to 1990 in the United States, along with the area harvested. Since 1960, the consumption of phosphorus and potassium has fallen far behind that of nitrogen. These data indicate that many farmers are aware of the residual accumulations of phosphorus and potassium and are reacting accordingly.

Kummer and Wichmann (1983) point out that the required proportion of water-soluble and citrate-soluble phosphate is dependent on the level of available soil phosphorus as well as the rate of applied phosphate fertilizer. Werner (1978) concluded that the differences in the phosphorus status in the soil should not determine the type of phosphate fertilizer required but only the rate applied.

It is expected that residual effects of phosphorus application will also be found in those developing countries where fertilizer has been heavily subsidized to stimulate increased use. With repeated applications of fertilizer phosphorus, it is quite likely that yield responses will become less marked. Workers in Indonesia have found indications of lower yield responses on "lowland"



Source: Berry and Hargett (1988).

Figure 3. Consumption of N, P_2O_5, and K_2O in the United States along with the number of hectares harvested.

soils in Java with repeated applications of phosphate (Adiningsih et al., 1988). In Malaysia, Pushparajah et al. (1990) found the same pattern occurring in soils on which rubber trees had been fertilized with phosphate fertilizers for 18 successive years. Mokwunye (1979) found that annual applications of phosphate rock raised the soil phosphorus level significantly on Nigerian savanna soils. Howeler (1985) found in Colombia that continuous application of phosphate fertilizer for cassava produces a long-term residual effect; once the soil phosphorus level is raised above the response level, "further applications can be greatly reduced or entirely eliminated." For further discussion of residual phosphorus, see Barrow (1980).

Soil Temperature

Soil temperature, or climate in general, for a given area has much to do with determining the importance and/or need for water-soluble phosphorus. If the soil is relatively cool at the time of planting the crop, it is likely that root growth will be decreased and an early-growth response will be observed with water-soluble phosphorus. If the crop has a relatively short growth period, this growth increase may well persist and result in improved final yield. On the other hand, if the crop has a relatively long growth period, final yield increases will be less likely.

Fixen and Leikam (1988) noted that placement of phosphorus seems more important for small grains than for row crops. They concluded that this may be due to a colder soil environment and a less extensive root system for the small-grain crops.

One relatively recent change that relates to soil temperature is the shift toward conservation tillage in some areas. This type of tillage system leaves substantially more crop residue on the soil surface, providing an insulation effect that can decrease soil temperatures several degrees. Lower soil temperature decreases the rate of organic phosphorus mineralization and also the rate of root growth. Crops planted in the early spring and late fall under reduced-tillage conditions may be more responsive to water-soluble phosphorus. If the soil is warm at planting time, phosphorus water solubility is less important, particularly for long-season crops.

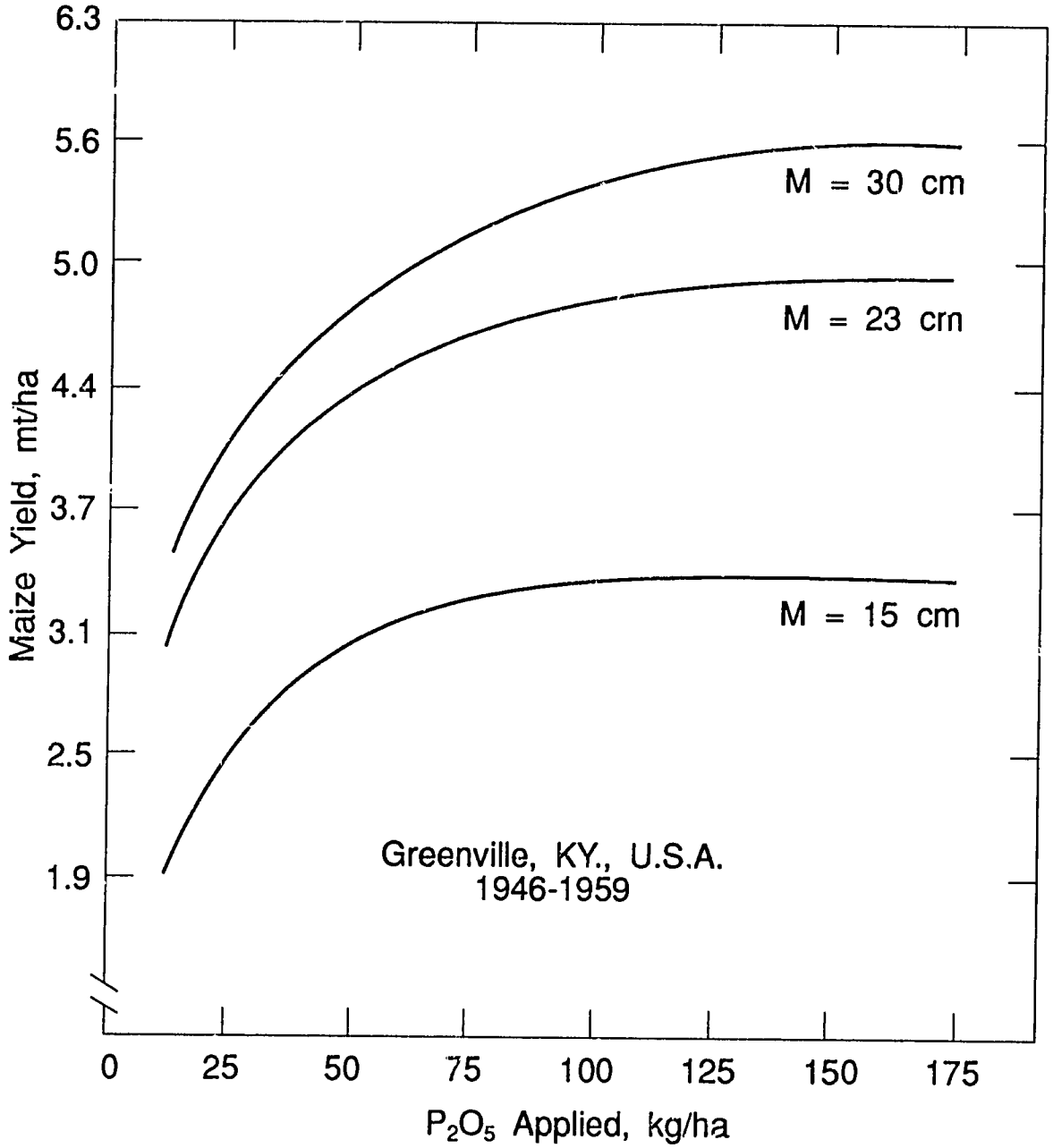
Length of the Crop Growth Period

The length of the crop growth period has been referred to several times already; it is an important factor, especially in cool soils. If the crop has a short growth period and is planted in cool soil, chances of economic response to water-soluble phosphorus will be greater than if the crop has a longer growth period. Yield response to water-soluble phosphorus is most often reflected in such short-season crops as vegetables. In these crops, time is insufficient to permit utilization of significant amounts of soil phosphorus.

In warmer soils, such response to water-soluble phosphorus will be less likely, regardless of the crop growth period. On soils of low phosphorus status in warmer regions, phosphate fertilizer is needed, but water-solubility requirements will not be as critical.

Soil Moisture

As mentioned previously, phosphorus is normally considered an immobile nutrient. Plant roots must intercept this nutrient in soils, and the more robust and developed the root system, the more phosphorus is taken up. Root growth is encouraged by favorable soil moisture conditions. Thus, the curve for yield response to rates of applied phosphorus tends to move upward in response to increasing moisture levels. Figure 4 shows an example of this relationship for maize.



Source: Engelstad and Doll (1961).

Figure 4. Maize yield response to applied phosphorus as affected by variation in June plus July rainfall.

Crop Classification and Estimated Phosphate Solubility Requirements

Various crops are categorized according to similarities in their growth pattern, length of growing period, and the agroclimatic zone in which they are grown. These are the characteristics that relate to water-solubility requirements of phosphorus. However, generalizations are hazardous because many crops are quite adaptive, and plant breeding has made some varieties/cultivars suited to even wider ranges of conditions. Yet, it

should be possible to set tentative minimum requirements of phosphorus water solubility for each species or group of species.

It may be of interest to examine Table 2 at this point; this table shows the approximate amounts of N, P_2O_5, and K_2O removed per hectare by the harvested grain of various crops. Also, refer to Figure 5 for the global distribution of harvested area used to grow the major food and feed grain crops discussed below.

Wheat

This crop is grown, for the most part, in temperate climates. Wheat can be grown in some areas of the tropics and subtropics at higher elevations or where winter temperatures are low enough; however, most of the harvested area is found in the cooler temperate areas of the world. If the crop is seeded in the fall and harvested the following spring, it is called winter wheat; if seeded in the spring and harvested the following summer, it is called spring wheat. Generally speaking, spring wheat is seeded into colder soils than is winter wheat.

In most cases, spring-seeded wheat (spring wheat) receives a relatively low rate of fertilizer in the seed row to stimulate early growth. The fertilizer grades used are usually rather high in phosphorus relative to nitrogen and potassium. Because the fertilizer is most often applied in granular form in the seed row (band) to relatively cool soil, water solubility should be relatively high; at least 60% of the total phosphorus should be water soluble.

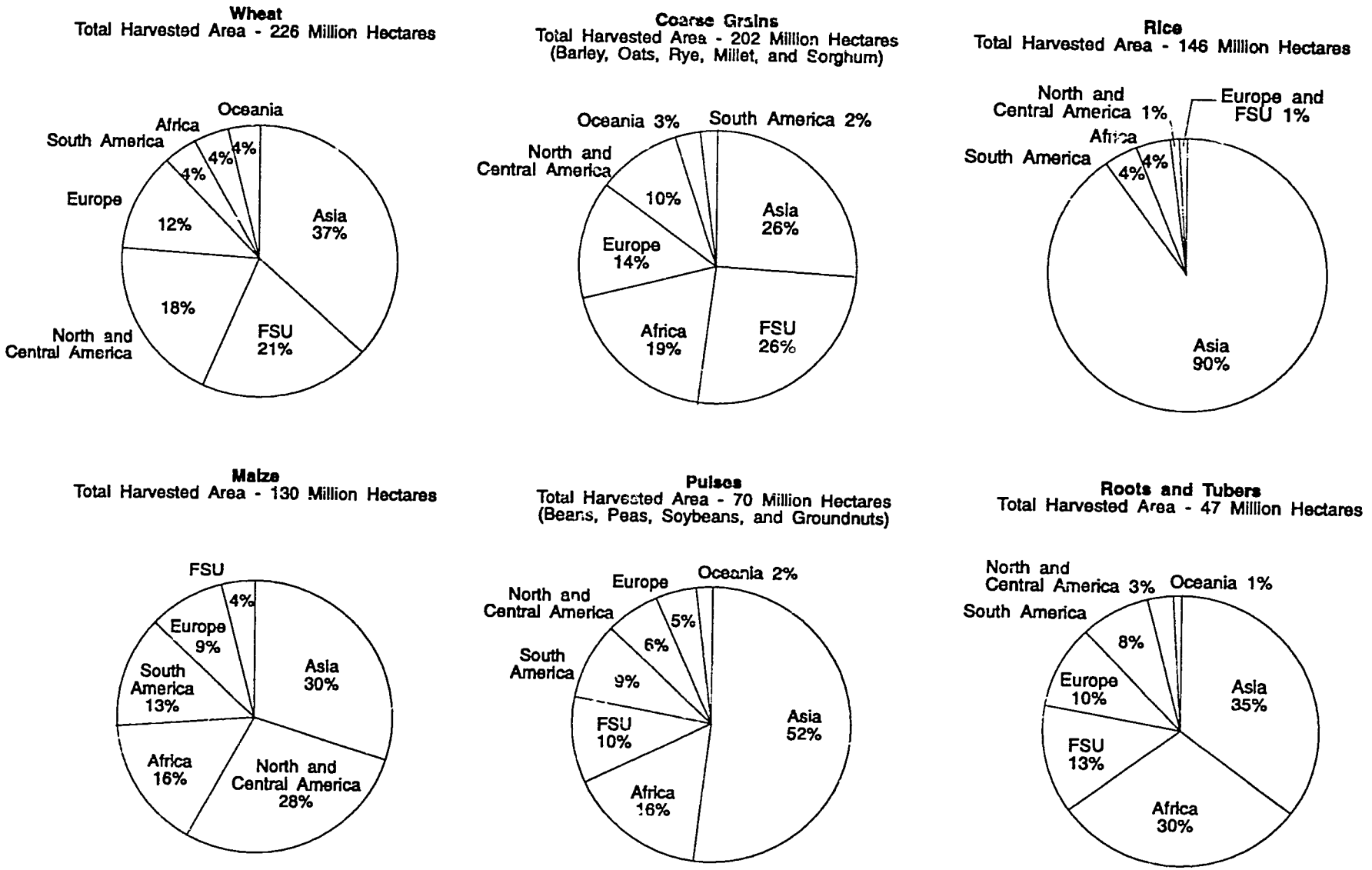
For fall-seeded wheat (winter wheat), the requirement for water-soluble phosphorus would not be as high. Winter wheat is grown where the soils are apt to be warm in the fall when the crop is seeded. In the United States, winter wheat is often fertilized by a technique called "dual placement." This involves pre-plant applications at 10-15 cm depth of a band of anhydrous ammonia plus a band of either fluid 10-34-0 or dry diammonium phosphate. These fertilizers are placed below the seed, so damage to young seedlings is minimal. In either case, the phosphate source is highly water soluble.

Mishra et al. (1986) compared nitrophosphates varying in water solubility with triple superphosphate of 90% water solubility for wheat in India. The levels of water solubility were 30%, 45%, 60%, and 75% for the nitrophosphates. Soil tests indicated that the site chosen was low in phosphorus.

Table 2. Approximate Amounts (kg/ha) of Primary Nutrients Contained in Various Grains at Indicated Yield Levels[a]

	Grain Yield (t/ha)	Total Nutrients (kg/ha)	Nitrogen (N) (kg/ha)	Phosphorus (P_2O_5) (kg/ha)	Potassium (K_2O) (kg/ha)
Wheat	2.7	101	56	28	17
Rice (paddy)	4.0	89	56	22	11
Barley	2.2	67	39	17	11
Maize	9.4	255	151	59	45
Sorghum	3.8	101	56	28	17
Oats	2.9	95	56	22	17
Rye	1.9	61	39	11	11
Soybean	2.7	269	168	39	62

a. Calculated from data in Table 2, *The Fertilizer Handbook*, published by The Fertilizer Institute, 1015 Eighteenth St., N.W., Washington, D.C., 1982.



Note: FSU refers to Former Soviet Union.

Source: FAO (1990).

Figure 5. Regional distribution of harvested area for major food and feed-grain crops (821 million harvested hectares) - 1989.

The rates chosen were 30, 60, and 90 kg P_2O_5 per hectare, and the phosphate fertilizers were mixed with the soil. It was concluded that the nitrophosphates having 30% and 45% water solubility were inferior to triple superphosphate; it was not possible to distinguish between the effectiveness of the nitrophosphate fertilizers having 60% and 75% water-soluble phosphorus and that of triple superphosphate.

Overall, the water-soluble phosphorus requirement for winter wheat would not exceed 40% for most acid soils, assuming the remainder is mostly citrate soluble. If the soil is alkaline or calcareous, the phosphate used should be at least 60% water soluble.

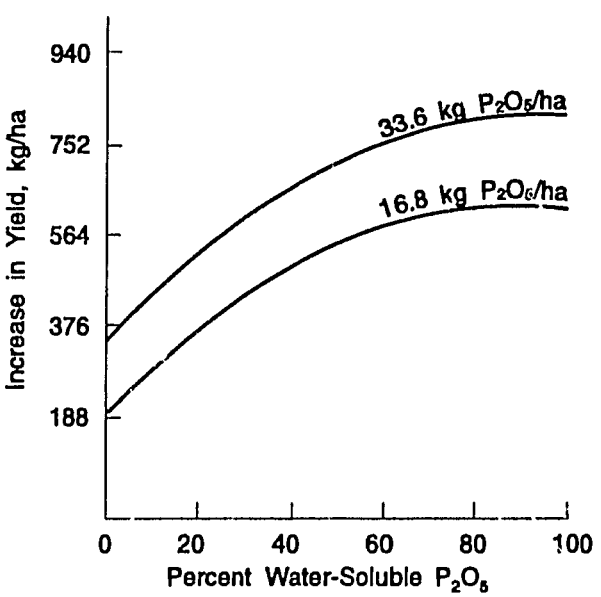
Rice

Rice grown under flooded conditions is not as dependent upon fertilizer phosphate as are other annual crops because the reducing conditions created by flooding render soil phosphorus more soluble. More soil phosphorus is therefore available to flooded rice than to nonflooded crops, other conditions being equal. There are many areas, of course, where soil phosphorus release is not adequate to meet the need. In most cases in the tropics, fertilizer phosphate for flooded rice is broadcast as a basal dressing and the water-soluble phosphorus requirement would be low; 40% would be adequate for most situations. In temperate regions where rice is often seeded into dry soil, fertilizer phosphate applied in bands should be at least 50% water soluble. For more information on the phosphorus needs of rice, see De Datta (1981).

Maize

Maize is an important human food crop in much of the developing world, but it is used primarily for livestock feed in the developed world. Maize is an important crop in the United States and receives substantial amounts of fertilizer. It is a fairly long-term summer crop that takes up most of its nutrients and does most of its growing while the soil is favorably warm. This condition decreases its reliance on fertilizer phosphorus and increases the value of the soil reserves as the growing season progresses. Although early-growth response to water-soluble phosphorus is often observed, the response often disappears by harvest. This is in part due to the relatively long growth period and the extensive root system of the maize plant.

Webb and Pesek (1958) showed that in 20 field experiments conducted on maize in Iowa over a 6-year period, 90% of the yield increase occurred with 60% water-soluble phosphorus (Figure 6). There was very little yield enhancement obtained above 60% water-soluble phosphorus. The work was conducted during the period 1951 to 1956 when soil phosphorus levels at these experimental sites were generally low or very low. This level of soil phosphorus would have considerable bearing on the final yield



Source: Webb and Pesek (1958).

Figure 6. The effect of rate and water solubility of phosphorus fertilizer applied in the hill on the yield of maize.

responses to hill-applied phosphate. Finding experimental sites of such low soil phosphorus levels in the United States would be very unlikely now because of buildup of soil phosphorus through continued fertilization over the past 40 years. These researchers later reported that phosphorus water solubility was of little importance for maize when various phosphate sources were broadcast and plowed under (Webb and Pesek, 1959).

Overall, the level of water-soluble phosphorus required for maize would not be very high. For maize grown on acid, cool soils of low phosphorus level, ISMA (1980) suggests that fertilizer banded near the seed row should have at least 40% of its phosphate in the water-soluble form; when the fertilizer is banded in alkaline or calcareous soils under similar conditions, ISMA suggests that 80% of the phosphorus should be in the water-soluble form. These are rather extreme conditions; normally, most soils on which maize is grown in developed countries have been elevated to at least a medium level of soil phosphorus. The 40% water solubility on acid soils seems acceptable; the 80% water solubility on alkaline or calcareous soils appears to be high. Perhaps 60% in the latter case would be more appropriate.

Coarse Grains

This category usually includes barley, oats, rye, millet, sorghum, and maize. However, because of its importance, maize has been discussed separately.

Much of what was reported for wheat in regard to water-soluble phosphorus requirements would also be true for barley, oats, and rye. Field experiments conducted with oats (Webb et al., 1961) showed some positive effects of the water-soluble phosphorus level, but it was not possible to arrive at a minimum level. Soil pH appeared to be the most important factor relating to the effectiveness of fertilizer phosphorus sources. Generally, the degree of phosphorus water-solubility was of greater importance on calcareous soils, and placement was more important on acid soils.

Sorghum is similar to maize in its growth pattern and nutritional needs. In fact, it is sometimes called the maize crop of the dry regions because it is significantly more drought resistant than maize. Sorghum responds well to fertilizer applications, but because it is grown in somewhat warmer regions than is maize, phosphorus water solubility would be expected to be less important. However, no definitive information was found in the literature for sorghum or millet regarding needs for phosphorus water solubility.

Roots and Tubers

Yams, taro, cassava, and Irish potatoes are included in this category. For the first three crops, the determining factor is that these are generally grown in warmer climates. This in itself would lessen the requirements for water-soluble phosphorus; de Geus (1973), for example, reported that yams, taro, and cassava do not respond markedly to phosphate fertilizer. More recently, Howeler (1985) reported that cassava responds well to partially acidulated phosphate rock in acid soils. Also, Hammond et al. (1986) reported marked cassava yield response to reactive North Carolina (United States) and Bayovar (Peru) phosphate rocks; up to the rate of 100 kg/ha P_2O_5, these sources were nearly as effective as triple superphosphate. Such data would indicate that there is not a strong need for water-soluble phosphorus for cassava. To the extent that these crops are grown in warmer regions of the world, including temperate as well as tropical zones, water solubility should not be very important.

There is more information on the phosphorus water solubility needs of Irish potatoes. Cooke, in an unpublished manuscript entitled "The Agricultural Value of Phosphate Fertilizers With Special Reference to Their Solubility in Water," put this crop into

a special category requiring about 80% water-soluble phosphorus. Van Burg (1963) concluded from his studies that 75% water solubility was adequate. For potatoes grown in southeastern United States, Mullins and Evans (1990) found no differences in effectiveness between band-applied phosphate sources varying from 81% to 94% water-soluble phosphorus. This crop is special, as Cooke indicated, in the sense that it requires the highest level of phosphorus water solubility of the important food crops.

Pulses, Including Beans, Peas, Soybeans, and Groundnuts

The distinguishing characteristic of this group of crops is that they are legumes and can, with the help of nitrogen-fixing bacteria, obtain nitrogen from the atmosphere by the process called symbiotic fixation. With regard to phosphate, soybeans are not usually fertilized directly but must depend on residual fertility left from previous crops. In such cases, water solubility is not considered important. It has been reported by de Geus (1973) that groundnuts do require substantial amounts of phosphate fertilizer. Field trials conducted by the International Fertilizer Development Center showed significant but equal yield response by groundnuts to equal applications of Tilemsi phosphate rock and triple superphosphate (IFDC, 1985). Again, this would indicate that high levels of water-soluble phosphorus are not required for some crops grown on acid soils in warmer regions of the world.

Restoration of Soil Fertility and/or Land Reclamation

Soil fertility restoration involves consideration of several important factors including the following.

Badly Eroded Soil

Where topsoil has been removed by erosion or other means, fertility is often extremely low in the exposed subsoils. This is particularly true where the soil has been subjected to a long period of weathering in a warm, humid climate. In addition to at least partial restoration of organic matter, other aspects of fertility must be restored. Often this requires large applications of fertilizer, including phosphate. The fertilizer would be broadcast for the most part, and water solubility would not be important for most cropping uses. Lime may be required as well as the possible application of other nutrients.

Highly Acidic Soils

Some soils of the tropical regions are quite acidic due to extreme weathering and leaching of such exchangeable bases as calcium and magnesium. Examples are the Campo Cerrado of Brazil and the Llanos of Colombia and Venezuela. These soils are naturally acidic and characterized by large amounts of exchangeable aluminum, especially on soils of pH below 5.0. Kamprath (1972) pointed out that exchangeable aluminum is present in only small amounts in soils of pH higher than 5.6. Liming to raise the soil pH to this level is beneficial on such soils. Liming is less important when aluminum-tolerant cultivars are available.

IFDC (1986) reported that soil acidity was increased in Cameroon by the long-term use of such acidifying fertilizers as ammonium chloride and ammonium sulfate. In such cases, the same remedy (liming) would apply. After soil pH has been raised by liming to at least 5.5, then adequate phosphorus and other nutrients should be added as needed. Where aluminum toxicity is not a serious problem, phosphate rock can be applied to acid soils without liming. Some phosphate rocks contain appreciable amounts of calcium as an impurity, and this calcium can have a

significant liming effect (Hellums et al., 1989; Chien, 1990).

A third category of high acidity relates to coal mine spoils. Mays and Bengtson (1978) stated that some soils are extremely acidic due to careless handling of sulfur-bearing overburden. With oxidation of sulfur-containing compounds (iron pyrites), a pH as low as 2.2 to 3.5 can result. Although liming can be beneficial, these authors point out that pyritic spoils have potential for very high residual acidity, which often requires large lime applications over long periods of time.

Land Reclamation

If trees are to be planted on land that has been reclaimed, phosphates of low water solubility should be quite satisfactory, provided that the soils have not been overlimed. Mays and Bengtson (1978) point out that fertilization can cause competition from other fast-growing species that can retard the growth of young trees. If the trees are first grown in highly fertilized nurseries, they may not need additional fertility for a time after transplanting. In many cases, mycorrhizal association with the roots is beneficial for phosphorus uptake.

If pastures are to be established, the water-soluble phosphorus need would ideally be determined by soil pH and by method of application. Generally, however, it would be best to apply a phosphate with at least 70% water-soluble phosphorus for establishment; for subsequent maintenance applications, sources of much lower solubility would suffice. It would appear that a basic application of phosphate rock would be useful on those sites that are quite acidic. For example, such application on the mined-out bauxitic soils of Jamaica coupled with use of a water-soluble phosphate for establishment should be a useful system.

One type of land reclamation that requires little or no phosphate fertilizer application is that of the mined-out phosphate lands. Research is being conducted by Mislevy et al. (1991) to restore agricultural productivity to mined-out areas. In this type of restoration, phosphatic clays are mixed with dewatered sand tailings at a 1:2 clay-sand ratio before deposition. Agricultural crops grown on these mixtures show that such mixing decreases the severity of productivity problems associated with the individual materials. Given the large quantities of these mine spoils in mined-out phosphate areas, such research is very important.

Phosphate Sources for Irrigated Agriculture

Where conventional furrow or sprinkler irrigation systems are used without the addition of fertilizer to the irrigation water, no special requirements apply as far as the phosphate source is concerned. However, when phosphorus is applied by means of sprinkler or drip irrigation, special phosphate sources are required. Mikkelsen (1989) reports that for drip irrigation, phosphorus sources not only must be water soluble but must also be acidic to prevent precipitation of insoluble salts of calcium and magnesium that may be contained in the irrigation water. Two such sources tested by Mikkelsen with good results were orthophosphoric acid and urea phosphate. The phosphate fertilizer specifications for sprinkler application are less rigid than those for drip systems, but precautions must be taken to avoid fouling the system with insoluble residue.

Future Research Needs

As previously noted, much of the information contained in this review relates primarily to soils of temperate climate with low levels of readily soluble phosphorus. This information is still applicable to many soils

in the developing countries where soluble phosphorus levels are below critical levels required for crop production. While these soils would benefit from the use of completely soluble phosphorus sources, the economics associated with their use is often the limiting factor. Under such conditions, indigenous phosphate rock or partially acidulated phosphate rock may offer more economical solutions for providing critical levels of phosphorus as required for crop growth. Many of the developing countries are located in the tropics where soil conditions, length of growing season, and climate are conducive to increased dissolution of phosphorus sources lower in water solubility. In addition, previously mentioned economic factors such as fertilizer subsidies, fertilizer unavailability due to importation, employment generated, and foreign exchange saved through use of indigenous resources can encourage the use of less soluble phosphorus sources.

However, for most agricultural soils in the developed world, fertilization is geared to maintenance of relatively high levels of soil phosphorus attained through years of application of water-soluble phosphorus sources (e.g., TSP, SSP, MAP, DAP). Fertilization above the critical level does not increase yields; therefore, it is neither economical nor practical. The question for these soils is whether the less soluble phosphorus sources can maintain critical soil phosphorus levels when the amount of phosphorus applied is based on that removed through harvesting.

Additional research is also needed to determine how important a role mycorrhizal infection plays in crop response to different levels of soluble phosphorus additions. For those crops with mycorrhizal infections, there is a greater potential to extract phosphorus from less soluble sources due primarily to an increased soil volume subject to exploration and nutrient removal by the mycorrhizal fungi. In addition, previous studies indicated that fungi appear to be able to absorb phosphorus at lower soil solution concentration than that required for an uninfected plant root (Paul and Clark, 1989). All of these research questions need to be addressed. Only when the results of such investigations are combined with present levels of knowledge can one best assess the importance of water solubility in choosing the proper phosphorus fertilizer.

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