

# Phosphorus deficiency in tropical soils as a constraint on agricultural output

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Highly weathered soils in the tropics, such as Ferralsols, Acrisols, and Luvisols are generally deficient in phosphorus. The amount of phosphorus adsorbed by soils is highly correlated with exchangeable aluminum, total iron, organic matter, and low pH. In highly weathered soils, the phosphorus is mainly in the organic and occluded forms. Iron-phosphorus is dominant in an active form.

Because the availability of phosphorus in soils is a function of the quantity-intensity relationship, estimates of the phosphorus requirement can be obtained from adsorption isotherms.

Various soil tests can be used to estimate phosphorus availability. Among ordinary chemical tests, the amended Olsen method has generally given high correlation with plant growth for drained soils as well as for flooded soils under acid or alkaline conditions. The critical limits of phosphorus availability are related to the total nitrogen content of the soil

$$\frac{P}{N} = \frac{1}{40}$$

and increases with high fixation capacity.

Recent trends in phosphorus fertilization are the conservation of excessively soluble phosphates by mixing them with rock phosphate and improving the technology of placement, additional amendments, and management practices. Research is needed to determine methods of more efficient application of fertilizer.

ABOUT 100 MILLION t of complete (NPK) fertilizers are used annually in the world – about 25 million t in developing countries (von Peter 1978). Of the constituents, phosphate accounts for 25%, potash 25%, and nitrogen 50%. Fer-

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tilizer consumption figures vary considerably from one region to another. Some African countries use small amounts, but many Asian and Latin American countries have made substantial gains in fertilizer use and themselves produce fertilizers.

It is difficult to give a global assessment of phosphorus requirements because they depend on crop density and yield, and variable soil requirements. The requirements are also related to the type of soil, length of time and intensity of uptake, and to other inputs.

Tropical soils that have reached an advanced degree of development seem to have the highest phosphorus deficiency probability. A survey by IMPHOS and GERDAT (Roche et al 1978) shows that Ferralsols and Acrisols (FAO classification, ferrallitic soils in the French classification) and Luvisols (tropical ferruginous soils), as well as Gleysols and Vertisols, in most cases (about 66%) show serious to very serious phosphorus deficiencies. Cambisols (soils with inorganic reserves) show average phosphorus deficiency, and Fluvisols (alluvial soils) and Nitisols (well-structured clayey soils) often show low to no deficiency. The nature of the parent rock, pH, the presence of fixing compounds such as sesquioxides, and the organic reserve are essential factors in the phosphorus resources of soils. Over vast areas of the Sahel, soils low in organic matter content are also low in phosphorus, but this deficiency is often obscured by an even greater nitrogen deficiency. Large yield increases connected with nitrate fertilizer, manure, and organic amendments require the addition of phosphorus. Phosphorus contents of soils in moist regions, which are high in humus, are variable, and the N-P<sub>2</sub>O<sub>5</sub> ratios and fixation capacity of those soils are predominant factors in phosphorus fertilizer requirements.

#### CHEMICAL FIXATION OF PHOSPHORUS

##### Buffer capacities of soils

The supply of phosphates to plants depends on the concentration of soluble phosphate ions in the soil solution, as well as on the soil's capacity to maintain this concentration. The *buffer capacity* of the soil is represented by the ratio of quantity ( $Q$ ) to intensity ( $I$ ) and is related to the soil's phosphorus fixing capacity (Schofield 1955).

A graph of adsorbed phosphorus ( $Q$ ) against phosphorus in solution ( $I$ ) provides isothermal curves. With it, Olsen and Watanabe (1970) showed that the buffer capacity affects phosphate supply to plants, and that for a proper supply to roots a low  $Q$ - $I$  ratio requires a high concentration, and vice versa.

Phosphorus concentrations of the soil solution ranged from 0.3 to 3 ppm (Mengel and Kirkby 1978, Hossner et al 1973), but levels of 0.05 to 0.08 ppm frequently occur in tropical soils and are regarded as adequate for optimum growth of rice plants (Katyal 1978).

In most acid tropical soils with high levels of iron and aluminum oxides, phosphorus adsorption is high and the solution concentration is low. Conse-

quently, the quantity factor must play a major role in plant nutrition. In addition, the high temperature in tropical soils leads to a faster replacement of solutions, accompanied by a quicker decomposition of organic and inorganic reserves of low solubility. Measurement of the fixation capacity of soils remains an essential factor in evaluating the levels of exchangeable or assimilable phosphorus so as to ensure adequate phosphorus nutrition.

Not all measurements of fixation capacity are standardized. They depend on the ratio of soil to solution. Gachon (1969) defined this capacity as the quantity of phosphorus ( $P_2O_5$ ) needed to obtain a 2 ppm concentration in equilibrium in a 1-4 soil-solution ratio. The percentage of phosphorus in solution can also be measured in a 1-4 ratio of soil to liquid. Examples of measurements (Oliver 1972, Le Buanec 1973) are shown in Table 1.

Fixation rates are more or less constant for solutions of between 200 and 1,000 ppm of an  $NH_4Cl$  extract on air-dried ferrallitic and ferruginous soils (Dabin 1970).

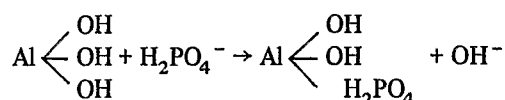
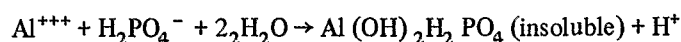
Juo and Fox (1977) determined the requirement as 0.2 ppm phosphorus in an equilibrium solution after 6 days.

#### Factors affecting phosphorus fixation capacity

*Effect of oxides.* Phosphate ions in the soil solution depend on pH:

- $H_2PO_4^-$  = for highly acid solution,
- $HPO_4^{2-}$  = for medium-acid solution, and
- $PO_4^{3-}$  = for alkaline solution.

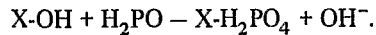
The ions react with exchangeable aluminum or aluminum hydroxide in accordance with the following formulas:



**Table 1.** Fixation of phosphorus by various soils based on an initial phosphorus concentration of 200 ppm.

Soil	Final conc after 24 hours (ppm P)	% remaining in solution
Hydromorphous soil, medium organic (Madagascar)	0.105	0.05
Ferrallitic soil on gneiss (Madagascar)	0.65	0.3
Ferrallitic soil in forest land (Ivory Coast)	20	10
Central grassland soil (Ivory Coast)	34	17
North grassland soil (Ivory Coast)	62	31

Fixation depends on the ratio of  $R_2O_3$  to  $P_2O_5$ . Clay and allophanes fix  $PO_4$ . The 1:1 clays fix more than 2:1 clays via the hydroxy groups on the surface:



Similarly, in dilute solution  $PO_4$  is fixed by goethite via reaction with FeOH groups on the iron oxide surfaces.

Phosphorus fixation is rapid at the start and then increases slowly with time. Physical fixation is distinguished from chemical fixation and can be determined by extracts using 0.1N soda, citrate dithionine, or bicarbonate. Chemically fixed forms include those that diffuse through a porous material (Ryden et al 1977). Isotopic exchange tests with P-32 have shown that as the adsorption period lengthens, ease of desorption and the isotopic exchange capacity of adsorbed phosphorus decreases with time. The isotopic exchange capacity of physically fixed phosphorus is 10 times higher than for chemically fixed phosphorus. In Andosols, the complexes containing allophane and imogolite possess the highest fixation capacity (8,000 to 15,000 mg  $P_2O_5/1,000$  g soil); similarly, iron and aluminum combined with humus, compounds related to allophane, and gel materials rich in alumina also contribute to phosphorus fixation.

Correlations established (Roche et al 1978) between the fixation capacity according to Gachon (1969) and other factors measured in 114 soils of various origins are as follows:

Fixation capacity with regard to phosphorus correlated with clay and fine silt (0.51), organic matter (0.7), total aluminum (0.63), exchangeable aluminum (0.86), total iron (0.55), all significant at 0.1%.

Presence of montmorillonite, vermiculite, illite, chlorite,  $r = 0.31$ , significant at 1%.

Presence of gibbsite,  $r = 0.4$  significant at 1%.

Ferralsols-Acrisols have a correlation with fixation capacity,  $r = 0.54$ , significant at 1%.

*Effect of pH-value on fixation capacity.* The fixation capacity of iron and Al. hydroxides is greatest below pH 5.5; it decreases between pH 5.5 and 7, and is least at pH 7. Above pH 7.5, phosphorus is fixed by calcium and magnesium. Tests in Colombia (Gildardo Marin 1977) with 3 t lime/ha on soils of volcanic origin, with high fixation capacity, produced wheat yield increases equivalent to those obtained by 160 kg  $P_2O_5/ha$ .

#### **Fixation of soluble phosphorus by the solid soil phase**

Chang and Jackson's (1957) fractionation method has been used for studies of fixation of soluble phosphorus by the solid soil phase.

Phosphorus is extracted by means of various successive reagents. The quantities of  $PO_4^{-3}$  in the various extracts represent soluble phosphorus and fractions linked to aluminum, iron, and calcium, which are shown conventionally as soluble P, Al P, Fe F, and Ca P, although these are not clearly defined chemical or mineralogical species. Many analyses of widely differing soils show a good

relationship between the distribution of soluble phosphorus fractions and soil physical and chemical properties. In acid, oxide-rich soils, the Fe P and Al P forms predominate. The proportion of Ca P is greatest in calcareous soils.

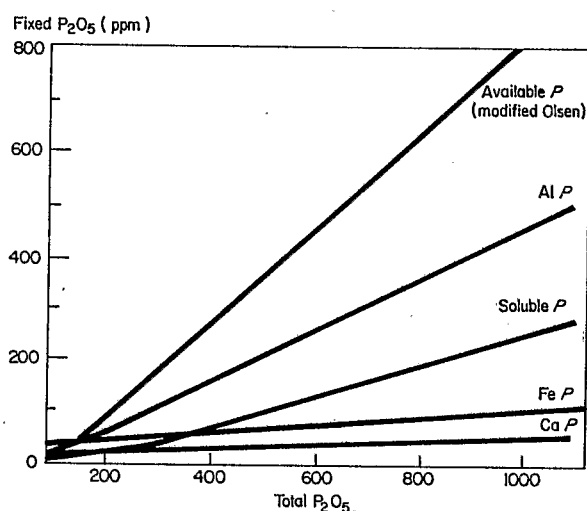
Distribution among active forms, occluded forms, and organic forms of phosphorus in the solid soil phase depends on the degree of evolution of the soil.

In young soils and in calcareous or calcic soils, apatite (Ca P) predominates. As the original materials weather, a large quantity of phosphorus dissolves and is lost; another part is fixed in an adsorbed or active inorganic form (non-occluded), and a large fraction evolves toward occluded forms (occluded P) and the organic form.

In a tropical soil at a medium stage of evolution, organic, occluded inorganic, and adsorbed inorganic forms of phosphorus each account for about one-third of the total. In highly evolved soils, adsorbed active forms diminish in favor of organic and occluded forms. For example, in acid Nigerian soils (Alfisols, Ultisols, Oxisols, Vertisols; pH 4.5 to 6), Fe P represents 60% of the active form when the  $\text{Fe}_2\text{O}_3$  content ranges from 2–7%. Ca P is the lowest, and Al P is less than 1% (Udo and Ogunwale 1977) occupies an intermediate position except when  $\text{Fe}_2\text{O}_3$  is less than 1%.

#### Short-term and long-term phosphorus fixation

Chang and Chu (1961) have shown that when a soluble phosphate is added to soils of average moisture content and pH values from 5.3 to 7.5, fixation after 3 days is mainly in the form of Al P or Ca P depending on the pH value. In a



1. Chang and Jackson fractionation on enriched soil Sandy hydromorphic soil, Chad. 3 days contact – soluble phosphate.

soil suspension the form Fe P may predominate even in a short time. After 100 days, Al P and Ca P decrease and Fe P increases. The increase is particularly rapid in a very moist soil.

In short-term (3 days) fixation test with soils with medium to high fixation capacity, Dabin (1970) found that the quantities of phosphorus fixed between 0 and 1,000 ppm  $P_2O_5$  in various forms (soluble P, Al P, Ca P, Fe P) increased linearly in relation to the quantity added. The slope of the lines measured the reactivity of each form.

In most acid soils with sesquioxides, it is Al P (Fig. 1) that shows the highest reactivity; Fe P has a slightly less steep slope, and Ca P a very slight slope. In moist goethite-rich forest soils (Fig. 2), it is the Fe P fixation slope that is steepest, because of its reactivity in the surface horizon. In soils with a pH value of less than 5.5, soluble phosphorus is very slight; between pH 5.5 and 7.5, soluble phosphorus increases steadily. In humus-bearing calcic soils of pH 7.5, soluble phosphorus is extensive, and the Ca P is greater than Al P or Fe P.

#### Biological phosphorus fixation

In soils with high organic content and a high carbon-phosphorus ratio, biological fixation of phosphorus in microbial bodies may occur. This fixation is reversible.

#### Phosphorus fixation in the case of submerged soils

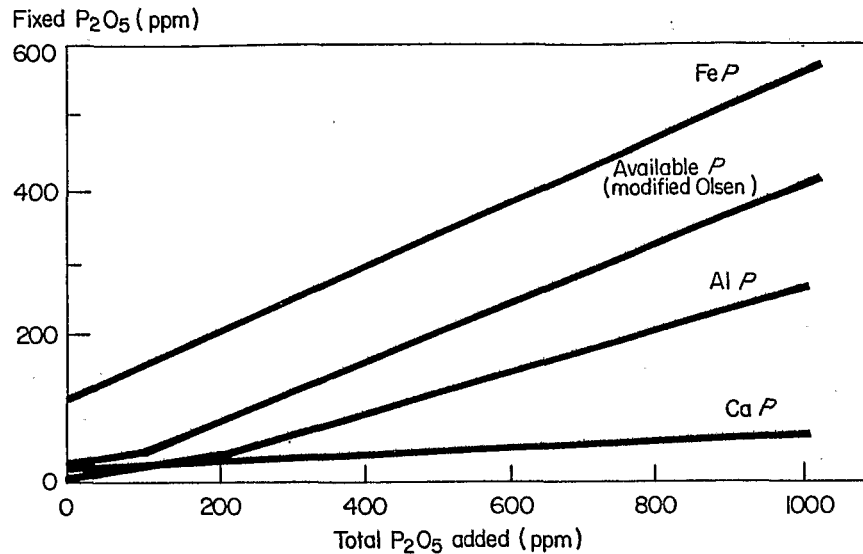
Fixation of phosphorus in submerged soils depends on alterations in the forms of fixing compounds caused by the drop in Eh (redox potential).

Ponnamperuma (1972) showed that the pH in acid soils grows steadily, and tends asymptotically toward pH 6.7 to 7.2 in high humus, iron-rich soils; in low humus, iron-poor soils, it levels out at less than pH 6.5. In calcareous and sodic soils, on the other hand, the pH tends to decrease because of accumulation of the carbon dioxide ions.

In submerged soils, iron as ferric oxide is reduced to the ferrous form, making it more soluble and likely to migrate. Similarly,  $Mn^{++++}$  is reduced to soluble  $Mn^{++}$ . Soluble iron and manganese move toward oxygenated surfaces where they precipitate again in oxidized form. Iron reduction is greatest below pH 6, and slows considerably at pH 7 and above. Because of the reducing substances that organic matter contains, its presence contributes to solubilization of the iron.

In an acid medium-moist soil (pH of 5.4), iron phosphate is insoluble. Under flooding the solubility of Fe P (60 kg  $P_2O_5$ /ha) increases from 4 to 12 ppm after 10 to 75 days flooding; it reaches a maximum on the 75th day, then decreases between 75 and 105 days (Kar et al 1977). The pH may reach 6.1 at the end of the period. The solubility of superphosphate, which is very soluble (16 ppm) at the beginning of flooding, decreases rapidly with time and becomes less than that of iron phosphate after 45 days. The solubility curve of Fe P is parallel to that of iron.

In slightly calcareous soils, submersion decreases phosphorus fixation and the addition of organic matter increases phosphorus solubility after 32 days. In



2. Chang and Jackson fractionation on enriched soil. Ferrallitic soil, Cameroun. 3 days contact, soluble phosphate.

calcareous soils a drop in pH from 7.4 to 7.1 was probably due to the effect of carbon dioxide on calcium carbonate (Shantamallaiah 1976). Ca P is released as the pH drops, and Fe P and Al P are released when it rises.

Moisture conditions altered phosphorus fixation (Mandal and Khan 1975). The increase of Fe P in acid soils submerged for 30 days was lower than in soils kept at field capacity. In neutral soils, on the other hand, phosphorus fixation at various sites remained high regardless of moisture conditions.

Black clayey calcic soils (Vertisols) present a special case. When they are adequately drained (e.g. as for a cotton crop), no serious phosphorus deficiency occurs. When flooded (rice paddy), however, phosphorus deficiency is frequent. These calcium-rich soils of neutral pH contain fairly large quantities of iron and manganese in the clay.

Fixation capacity, which is not very high in a dry soil because of the neutral pH and favorable structure, increases under flooding through an increase of contact surfaces with clay and oxides.

#### METHODS OF MEASURING AVAILABLE PHOSPHORUS IN SOIL

There are many methods of measuring available or assimilable phosphorus. (Actually, use of the term *labile P* is preferred.) Different methods give variable

results, according to the type and concentration of extraction reagents, the soil-solution ratio, agitation time, and temperature. Consequently, the results must be accompanied by the name of the method used. In addition, the data must be calibrated with crop tests.

The best measurement methods are those that give the highest correlations with plant growth and yields. Historically, the different methods developed in different countries have been found most suitable for conditions (soil, climate, plants) in the area where they were developed. Many authors have tried to compare the methods and define their conditions of use more clearly. Others have done more fundamental research on phosphorus dynamics in soils, using the isotope  $^{32}\text{P}$ .

#### Commonly used techniques

The traditional techniques using chemical reagents are listed:

- *Organic extracting solutions*
  - Dyer – 2% citric acid
  - Joret Hebert – 0.2 N ammonium oxalate
  - Morgan – 0.75 N sodium acetate in 0.5 N acetic acid, pH 4.8
  - Egner – 0.1 ammonium lactate in 0.4 N acetic acid, pH 4.
- *Acid inorganic extracting solutions*
  - Truog – 0.002 N  $\text{H}_2\text{SO}_4$  buffered to pH 4.8 with ammonium acetate
  - Mehlich or North Carolina method
  - 0.025 N  $\text{H}_2\text{SO}_4$  in 0.5 N HCl
  - Other methods using  $\text{H}_2\text{SO}_4$  or HCl at higher concentrations, 0.2 N or 0.5 N.
  - Bray 1 – 0.03 N  $\text{NH}_4\text{F}$  in 0.02 N HCl
  - Bray 2 – 0.03 N  $\text{NH}_4\text{F}$  in 0.1 N HCl
- *Alkaline reagents*
  - Olsen – 0.5 N  $\text{NaHCO}_3$  at pH 8.5
  - Saunders – 0.1 N NaOH
  - Modified Olsen – 0.5 N  $\text{NaHCO}_3$  + 0.5 N  $\text{NH}_4\text{F}$  buffered to pH 8.5 by NaOH (Dabin 1967)
  - 0.5 N  $\text{NaHCO}_3$  + EDTA
- *Water and very dilute saline solution*
  - Distilled water
  - 0.01 M  $\text{CaCl}_2$  Schofield – equilibrium potential (Aslyng 1964)
  - Anionic resin and soil suspension in water
- *Isotopic methods*
  - E value – Isotopic exchange with P-32 without using plants (MacAuliffe)
  - L value – Isotopic exchange with P-32 using plants (Larsen)

Many scientists have adopted the isotopic techniques. The traditional techniques are most often used as routine laboratory methods. Other methods are research tools for learning more about phosphorus dynamics, particularly its rate of desorption in relation to time. This is the case with Fardeau's isotopic methods and also the use of adsorption isotherms. Phosphorus extracted by a



strong acid (concentrated nitric acid or perchloric acid) is routinely used for tropical soils.

#### Comparison of methods

Many reports provide comparison among methods. Soils in 43 different regions on all 5 continents have been tested by 43 authors using the techniques mentioned earlier. Recent studies of soils of both temperate and tropical regions include van Raij's comparison (1978) of 12 different methods. The selection criterion is restricted to results of pot tests with measurement of the phosphorus extracted by test plants in the absence of phosphate fertilizers but with all other conditions for plant development.

The Olsen and Bray methods are frequently used and show fairly consistent correlations with pot results; the results of other chemical methods vary more from one region to another. Of all chemical methods Olsen's appears to give the best results. One reason for its overall superiority is that, unlike other methods, it gives good correlations for both submerged and aerobic soils, even with air-dried soils.

Acid reagents appear to be less effective for tropical soils high in sesquioxides, where labile phosphorus consists mainly of Al P and Fe P. Better extraction is obtained by Olsen, Bray, and resin methods. The Olsen method is also effective for acid and saline soils.

Roche et al (1978) used 168 different soils, graded according to the FAO/UNESCO classification, to show correlations between phosphorus uptake in pot tests and the results of analyses of soil phosphorus using a number of methods. The best correlations for all soils (0.884) were by the Gachon (1969) index. The L value (0.796), Dabin-modified Olsen method (0.633), and the Saunder method (0.613) are all significant at 1%.

Other methods are more difficult to use. Anionic resin gives the best results; isotopic techniques (*E* and *L* values) give satisfactory results but they are slightly inferior to those using resin.

#### Relations between assimilable phosphorus methods and Chang and Jackson fractions

Chang and Juo (1963) correlated results obtained by routine assimilable phosphorus analysis techniques with forms of phosphorus. Acid extracts represent assimilable phosphorus better when Ca P predominates; alkaline extractants are better when Fe P and Al P predominate; mixed extractants (Bray, amended Olsen), which contains  $\text{NH}_4\text{F}$ , are better when the different forms are balanced.

For rice grown in pots with soils where Fe P predominates, alkaline extracts give the best correlation with the response to phosphate fertilizers; the correlation is not so good with acid-fluoride extract, and poor with an acid extract.

Alban et al (1964) investigated the reduction in certain fractions in pot tests in correlation with uptake of phosphorus by plants in reddish-brown lateritic soils in Oregon. The quantity of Al P ( $\text{NH}_4\text{F}$  extraction) lost during crop growth

showed the closest correlation with phosphorus taken up by oats and clover.

Maida (1978) made a recent comparison of nine methods on Malawi soils. These methods correlate significantly with one another. Aslyng P and Morgan P variations correlate with the phosphorus fraction related to soluble phosphorus; Al P is in correlation with Dyer, North Carolina, Olsen, Bray 1, resin and acetic acid. Fe P is the second variable contributing to total variation of phosphorus extracted by 0.1 N NaOH, Olsen P, North Carolina P, resin, and Dyer, in decreasing order of importance. Fuleky (1977) shows that lactate solutions mainly dissolve Ca P, and alkaline solutions to a lesser degree dissolve Al P and Fe P. Using 73 Indian soil samples, Kanwar and Tripathi (1977) compared Bray, Olsen and Morgan, and forms of phosphorus extracted by Chang and Jackson. Ca P forms have little effect on Olsen and Bray 1, but partly explain results with Morgan; Al P, and Fe P fractions contribute significantly to Bray 1 and Olsen extractions, which are similar in their phosphorus form extraction diagrams.

#### Some characteristic levels of phosphorus in soils

Total phosphorus in tropical soils ranges from 50 to 2,000 ppm  $P_2O_5$ . The poorest are the sandy savannah soils in arid regions, and the richest are those formed from volcanic rocks in humid regions.

In 1956 a relationship between the total nitrogen (Kjeldahl) and total phosphorus content was established (Dabin 1950) in the upper horizon of numerous tropical African soils. A linear relationship exists between nitrogen and phosphorus, between 0.02 and 0.1% N and 0.01 and 0.05% of total  $P_2O_5$ , with a N- $P_2O_5$  ratio of about 2. Above 0.1% N and 0.05%  $P_2O_5$ , the increase in phosphorus is less than proportional. The N- $P_2O_5$  ratio can reach 4 for 0.8% N. Empirically, the average representative curve of N against  $P_2O_5$  corresponds approximately to critical levels of  $P_2O_5$  below which phosphorus deficiency begins to appear.

These results have been confirmed for a number of crops: with nitrogen levels of 0.025, 0.045, and 0.1 to 0.14%,  $P_2O_5$  was 0.012% for peanut in Senegal (aridic sandy soils), 0.02 to 0.025% for cotton or rice in the Niger Delta (alluvial soils, Gleysols, Vertisols), and 0.05 to 0.07% for cotton or corn in the Ivory coast (Alfisols, Luvisols, Acrisols).

In 2 soils in rice in Madagascar, total  $P_2O_5$  ranged from 0.075 to 0.17% for respective nitrogen contents of 0.15 to 0.46% (Pichot et al 1976). The first soil responds to 100 kg  $P_2O_5$ /ha, but the second reacts only to larger amounts because of its high fixation capacity. This relationship between total phosphorus and plant response may be due to the fairly constant percentages among the various forms of phosphorus in highly weathered tropical soils:

- Active forms (Soil P, Al P, Fe P, Ca P) 10 to 20% of total
- Organic forms 10 to 30% of total
- Occluded and residual forms 50 to 80% of total

Soils formed from basalt rocks are often richest in phosphorus because of the phosphorus content of such rocks, and also mainly because of the high iron and organic matter content in soils formed from basic rocks.

*Available phosphorus.* Critical levels of available phosphorus are the amounts in the soils when the ratio of the yield from complete fertilizer minus phosphorus to the yield with complete fertilizer exceeds 80% of maximum yield. This value depends on the method of measurement, sometimes on the crop, but mainly on the absorbing capacity of the soil; it also depends on other conditions such as physical properties.

When measured by the amended Olsen method ( $0.5 \text{ NaHCO}_3 + 0.5 \text{ N NH}_4\text{F}$ ) with cotton on ferruginous soils in the Ivory Coast, 48 to 60 ppm  $\text{P}_2\text{O}_5$  (25 ppm P) gave 86 to 89% of maximum yield and a level of 0.36% P in leaves (Dabin 1970). The figures were confirmed by Fritz and Vallerie (1973) for cotton on various soils in northern Cameroon.

Working with corn in northern Ivory Coast, Le Buanec (1973) reported a critical level of 26 to 32 ppm P in low-fixing soils, and 72 ppm P in a ferrallitic soil with high fixation capacity. Pichot and Le Buanec (1978), working with ferrallitic soils derived from gabbros in the Ivory Coast, calculated correlations of 0.2 to 0.35% ( $r = 0.778$ ) between corn yield (2–6 t/ha) and phosphorus content in leaves: for the Saunder method ( $r = 0.799$ ), amended Olsen ( $r = 0.739$ ), total phosphorus ( $r = 0.473$ ), and L value ( $r = 0.786$ ). Critical levels were leaf P, 280 ppm; L (Larsen), 30 to 35 ppm P; amended Olsen, 60 ppm P; Saunder, 120 to 135 ppm P.

Pichot et al (1976) studied two Madagascar rice-growing soils with nitrogen contents of 1.5% and 4.6%, Gachon fixation levels of 485 ppm and 1,050 ppm P, total P of 377 and 875 ppm, Olsen 25 and 268 ppm, Saunder 166 and 402 ppm, Truog 0 and 5 ppm, Larsen 33 and 69 ppm. One soil produced an additional 1 t/ha with 100 kg  $\text{P}_2\text{O}_5$ ; the other soil responded only to higher amounts.

In fertilized plots, correlations between yields and all analytical methods, except Truog and Saunder, are highly significant; modified Olsen and total phosphorus are more suitable for rice (Gleysols).

*Synthetic data relating to critical phosphorus levels.* Roche et al (1978) provide critical levels for different methods for a large group of soils. The levels range from 250 to 450 ppm for total P, 70 to 780 ppm for Saunder, 10 to 17 ppm for Bray 2, 30 to 70 ppm for amended Olsen, 50 to 140 ppm for carbonate (Dalal), 15 to 40 ppm for L value, and 4 to 9 ppm for Gachon index. The levels are lowest for Luvisols and highest for Gleysols, which correspond to the group with high fixation capacity.

For modified Olsen P, the following empirical rule is generally given: for average to low fixation capacity, the minimum critical phosphorus level is estimated at 2.5% of the total nitrogen rate; for a high fixation capacity that level can be doubled. For a very high fixation capacity the level can be increased even further.

Using  $\text{NH}_4\text{Cl}$  extract of air-dried soil after the addition of 100 ppm of soluble phosphate, an average fixation capacity is less than 10% of the phosphorus remaining in the extract; a high fixation capacity is less than 1% and very high is less than 0.1%.

## PHOSPHATE FERTILIZATION

A large number of experiments have illustrated the effectiveness of phosphorus fertilizers, particularly in combination with nitrogen fertilizers. The main problems involved are diagnosis of fertilizer requirements and quantities to be used; determination of most efficient forms of fertilizers, placement, and application dates; and economic factors.

Deficiencies can be diagnosed by soil analysis, or by subtractive pot and field tests. The effect of fertilizers on increasing or decreasing nutrient levels can also be determined by analysis.

The quantity of phosphorus needed depends on the kind of plant and the desired yield. One ton of wheat takes up 20 kg  $P_2O_5$ , and a ton of rice takes up 25% of that. Crop composition at harvest can provide a basis for estimating annual fertilizer needs, but tests with tracers have shown that about 20% of phosphorus fertilizer is used by the plant and about 80% remains in the soil. Forms of fertilizers have variable levels of solubility, and give different reaction products with the soil.

In flooded soils with a high active iron content, 86% of the phosphorus in superphosphate was converted in 15 days to a low available form, but natural phosphates or basic slag maintained a higher availability level. Most quantitative fertilizer tests have been done using soluble forms such as ammonium phosphates or superphosphates, with the initial objective the determination of quantities that gave the highest yields. The response curve method (Chaminade 1964) consists initially of determining the quantity of nitrogen providing maximum yield in the presence of excess phosphorus and potassium, then investigating the effect of increasing amounts of phosphorus in the presence of the optimum amount of nitrogen, etc.

The amount of phosphorus corresponding to the maximum yield or *potential fertility* of the soil can be the basis for a corrective application, after which fertility can be maintained by minimum applications based on yields. This method, which has given spectacular results in Madagascar, involves high investment costs and is not always suitable for small holdings.

Methods that determine previously maximum quantities of fertilizers to be applied involve investigating the best balances among elements. Examples are the *systematic variant* method applied by Braud et al (1959) to cotton crops, and the so-called *factorial methods*, which are still used. These methods, applied in experimental centers, have facilitated the establishment of fertilizer formulas for various crops throughout large regions.

In many developing countries local products are used with techniques that will ensure maximum efficiency in the use of expensive imported fertilizers. There has been progress in research into methods of application, placement, date of application, position in crop rotation, and the use of supplementary products.

Maertens' (1978) investigations of fertilizer placement have shown that roots can absorb 15 to 20 times the plant's needs, but placement must not slow down

the development of other roots and adequate water supply must be ensured. Absorption increases in relation to the concentration of soluble phosphorus in the soil and proper placement increases fertilizer efficiency in a soil with high fixation capacity. A small number of roots in a rich soil can feed a whole plant. Another factor is the level of absorption of phosphorus by young roots at the beginning of growth, on which complete nutrition of the plant may depend. Finally, by reducing contact between soluble phosphate fertilizers and the mass of soil, fixation is reduced.

#### Submerged soils

In connection with soluble superphosphates for rice crops, Katyal (1978) noted that fertilizer broadcast on the soil surface is more efficient than the same fertilizer placed at 15-cm depth. Fertilizer applied in one operation (50 kg  $P_2O_5$ /ha) at the beginning of cultivation is more effective than that applied late or in split applications (60 kg  $P_2O_5$ /ha in three 20-kg applications).

Dipping the rice roots before planting in a mixture of soil and superphosphate reduces by 50% the quantity of phosphorus needed for the same increase in yield (Katyal 1978). The dip mixture can be made with superphosphate or nitrophosphate.

Placement is different if rock phosphate of low solubility is used. The effectiveness of rock phosphate depends on its fineness and solubility in citrate (Hammond et al 1977). The effectiveness increases as the amount applied increases and is incorporated in the soil.

Absorption by plant roots of phosphorus from fairly insoluble phosphorus sources depends partly on the probability of the roots' growing near enough to phosphorus particles to absorb them from the surrounding solution. According to Blanchet (1978) the effective distance is only 1 mm for phosphorus compared to 5–10 mm for potassium.

#### Comparison of soluble phosphates and rock phosphates

Superphosphates and hyperphosphates, like ammonium phosphate, are used widely throughout the world. In most soils, particularly those with low pH, crop response is better than with most rock phosphates, mainly in short-term tests. Over longer periods, for example after 14 years' application, the increase in labile phosphorus is higher for rock phosphate and residual effects on crops are high (Mandal 1975). In a soil of pH 5 after 8 years of fertilization, superphosphate increased Fe P, but rock phosphate increased all fractions. In lateritic and acid soils in India, citrate-soluble phosphate fertilizers and rock phosphates can replace water-soluble phosphates, but applications have to be at least twice the amount of superphosphate on the basis of  $P_2O_5$  content.

In flooded rice soils, where the phosphate is incorporated into a humid soil 3 weeks before flooding, Ca P (citrate-soluble and slowly-soluble) is converted into Al P, thus increasing P availability by hydrolysis and solubilizing Fe P by reduction. These changes do not occur in neutral or calcareous soils and in this

case the addition of organic matter may have a beneficial effect.

For many crops, rock phosphate may be as effective as superphosphate in quantities of 100 kg/ha after 3 years' application. For higher levels of natural phosphate, the available phosphorus is significantly higher. Another series of experiments has shown that it may be better to apply a certain quantity of superphosphate in addition to rock phosphate, e.g. 33% the first year, 25% the second year, and none the third and fourth years. Rock phosphate may also be partly acidified with  $H_2SO_4$ ,  $H_3PO_4$ , or  $HNO_3$ . Phosphoric acid is best but 20%  $HNO_3$  is also effective. In general, phosphate fertilizers containing 20 to 50% soluble phosphorus were as effective as those completely soluble.

#### Amendments improving the effectiveness of phosphate fertilizers

It has been found that liming acid ferrallitic soils improves phosphate uptake by plants. Organic matter encourages plant growth and rooting, thus causing greater phosphorus mobility. It may, however, increase the phosphorus fixation capacity of oxide-rich soils, which become more reactive in the presence of organic matter. Loss of organic matter in the surface horizon of soils causes loss of phosphorus. In calcic or calcareous soils, organic matter increases phosphorus solubility.

#### CONCLUSION

Tropical soils usually possess limited phosphorus reserves and have high absorbing capacity. Economic application of fertilizers should allow these reserves to be increased economically and gradually to improve general soil fertility. Future research could cover better integration of the results of analysis of phosphorus with other soil properties — morphological, physical, and chemical. Because phosphorus fertilization depends on general plant-rooting conditions related to multiple factors as well as to phosphorus content, computer models may help. Regarding laboratory research, the dynamics of phosphorus desorption in tropical soils must be defined. More sensitive techniques for measuring phosphorus in solution should be developed.

The action, as well as the residual effects, of organic matter and of phosphate fertilizers must be defined in long-term experiments.

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