AGENCY FOR INTERNATIONAL DEVELOPMENT
WASHINGTON, D. C. 20523

BIBLIOGRAPHIC INPUT SHEET

FOR AID USE ONLY

1. SUBJECT CLASSIFICATION

A. PRIMARY: Agriculture — AF25-0000-GG50

B. SECONDARY: Soil fertility,fertilizers,and plant nutrition

2. TITLE AND SUBTITLE

Soil phosphorus and sulfur

3. AUTHOR(S)

Olson,R.A.; Engelstad,O.P.

4. DOCUMENT DATE: 1972

5. NUMBER OF PAGES: 20p.

6. ARC NUMBER: ARC

7. REFERENCE ORGANIZATION NAME AND ADDRESS

TVA

8. SUPPLEMENTARY NOTES (Sponsoring Organization, Publishers, Availability)

(In National Acad.of Sciences,Washington,D.C. Soils of the humid tropics,p.82-102)

9. ABSTRACT

10. CONTROL NUMBER: PN-RAA- 208

11. PRICE OF DOCUMENT

12. DESCRIPTORS

Humidity
Phosphorus
Sulfur
Tropics

13. PROJECT NUMBER

14. CONTRACT NUMBER: PASA RA (QA) 5-69 Res.

15. TYPE OF DOCUMENT

AID 590-1 (4-74)

10

4-147 National Acad. of Science. Soil of the Humid Tropics Washington, 1972. p. 82-101

R. A. OLSON AND O. P. ENGELSTAD

Soil Phosphorus and Sulfur

Phosphorus and sulfur are similar elements in the soil-plant continuum in that they are required in approximately equivalent amounts for crop nutrition and a significant portion of each is stored in the soil's organic component. Experimentation with these elements to date has provided only partial understanding of the dynamics involved in their accumulation, storage, utilization, and loss in the various soil, climatic, and ecological regions of the tropics. Principles established for soils in temperate regions no doubt apply, but with qualifications imposed by the more intensive weathering and leaching forces and the different mineralogical and organic character of soils in the humid tropics.

OCCURRENCE OF PHOSPHORUS AND SULFUR IN TROPICAL SOILS

Total Amounts and Forms

Phosphorus

Extensive investigations with soils of temperate regions have shown declining levels of total phosphorus in surface soils with increasing

intensity of weathering. Total phosphorus in surface soils ranges from an average of 3,000 ppm in the subhumid cool temperate region to less than 500 ppm in the humid warm temperate region (Pierre and Norman, 1953). This projection seemingly carries through into the humid tropics, as evidenced by the common finding of less than 200 ppm total phosphorus in mature upland soils (Bouyer and Damour, 1964; Enwezor and Moore, 1966; Middleton, 1954; Nye and Bertheux, 1957). Beyond the fact of decreasing total phosphorus with increasing intensity of weathering is the recognized higher proportion of organic and occluded forms of phosphorus in Latosols (Oxisols). Relative distribution of the inorganic phosphorus of surface soil as water-soluble surface-adsorbed aluminum phosphate, iron phosphate, and calcium phosphate is about as variable from site to site as are tropical soils *per se*. Generally speaking, however, within a given soil group, aluminum phosphate increases as calcium phosphate decreases with declining pH; iron phosphate in occluded form with iron coating predominates as soils become ferruginous in character (Bouyer and Damour, 1964; Chang and Jackson, 1958). Rate of phosphorus loss from soils of the tropics is determined primarily by cropping intensity and erosion, leaching being slight except on very sandy soils. Gains depend entirely on the amount of phosphorus added in manure or commercial fertilizer.

Sulfur

Total sulfur in soils varies perhaps even more than total phosphorus, depending especially on soil-forming processes and the amounts of organic matter and clay in the soil. The presence of sulfur is closely tied to the accumulation of soil nitrogen, e.g., in the ratio of 10 nitrogen to 1.2 sulfur in acid soils of eastern Australia (Barrow, 1960), so that the role of sulfur in the accumulation and turnover of organic matter cannot be disregarded. As with phosphorus, investigations of soils in temperate regions show declining sulfur levels with increasing intensity of weathering, and average values of 540, 396, and 210 ppm of total sulfur for Chernozem (Mollisols), Brunizem (Alfisols and Mollisols), and Red-Yellow Podzolic (Ultisols) surface soils, respectively (Jordan and Reisenauer, 1957). It seems reasonable to project values generally below 100 ppm for most intensively weathered upland soils of the tropics. Most of the sulfur in surface soils is found in organic combination (Evans and Rost, 1945), whereas varying amounts of inorganic compounds such as gypsum and

pyrite may be found in lower horizons associated with specific leaching or drainage conditions. Important to crop nutrition are smaller quantities of inorganic sulfate ions in water-soluble or adsorbed form, the latter being particularly significant in subsoils containing kaolinite and hydrous oxides of iron and aluminum (Ensminger, 1954; Neller, 1959).

Influence of Soil and Climatic Conditions on Availability

Phosphorus

Phosphorus availability to plants grown on tropical soils varies tremendously with the morphological properties of the soil, previous management, and the local climatic environment. Surface soils of the derived savanna, which have been subjected to long periods of intermittent cropping and bush fallow, are likely to be very low in total phosphorus content and correspondingly low in their capacity to deliver available phosphorus (Nye and Bertheux, 1957; Russell, 1968). Moreover, increasing population pressure, which has resulted in shorter fallow periods, has been responsible for increased incidence of phosphorus deficiency (Enwezor and Moore, 1966). Fixation of applied increments of phosphorus is far more serious in certain tropical soils than in soils in temperate regions and is related to the clay mineralogy and the amorphous nature of the colloidal hydrated oxides of iron and aluminum. Hawaiian workers' ranking of fixation capacities of the more common components of the clay fraction of soil is pertinent: amorphous hydrated oxides > gibbsite – goethite > kaolin ≥ montmorillonite (Fox *et al.*, 1968). Phosphorus fixation is recognized as the major obstacle to agricultural development of volcanic ash soils in Hawaii, where upwards of 1,350 kg of phosphorus per hectare may be needed to satisfy the phosphorus fixation capacity (Younge and Plucknett, 1966). Fixation is especially rapid and strong on ferralitic soils (Oxisols) high in goethite in West Africa (Dabin, 1970). The periodically humid tropical climate has indirectly contributed to fixation by its influence on the intensity of soil mineral weathering and by the potential for year-round chemical reaction between any phosphate increment and the soil's colloidal system.

Many soils of the humid tropics are very strongly acid by temperate region standards. Thus, liming the soil to a higher pH level has been responsible for enhanced phosphorus availability for crops

on the Campo Cerrado soils of Brazil, the eastern plains of Colombia, the Oxisols of Hawaii, the Ultisols of Central America and the southeastern United States, and the more acid soils of restricted drainage in Tanzania (Mtanana series). Benefits are usually attributed to an increased rate of decomposition of soil organic matter, which releases the phosphorus to the soil solution; a reduced aluminum uptake; and a blocking of fixation reactions. The pH level above which benefits cease and deleterious effects begin is usually between 5 and 6 (Fox *et al.*, 1964a; Kamprath, 1970, Le Mare, 1959; Spain and Ruiz, 1968), at which level most of the exchangeable aluminum has been neutralized. This is a notably lower pH level than is considered optimal for agriculture in temperate regions and may well account for the often-reported deleterious effects of liming in the tropics; i.e., rates based on experience in temperate regions may well have constituted overliming on the poorly buffered tropical soils.

Flooding the soil for rice enhances the availability of soil phosphorus for the crop (Bartholomew, 1931). This has been ascribed to the reduction of the iron in ferric phosphates under chemical reducing conditions induced by oxygen depletion and to the production of reduced inorganic and organic soil phosphorus compounds of greater solubility (Ahmad, 1967; Gasser and Bloomfield, 1955; Islam and Elahi, 1954). Thus a sharp break is noted in the curve relating extractable phosphorus to controlled redox potentials at +200 mV, which is the potential at which ferric iron begins to be reduced to the ferrous form (Patrick, 1964).

Sulfur

Sulfur availability in tropical soils is also highly variable, depending especially on the organic matter content of the surface soil, soil texture, and previous management of the soil. Much less investigational work has been done on soil conditions that influence sulfur availability than with phosphorus. As with phosphorus, problems of deficiency to date appear to be associated especially with upland savanna (Greenwood, 1951; McClung *et al.*, 1959). Presumably, this is a manifestation of the lower organic matter content of the surface soils of the savanna than of the forest soils, and the deficiency seems to be accentuated by drought (Dutt, 1962). In upland soils with good drainage, even where the organic matter content is substantial, leaching of available sulfur is appreciable to excessive with increasing rainfall. Losses of sulfur from tropical soils are associated with cropping

intensity, erosion, and leaching. Replenishment comes from various fertilizers, insecticides, fungicides, and irrigation water. Rainfall is not the contributing factor in the tropics that it is in industrialized temperate regions; moreover, the replenishment of sulfur in nitrogen and phosphorus fertilizers is rapidly disappearing with the trend toward manufacture of higher-analysis materials without a sulfur impurity.

Some tropical soils have productivity problems associated with excess sulfur, especially the acid sulfate "cat clays." Large quantities of reduced sulfur compounds have accumulated in these soils under the natural marshy environment of tidelands. When such areas are drained, the sulfur is oxidized to sulfate, and the pH is drastically reduced to as low as 2.5 (Bloomfield *et al*, 1968). In submerged rice culture in the Far East, sulfur can have deleterious effects. If the soil is old, degraded, and low in iron, excluding oxygen from the soil by waterlogging may cause added or native sulfate to be reduced to hydrogen sulfide, a toxic material thought to be responsible in part for Akiochi disease of rice.

CROP RESPONSES TO APPLIED PHOSPHORUS AND SULFUR FERTILIZERS

Phosphorus

Good crop responses to phosphorus fertilizers with existing systems of farming are obtained in most upland areas of the humid tropics, as demonstrated by thousands of simple trials conducted by the Freedom from Hunger Campaign (FFHC) Fertilizer Programme of FAO (FFHC Fertilizer Programme, 1968). Positive response to phosphorus has occurred in slightly more than 90 percent of the locations investigated, with frequency of response exceeded only by that due to nitrogen. Response is especially large in tubers and vegetable crops, as evidenced by the following summation for West Africa and northern Latin America.

	Increase Due to Phosphorus (kg/ha)
West Africa	
Maize (794 trials)	173
Yam (377 trials)	895
Northern Latin America	
Maize (196 trials)	401
Potato (53 trials)	2,762

Other fertilizer trials in the humid tropics have demonstrated similarly that the majority of soils are deficient in phosphorus for the production of most crops (Bradfield, 1963, Greenwood, 1951; International Soil Testing, 1968; Le Mare, 1959; Mikkelsen *et al*, 1963; Nye, 1952; Spain and Ruiz, 1968). The degree of response depends to a considerable extent on the length of the resting period and the time since the most recent fallow. Certainly, this would be expected from the known intensity of weathering and leaching in tropical environments and the basic chemistry of any existing phosphate in a medium high in iron and aluminum and low in silicon. Exceptions are certain locations where soils have developed in recent volcanic deposits; in coastal alluvium, inland alluvium, and lacustrine deposits, which have their origin in young geologic formations; and in fields with substantial manurial or chemical fertilizer history.

Sulfur

Responses to sulfur have been extensively recognized on acid soils of the Campo Cerrado of Brazil (McClung and Freitas, 1959), on soils of the Punjab in India (Dutt, 1962; Kanwar, 1967), throughout East Africa (Beauchamp, 1953; Russell, 1968) and West Africa (Braud, 1969; Greenwood, 1951; Nye, 1952) and in the Caribbean Islands. . Needs in other areas, especially Southeast Asia, seemingly have been masked by the sulfur carried in the ammonium sulfate and ordinary superphosphate that have enjoyed widespread use on plantation crops of the region.

Groundnuts and forage legumes seem particularly sensitive to sulfur deficiency, in part because of the relatively high sulfur content of legume tissues and the influence of sulfur on root nodulation. Perhaps indicative of the sulfur problem in tropical soils is the summation of 202 field trials in West Africa (Braud, 1969), which showed 18 percent of all locations in a state of "serious" sulfur deficiency. "Marked" deficiency was apparent in yield response at 38 percent of the locations, leaving only 44 percent of the sites without statistically significant sulfur deficiency.

FERTILIZER MANAGEMENT INVESTIGATIONS WITH PHOSPHORUS AND SULFUR

On first consideration, it would seem reasonable to expect that many of the results obtained from fertilizer management investigations in

temperate regions could be transposed to the tropics, with allowances. Management studies with phosphorus and sulfur would appear to take on particular significance for the humid tropics, however, in view of the totally different mineralogical environment, the year-round warm temperatures, the periodicity of wet and dry seasons, the different crops and cropping practices, and the greater need for maximum fertilizer efficiency.

Time of Application and Placement

Phosphorus

The coordinated rice fertilizer research project of the International Atomic Energy Agency (IAEA) carried on in several tropical countries has proved surface placement of phosphorus fertilizer superior to shallow or deep placement for submerged rice culture (Joint FAO/IAEA Division, 1970). Delayed application and splitting the phosphorus treatment resulted in no benefit or a slight reduction in utilization of the fertilizer. A similar coordinated research program on fertilization of tree crops that involves isotope tracers is under way. It has provided indication of zones of maximum root activity for eventual prescription of optimum depth and distance of placement of fertilizer phosphorus from the trunk (IAEA Laboratory Activities, 1969). Comparable studies with maize have indicated a greater utilization of fertilizer phosphorus when nitrogen and phosphorus are applied in the hill than when banded adjacent to the row. Presumably, this reflects a reduced fixation reaction in the soil by reason of restricted surface area of soil-fertilizer contact and perhaps, additionally, an enhanced positional availability to the plant.

Work in Tanzania on "grey sands" with a very low level of phosphorus in the subsoil showed root systems of the common crops to be confined to the "humic" topsoil (Hagenzieker, 1956). Preliminary experiments suggested that deep placement of phosphorus would be effective; this was confirmed by field experiments with soybeans and maize. The deepest placement of superphosphate (30 cm) afforded highest yields. Whether the recorded benefit is due to improved positional availability in relation to the supply of soil moisture or to an expanded root system for absorption of other nutrients and water is conjectural. Perhaps something analogous is achieved in the first case by the native practice of heavy ridging, which deeply covers fertilizer phosphorus placed near the row at planting.

Sulfur

Investigational work on placement and time of application of sulfur fertilizers has been very limited in the tropics. This is probably explained by the fact that agronomists, recognizing the need for sulfur, have anticipated that the traditionally used ammonium sulfate and ordinary superphosphate providing nitrogen and phosphorus would take care of the sulfur need In fact, recognition of the sulfur problem has developed largely since 1955, as high-analysis nitrogen and phosphorus fertilizers were being introduced without the sulfur component. Among chemical materials that might logically be used for correcting deficiencies, only elemental sulfur could present the problem of restricted plant availability, with its oxidation rate determining optimum time of application. Indications under West African soil conditions are, however, that microbial activity effects almost immediate mineralization of the elemental sulfur (Bockelee-Morvan, 1966); hence, little or no extra time before planting the annual crop should be required if finely divided sulfur is applied. Presumably, the dominant consideration as regards timing for applied sulfate would be similar to that for nitrogen under the high leaching potential of the humid tropics.

Rate of Application

Phosphorus

Numerous rate studies have been made with phosphorus fertilizers on many crops throughout the tropical regions. The picture derived from the resulting literature is quite cloudy. Many reports indicate good responses with appreciable residual effects from nominal rates (FFHC Fertilizer Programme, 1968, Greenwood, 1951; Le Mare, 1959, Nye, 1952; Russell, 1968), whereas other reports indicate the need to satisfy or "quench" the soil's phosphorus fixing capacity by heavy phosphorus dressings before effective crop response occurs (Bradfield, 1963, Le Mare, 1968; Younge and Plucknett, 1966). Fixation is especially severe in weathered soils developed on volcanic ash in which the inorganic colloidal complex is largely hydrated iron and aluminum oxides.

Rates of phosphorus application commonly reported as giving good results when applied to food crops are 10 to 20 kg/ha, but from 100 to 1,200 kg/ha are indicated for high yields at some locations.

The disparity is seemingly a result of the wide diversity among tropical soils. Heavy rates are needed particularly with the Oxisols and Ultisols and soils formed from volcanic ash parent material. Even with these, however, research needs to establish if the same result could be achieved with nominal annual rates assisted by optimum granulation and placement with the most suitable chemical carrier of phosphorus for the situation. The average small farmer producing the food crops of the tropics could not bear the cost of phosphorus fertilizer required to quench a soil of high fixing capacity.

Sulfur

A rather small number of sulfur rate studies *per se* in the tropics have been reported. Many of the indicated yield responses to sulfur were acquired because of its presence in superphosphate or ammonium sulfate. The total sulfur content of soils varies greatly from the severely eroded and strongly weathered cultivated site with a low level of organic matter to the less weathered native forest site high in organic matter; thus, the required rate of application could be expected to range between 20 and 0 kg/ha annually. This is based upon a crop removal of 5 to 10 kg/ha and an approximate leaching loss of 10 kg/ha, the reported average from lysimeter studies with different cropping conditions in Senegal (Tourte *et al*, 1964). In French-speaking equatorial Africa, fertilizer treatment for the responsive cotton crop, for example, by design supplies an average 15 kg/ha of sulfur in ammonium sulfate (Braud, 1969), a nitrogen-to-sulfur ratio of 7:3 being considered optimal. On acid soils of the Campo Cerrado in central Brazil, it is postulated that 22 kg/ha of sulfur would likely be needed with intensive cropping and sufficient nitrogen and phosphorus treatments (McClung *et al.*, 1959).

Effectiveness of Fertilizer Carriers

Phosphorus

"Single" superphosphate has proved superior to other phosphorus carriers for groundnut production in northern Nigeria (Greenwood, 1951), particularly haulm production. Its superiority, however, has been proved to be a result of the gypsum present.

Eleven phosphatic fertilizers were compared with single superphosphate at nine locations for groundnuts, sunflower, maize, and sor-

ghum in Tanzania (Le Mare, 1959). Each fertilizer was applied at the rate of 10 kg/ha of phosphorus. Concentrated superphosphate was distinctly superior at four of the locations, all with soils near neutral to slightly alkaline in reaction. Dicalcium phosphate was distinctly inferior at two sites, but superior at three; calcium metaphosphate was inferior at three and superior at three, soda phosphate was inferior at five; basic slag was inferior at seven and superior at one; Seychelles guano was inferior at all but one site, where it was superior; four sources of rock phosphate were generally quite ineffective, except at one site where all proved equivalent or superior to superphosphate; and silicophosphate was superior at two and inferior at six. Among crops, sorghum was most effective in its utilization of the less soluble sources of phosphorus, sunflower the least. Questions raised by the data are how much needed secondary and trace element nutrition was afforded by impurities in the low-analysis materials where they beneficially influenced yields; how much better the low-solubility carriers might have functioned had they been disked or plowed into the soil rather than placed; what influence varied degree of granulation might have had; and how much sulfur contained in the superphosphate benefited yields relative to the non-sulfur-bearing carriers.

A number of studies report comparisons between rock phosphate and superphosphate. On lateritic red earth of Northern Territory, Australia, superphosphate gave greater immediate response in sorghum, but its residual effects declined more rapidly than those from rock phosphate (Arndt and McIntyre, cited by Jackson, 1966). Cumulative yields over a 7-year period, however, favored the superphosphate. Experiments in semihumid areas of West Africa have demonstrated the greater efficiency of the more soluble forms of phosphate (monocalcium, dicalcium, ammonium) over rock phosphates and slags (Bouyer, 1965; Braud, 1967). Even in humid areas, the soluble forms afford a quicker action than rock, despite rapid and strong fixation reactions with soil iron oxides. There are, however, major differences in plant availability of rock phosphate sources from different origins, some of which prove nearly as effective as acidulated sources for some crops (Terman *et al*, 1970). Citrate solubility in relation to fineness of grind must be considered before the practicality of native phosphate sources can be discounted.

Studies in Costa Rica show that some of the less soluble phosphorus materials give excellent results compared with concentrated superphosphate when applied to an ashy isothermic Typic Dystrandept (Fassbender and Molina, 1969). Silicon contained in the mate-

rials of low solubility may have been partially responsible. An additional factor in this work was the extreme effect of granulation in promoting fertilizer phosphorus utilization by the crop—a sixfold yield increase was achieved with granulation of the superphosphate.

Of particular interest in the review of crop response to different phosphorus carriers in the tropics is the rather frequent reference to outstanding results from "silico-phosphates" (Fassbender and Molina, 1969; Tyson as cited by Jackson, 1966; Le Mare, 1959). These materials are usually called Rhenania phosphate and are prepared by heating rock phosphate with silica sand and sodium carbonate. Whether the crop response is due to a direct effect of silicon as such on the crop's nutrition or to an indirect enhancement of fertilizer phosphorus utilization is conjectural at this stage. Certainly, Hawaiian workers have found that addition of silicate slag has highly beneficial effects on sugarcane yields, with concomitant increase in phosphorus uptake and decrease in soluble soil aluminum (Baver and Sherman, 1963; Fox *et al.*, 1967); likewise, Japanese and Korean workers have measured a benefit of added silicate minerals like wollastonite for the rice crop. It would be of real value to know the extent to which silicate may be satisfying the soil's phosphorus fixation capacity in these cases, rendering added phosphorus fertilizer more available to the crop.

Sulfur

Comparisons of sulfur carriers in the tropics have been limited because the major fertilizers used in the past to supply nitrogen and phosphorus have provided a source of sulfur as well. Introduction of high-analysis materials without the sulfur component has modified the situation, however, and for much of the humid tropics a new sulfur source must be established. Research in West Africa suggests that similar effects are obtained from virtually all forms of sulfur used as fertilizer, including sulfites, sulfates, sulfur combined in fertilizer formulations, and mineral sulfur (Bockelée-Morvan, 1966), which conforms with findings in temperate regions. A question requiring resolution over a range of tropical soils concerns the effect that prilling of elemental sulfur for convenient handling and distribution might have on retarding the rate of mineralization and concomitant leaching losses. A strongly granulated gypsum product has been effective (Millington and Powrie, 1968).

Tests To Determine the Need for Supplementary Phosphorus and Sulfur

Discussion to this point has implied that the majority of soils in the humid tropics are deficient in phosphorus and sulfur and that getting corrective treatment under way should be the prime consideration. However, a portion of the land area in the tropics is well supplied with these nutrients, and prescribing more at the moment would constitute an unnecessary and costly burden to the peasant farmer (International Soil Testing, 1968; Nye, 1952). Furthermore, as fertilization practices become established, some system of checks will become increasingly necessary to prevent buildup of excess concentrations of the added elements in the low-buffer-capacity soils involved. The problem with sulfur would presumably be minor because of its high leachability in the sulfate form, but phosphorus will accumulate. In soils without high fixation capacity, excess phosphorus could become a problem because its interaction with certain other nutrient elements would limit their uptake.

Phosphorus

A number of early attempts to predict crop response to fertilizers by direct soil analysis procedures met with poor success in tropical regions (Birch, 1952; Friend and Birch, 1960; Nye, 1952; Russell, 1968). One explanation was that most of the phosphorus available to the crop is released by organic matter decomposition and is not readily determinable by quick test. Recently, however, a comprehensive international soil testing program in Latin America has proved effective in distinguishing phosphorus-responsive areas from those that do not respond to fertilizer. Similarly, correlation and calibration studies in individual countries give evidence that extraction procedures adapted to the soils involved can indeed give good indication of response probabilities to applied fertilizer (Ahmad, 1967; Ayres and Hagihara, 1955; Baver and Ayers, 1962; Braga and Yahner, 1968, Le Mare, 1959; Monteith, 1966). A series of well-conceived field experiments on the important crops and soils of the locality for effectively measuring response to applied phosphorus is required, followed by correlation of these data in the laboratory with soil-testing values from surface as well as subsurface horizons. The North Carolina method (dilute hydrochloric and sulfuric acid extraction) and

the Bray and Kurtz No. 1 extraction procedure have proved effective in many situations.

Sulfur

Although a far smaller number of extraction procedures have been conceived for estimating the available sulfur status of soils than for phosphorus, some have been investigated successfully with particular reference to tropical soils (Fox *et al.*, 1964b; McClung *et al*, 1959). It does appear that subsoil sources of adsorbed sulfate may be particularly important in tropical regions, considering the relative ease with which sulfate leaches from the surface soil. This will presumably necessitate testing of subsoil as well as surface soil (Ensminger, 1954; Hesse, 1957).

Conclusions

It seems likely on the basis of these experiences that soil testing can become a valuable tool in assisting in the judicious use of fertilizer phosphorus and sulfur and the development of an effective fertilizer marketing system in the tropics. Undoubtedly, a large amount of research will be required for placing soil testing on a sound foundation across the full range of soils and cropping practices of the tropics, but the costs will be small compared with any other measure that might be attempted with the same objective.

Efforts should be made to strengthen national laboratories in keeping procedures properly oriented and in monitoring test results. Experienced technical personnel might work with technicians in the national laboratories in organizing basic studies for evaluating the significance to calibration of such things as seasonal variations in pH and available nutrient levels. These have been found to be important in temperate regions (Grimes and Hanway, 1967; Olson *et al.*, 1954; Van Der Paauw, 1962) and also in rice culture of the tropics (Ahmad, 1967). Seasonal variations could be considerable where wet and dry seasons occur in the tropics. Likewise, there could be considerable variation between savanna and partial or full forest cover, between heavily ridged and flat cultivated surface, and with other extreme conditions of the soil environment peculiar to equatorial regions. Competence in foliar analyses should be built into these laboratories to assist in diagnosing nutrition problems of all the crops grown in the region.

Interactions of Applied Phosphorus and Sulfur with Other Amendments

Effects of Lime on Phosphorus and Sulfur Availability

Cotton grown on Campo Cerrado soils in Brazil evidenced a decreasing response to 39 and 77 kg/ha of phosphorus with increasing rates of lime from 0 to 6 tons/ha (McClung *et al.*, 1962). The interpretation was that the lime increased the rate of mineralization of native soil organic phosphorus to the available form, especially as soils were first brought under cultivation. Isotopic dilution studies on three soil series of the same region found evidence of increasing soil phosphorus availability with increasing lime rate (Malavolta *et al.*, 1964), as did work with Central American Ultisols (Cordoba, 1968). The Central American studies showed a beneficial effect of liming soils up to pH 6.4 on availability of both native and applied phosphorus. In all experiments, however, overliming reduced the availability of fertilizer phosphorus. Soils of the Llanos Orientales in Colombia similarly afforded maximum response of maize to applied phosphorus only with concurrent lime treatment (Spain and Ruiz, 1968). Increased availability of fertilizer phosphorus in these situations was undoubtedly related to elimination of exchangeable aluminum and a reduction in phosphorus adsorption with concomitant effects on phosphorus availability to the plant (Woodruff and Kamprath, 1965). Work on Hawaiian Latosols indicates an increased uptake of fertilizer phosphorus by plants with very modest rates of liming and small changes of pH (Fox *et al.*, 1964a). Minimum aluminum concentration in the plant corresponded with maximum phosphorus uptake in these studies.

It would seem that liming, where a source of native limestone is in reasonable proximity, should be considered a necessary step toward improving soil and fertilizer phosphorus relations in tropical soils with a pH below 5.5, particularly where ammonium sulfate is used to satisfy nitrogen requirements. Liming will undoubtedly speed up the mineralization of native soil organic sulfur and the oxidation of elemental sulfur as well by enhancing the activity of the *Thiobacillus* microorganism responsible for these processes. The more rapid rate of sulfate production, however, could increase leaching losses and hasten depletion of the soil sulfur supply. This seems likely, just as accentuation of nitrate leaching losses is a probability with liming of the acid tropical soil. Perhaps the minimal lime rates required for

eliminating exchangeable aluminum as previously discussed will not have the profound effect on nitrogen and sulfur oxidation observed with conventional liming of temperate region soils, nor will they have the effect of reducing yields often noted in early experiments (Russell, 1968). The research needed to confirm these suggestions remains to be done.

Effect of Ammonium on Phosphorus Uptake

Many field studies with fertilizers have demonstrated a complementary effect of one nutrient on another, whereby yield response to the two nutrients applied simultaneously exceeds the sum of the responses achieved by applying each separately (Russell, 1968). Such effects are encountered throughout biological systems and can be anticipated in any situation where more than one element is deficient. Beyond the mutual dependence aspect, fertilizer nitrogen, especially in the ammonium form, has been shown to enhance uptake of fertilizer phosphorus by plants if the phosphorus and nitrogen are chemically or physically associated (Grunes, 1959; Olson and Dreier, 1956). The phenomenon is most evident in the more acid soils where the ammonium ion persists longer against nitrification and is probably related to some plant metabolite that influences absorption and translocation of phosphorus.

Impact of nitrogen on uptake of fertilizer phosphorus accounts in considerable part for the widespread use of "starter" fertilizers containing nitrogen and phosphorus on many crops in temperate regions. It would seem to be especially significant for the tropics for some years to come, in view of the relatively high cost of fertilizer and the need for maximum efficiency of fertilizer utilization.

Silicon-Phosphorus Relations

Earlier discussion of phosphorus carriers covered the apparent silicon–phosphorus interaction in the production of some crops. Improved uptake of fertilizer phosphorus is generally noted where added silicate is beneficial to yield, just as high silicate content of native soil is associated with limited crop response to applied phosphorus (Birch, 1953; McGeorge, 1924; Némec, 1932). Alleviation of phosphorus fixation to some degree by the added silicate seems quite

probable in Oxisols and Ultisols, which have high levels of iron and aluminum and low levels of silicon (Bradfield, 1963).

Sulfur-Phosphorus Interactions

It is doubtful that applied sulfur will afford the benefit to phosphorus uptake by crops in the acid soils of the humid tropics that is reported for the neutral to alkaline soils in temperate regions. In the latter, the acidifying action of the applied sulfur has received credit for the prolonged availability of added phosphorus. It might rather be expected that further acidification of a tropical soil already strongly acid would accelerate phosphorus fixation reactions. Complementary beneficial effects on yields of the two elements added simultaneously could be expected, however, where both are nutritionally inadequate.

Deleterious Effects from Applied Phosphorus

Depressive action of applied phosphorus on zinc uptake of several crops is well established in temperate regions, particularly under conditions of high soil pH. There is good reason to expect that many of the highly leached soils of the tropics are currently at marginal availability levels for zinc and other heavy element nutrients, and that repeated application of high-analysis phosphorus fertilizers with little or no trace-element impurities could induce a deficiency state of those micronutrients. The Upper Veldt of Swaziland is perhaps a case in point; supplementary zinc and molybdenum are considered essential with applications of nitrogen and phosphorus for maize production (Jackson *et al.*, 1965).

Influence of Applied Sulfur on Other Nutrients

Sulfur applied in quantity has an acidifying influence on soils that can cause a sharp reduction in pH and concomitant excessive sulfur and manganese uptake by the plant (Hassan and Olson, 1966). Otherwise, sulfur treatment at moderate rates beneficially influences crop utilization of nitrogen, phosphorus, sulfur, manganese, zinc, iron, and copper on neutral and calcareous soils of a cool temperate region. Similar results could probably be expected in the neutral soils of the tropics, with deleterious effects being accentuated by increasing soil acidity.

REFERENCES

Ahmad, N. 1967. Seasonal changes and availability of phosphorus in swamp-rice soils of North Trinidad. Trop. Agr. 44:21-32.

Ayres, A. S., and H. H. Hagihara. 1952. Available phosphorus in Hawaiian soil profiles. Hawaiian Planter's Rec. 54:81-99.

Ayres, A. S., and H. H. Hagihara. 1955. Soil analyses as index of nutrient availability. Hawaiian Planter's Rec. 55.113-125.

Barrow, N. J. 1960. A comparison of the mineralization of nitrogen and of sulfur from decomposing organic materials. Aust. J. Agr. Res. 11:960-969.

Bartholomew, R P. 1931. Changes in the availability of phosphorus in irrigated soils. Soil Sci. 31:209-218.

Baver, L. D., and A. S. Ayres 1962. Soil analyses as basis for fertilizer recommendations in sugar cane. Trans. Joint Meet. Comm. IV and V, Int. Soc. Soil Sci., New Zealand. p. 835-841.

Baver, L. D., and G. D. Sherman. 1963. Calcium silicate slag as an amendment for sugar cane soils. Exp. Sta. Hawaiian Sugar Planters Association Spec. Rep., Directors Series No. 4.

Beauchamp, R. S. A. 1953. Sulphates in African inland waters. Nature 171: 769-771.

Birch, H. F. 1952. The relationship between phosphate response and base saturation in acid soils. Agr. Sci. 42:276.

Birch, H. F. 1953. Phosphate response, base saturation and silica relationships. Agr. Sci. 43:229-235.

Bloomfield, C., J. K. Coulter, and R. Kanaris-Sotiriou. 1968. Oil palms on acid sulphate soils in Malaya. Trop. Agr 45:289-300.

Bockelée-Morvan, A. 1966. Efficacité des diverses formes d'apport des éléments minéraux sur l'arachide. Oleagineux 21:163-166.

Bouyer, S., and M Damour. 1964 Les formes du phosphore dans quelques types de sols tropicaux. Transactions 8th Int. Cong. Soil Sci. 4:551-561.

Bouyer, S. 1965. L'experimentation en matière de fertilization. Agron. Trop. 20: 1025-1028.

Bradfield, R. 1963. The soil chemist and food for peace, p. 42-51. *In* Food for peace. ASA Spec. Pub. No. 1. American Society of Agronomy, Madison, Wis.

Braga, J. M., and J. Yahner. 1968. Estudo comparativo de fosfata de Araxa e super fosfato simples em culture de milho, em um solo de vicosa, Minas Gerais. Experentiae 8 143-163.

Braud, M. 1967. L'experimentation sur les formes de phosphate en culture cotonnière. p. 862-873. *In* Colloque sur la fertilite des sols tropicaux, Tananarive. Vol. 1. Institut de Recherches Agronomiques Tropicales, Paris.

Braud, M. 1969. Sulphur fertilization of cotton in tropical Africa. Sulphur Inst. 5:3-5.

Chang, S. C., and M. L. Jackson. 1958. Soil phosphorus fractions in some representative soils. J. Soil Sci. 9:109-119.

Cordoba, F. 1968. The effect of lime on the availability of P in soils of the Tropics. Diss. Abst. Sec. B. 29:840 B.

Dabin, B. 1970. Méthode d'étude de la fixation du phosphore sur les sols tropicaux. Coton Fibres Trop. 25:213-234.

Dutt, A. K. 1962. Sulphur deficiency in sugarcane. Emp J. Exp. Agr. 30: 257-262.

Ensminger, L. E. 1954. Some factors affecting absorption of sulfate by Alabama soils. Soil Sci. Soc Am Proc. 18.259-264.

Enwezor, W. O., and A. W. Moore. 1966. Phosphorus status of some Nigerian soils Soil Sci. 102:322-328.

Evans, C. A., and C. O. Rost. 1945 Total organic sulfur and humus sulfur in Minnesota soils Soil Sci. 59.125-137.

FFHC Fertilizer Programme 1968. Physical and economic summary of trial and demonstration results, 1961/62-1965/66. FAO Report LA:FFHC/68/14. Food and Agriculture Organization, Rome.

Fassbender, H W, and R Molina. 1969. Effects of silicates and liming on soil phosphates in volcanic ash soils of Costa Rica, Sec. C2, p. 1-12, *In* Panel on Volcanic Ash Soil in Latin America Inter-American Institute of Agricultural Sciences, Turrialba, Costa Rica.

Fox, R. L, S K. DeDatta, and J. M. Wang. 1964a. Phosphorus and aluminum uptake by plants from Latosols in relation to liming Transactions 8th Int. Cong. Soil Sci. 4.595-603.

Fox, R. L., R A. Olson, and J. F. Rhodes. 1964b. Evaluating the sulfur status of soils by plant and soil tests. Soil Sci. Soc. Am. Proc. 28:243-246.

Fox, R. L., J. A. Silva, O. R. Younge, D. L. Plucknett, and G. D. Sherman. 1967. Soil and plant silicon and silicate response to sugar cane. Soil Sci. Soc. Am. Proc. 31:775-779.

Fox, R. L., D. L. Plucknett, and A. S. Whitney. 1968. Phosphate requirements of Hawaiian Latosols and residual effects of fertilizer phosphorus. 9th Int. Cong. Soil Sci. 2:301-310.

Friend, M. T., and H. F. Birch. 1960. Phosphate responses in relation to soil tests and organic phosphorus. Agr. Sci. 54:341-347.

Gasser, J. K. R., and C. Bloomfield. 1955. The mobilization of phosphate in water-logged soils. J. Soil Sci. 6:219-232.

Greenwood, M. 1951. Fertilizer trials with groundnuts in Northern Nigeria. Emp J. Exp. Agr 19:225-241.

Grimes, Donald W., and John J. Hanway. 1967. Exchangeable soil potassium as influenced by seasonal cropping and potassium added in crop residues. Soil Sci. Soc. Am. Proc. 31:502-506.

Grunes, D. L. 1959. Effect of nitrogen on the availability of soil and fertilizer phosphorus to plants. Adv. Agron. 11:369-396.

Hagenzicker, F. 1956. Studies on subsoil placement of fertilizer at Urambo, Tanganyika Territory, East Africa. Plant Soil 9:97-113.

Hassan, N., and R. A. Olson. 1966. Influence of applied sulfur on availability of soil nutrients for corn (*Zea mays* L.) nutrition. Soil Sci. Soc. Am. Proc. 30:284-286.

Hesse, P. R. 1957. Sulphur and nitrogen changes in forest soils of East Africa. Plant Soil 9.86-96.

IAEA Laboratory Activities. 1969. Tech. Rep. Ser. No. 98. International Atomic Energy Agency, Vienna.

International Soil Testing. 1968. The fertilizer requirements of countries in Latin America. Annu. Rep. Contract AID/csd-287. North Carolina State University, Raleigh.

Islam, M. A., and M. A. Elahi. 1954. Reversion of ferric iron to ferrous iron under waterlogged conditions and its relation to available phosphorus. J. Agr. Sci. 45:1–2.

Jackson, F. A. 1966. Phosphorus fertilizer research in Australia. Bull. 284. Commonwealth Industrial and Research Organization, Melbourne.

Jackson, P., A. Venn, and J. l'Ons. 1965. Responses on Swaziland soils to lime and trace elements, p. 305–323. *In* Symposium on the maintenance and improvement of soil fertility, Khartoum. OAU/STRC Pub. No. 98. Commission for Technical Cooperation, Africa, London.

Joint FAO/IAEA Division. 1970. Rice fertilization. Tech. Rept. Ser. No. 108. International Atomic Energy Agency, Vienna.

Jordan, H. V., and H. M. Reisenauer. 1957. Sulfur and soil fertility. *In* Soil. The yearbook of agriculture. U.S. Department of Agriculture. U.S. Government Printing Office, Washington, D.C.

Kamprath, E. J. 1970. Exchange aluminum as a criterion for liming leached mineral soils. Soil Sci. Soc. Am. Proc. 34:252–254.

Kanwar, J. S. 1967. Sulfur deficiency a key factor in Indian agriculture. Fert. News 12:9–13.

Le Mare, P. H. 1959. Soil fertility studies in three areas of Tanganyika. Emp. J. Exp. Agr. 27:197–222.

Le Mare, P. H. 1968. Experiments on the effects of phosphate applied to a Buganda soil. II. Field experiments on the response curve to triple superphosphate. J. Agr. Sci. 70.271–279.

Malavolta, E., O. J. Crocomo, and R. G. Andrade. 1964. Effect of liming on the availability of P in cerrado soils of Brazil. Proc. 3rd Int. Conf. Peaceful Uses Atom. Energy 15:507–510.

McClung, A. C., and L. M. M. de Freitas. 1959. Sulphur deficiency in soils from Brazilian campos. Ecology 40·315–317.

McClung, A. C., L. M. M. de Freitas, and W. L. Lott. 1959. Analyses of several Brazilian soils in relation to plant responses to sulfur. Soil Sci. Soc. Am. Proc. 23:221–224.

McClung, A. C., L. M. M. de Freitas, D. S. Mikkelsen, and W. L. Lott. 1962. Cotton fertilization on Campo Cerrado soils. State of São Paulo, Brazil. IBEC Res. Inst. Bull. 27. New York.

McGeorge, W. T. 1924. The influence of silica, lime and soil reaction upon the availability of phosphates in highly ferruginous soils. Soil Sci. 17:463–468.

Middleton, K. R. 1954. Distribution of total phosphate in certain Sudan soils. Trans. 5th Int. Cong. Soil Sci. 3:218–222.

Mikkelsen, D. S., L. M. M. de Freitas, and A C. McClung. 1963. Effects of liming and fertilizing cotton, corn and soybeans on Campo Cerrado soils. State of São Paulo, Brazil. IRI Res. Inst. Bull. 29. New York.

Millington, R. J., and J. K. Powrie. 1968. Dissolution and leaching of fertilizer granules. Trans. 9th Int. Cong Soil Sci 3:385–393.

Monteith, N. H. 1966. Use of soil phosphorus and potassium analyses for fertilizer advice on sugarcane lands in Fiji. Trop. Agr. 43:75–82.

Neller, J. R. 1959. Extractable sulfate-sulfur in soils of Florida in relation to amount of clay in profile. Soil Sci. Soc. Am. Proc. 23:346–348.

Némec, A. 1932. Méthode rapide pour déterminer l'effet des engrais phosphatés sur le rendement des cultures agricoles. Proc. 2nd Int. Cong. Soil Sci. 4:215–219.

Nye, P. H. 1952. Studies on the fertility of [illegible] Coast soils. III. The phosphate status of the soils Emp J. Exp. Agr. 2[illegible]47-55.

Nye, P. H., and M. H. Bertheux 1957. The distribution of phosphorus in forest and savannah soils of the Gold Coast and its agricultural significance. J. Agr. Sci. 49 141-159.

Olson, R. A., M B Rhodes, and A. F. Dreier. 1954. Available phosphorus status of Nebraska soils in relation to series classification, time of sampling and method of measurement. Agron. J. 46:175-180.

Olson, R. A , and A F Dreier. 1956. Nitrogen a key factor in fertilizer phosphorus efficiency. Soil Sci. Soc. Am. Proc. 20.509-514.

Patrick, W. H 1964. Extractable iron and phosphorus in a submerged soil at controlled redox potentials. 8th Int. Cong Soil Sci. 4: 605-609.

Pierre, W. H., and A. G. Norman [ed.]. 1953. Soil and fertilizer phosphorus in crop nutrition. Agron. Monogr. Vol. 4. Academic Press, New York.

Russell, E. W. 1968. The place of fertilizers in food crop economy of tropical Africa. Proc No. 101. The Fertilizer Society, London.

Spain, J., and A. Ruiz. 1968 The Colombian Llanos Orientales. A preliminary mimeo report. Centro Internacional Agricultura Tropical, Bogotá, Colombia.

Terman, G. L., S. E. Allen, and O. P. Engelstad. 1970. Response of paddy rice to rates and sources of applied phosphorus. Agron. J. 62:390-394.

Tourte, R., P. Vidal, L. Jaquinot, J. Fauche, and R. Nicow 1964. Bilan d'une rotation quadriénnale sur sols de regénération au Sénégal. Agron. Trop. 19:1033-1072.

Van Der Paauw, F. 1962 Periodic fluctuations of soil fertility, crop yields and of responses to fertilization effected by alternating periods of low or high rainfall. Plant Soil 17:155-182.

Woodruff, J. R , and E. J. Kamprath. 1965. Phosphorus adsorption maximum as measured by the Langmuir-isotherm and its relationship to phosphorus availability. Soil Sci. Soc. Am. Proc. 29:148-150.

Younge, O. R., and D. L. Plucknett. 1966. Quenching the high phosphorus fixation of Hawaiian Latosols. Soil Sci. Soc. Am. Proc. 30:653-655.