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Use of phosphate rocks in the tropics

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Abstract

The use of finely ground phosphate rocks (PRs) as directly applied P fertilizers in tropical farming systems is a cheaper alternative to acidulated, water-soluble P products. However, the effectiveness of PRs in tropical environments depends on the extent to which the required P uptake rate of the crop plant can be maintained by the rate of PR dissolution in that soil. That extent that this outcome is achieved depends on the properties of the PR, the soil, climate, plant factors, and on management practice. Environmental conditions in the surface layers of highly weathered soils in the humid tropics are generally conducive of the attainment of satisfactory rates of PR dissolution, especially as the reactivity of the PR increases. In soils with very high P sorption capacities, however, the agronomic effectiveness of PRs is reduced as the acquisition of dissolved P by plant roots is restricted by competition from P sorption processes in the soil.

In determining the required reactivity of PRs for use in tropical regions one must consider the rate of P demand by the crop or pasture and the suitability of the soil environment for PR dissolution. The use of some water-soluble P in combination with the PR might enable PRs of low reactivity to also be used, where alone they would be relatively ineffective. The ability of PRs to provide Ca, in addition to P, needs further study because subsoil Ca deficiency is becoming more widely recognized as a production constraint in highly weathered tropical soils. The future use of PRs in tropical agriculture is expected to expand for plantation crops and pastures and especially for landlocked countries with local deposits of PR. Increased use of PRs will also occur where more reactive PRs can effectively be used to increase the yield of annual food crop.

Introduction

The tropics occupy that area of the world located between 23.5° North and South of the equator. They comprise somewhat more than a third of the earth's land surface yet they contain close to half the world's human population. As the major portion of the increase in human population is projected to occur in the tropical world, there is concern about potential shortfalls in food production in the tropics. Perhaps the major impediment to increasing food production in both the humid and dry tropics is that many soils are infertile [60]. One of the fertility constraints in tropical soils is the low level of available phosphorus (P) resulting from P deficiency *per se* in many soils and from the high capacity of other soils to immobilize P. Phosphorus inputs are essential if satisfactory levels of crop production are to be achieved on these soils.

The use of finely ground phosphate rocks (PRs), applied directly as P sources to tropical soils is an attractive option because they are considerably cheaper than water-soluble P fertilizers. They can cost, per unit of P, as little as one fifth the price of single superphosphate [61]. Many developing countries in the tropics are therefore attracted by the possibility of using PRs, particularly those that are indigenous to that country, to increase food production. However to be a viable option these PRs must be effective as P sources in overcoming the P deficiencies that limit crop productivity on the tropical soils. It is well known that PR sources vary widely in their agronomic effectiveness [43]. The key question is whether a given PR will be sufficiently effective in a given farming environment. The answer is dependent upon many factors that are operating in a particular PR/soil/plant/farming system.

This review paper will first describe the main edaphic and climatic properties and land-use activities of tropical farming systems which will have a bearing on PR effectiveness. The way that these properties influence PR effectiveness will be discussed. The reader is referred to excellent earlier reviews on this subject which have concentrated on PR effectiveness in both temperate [43] and tropical regions [32]. Guidelines for the use of PRs in tropical agriculture, based on research findings, will then be put forward. Finally we will explore the possible role that PRs will have in the future as P inputs for tropical farming systems.

Features of the agricultural environment in the tropics

Climate

The very nature of the circulation of air masses about the inter-tropical convergence zone, resulting from the unequal distribution of solar radiation on the surface of the planet, means that a substantial portion of the tropical region is humid. Indeed, about a quarter of the tropical land surface has a very humid climate where rainfall exceeds evaporation in all or most months: the larger areas here include the upper Amazon Basin, the Congo Basin and much of Indonesia, Malaysia and part of the Philippines [60]. Another half of the tropics have a seasonal climate where the wet and dry seasons are well defined. Included in this area are much of the Cerrado and Mato grosso in Brazil, the Llanos of Columbia and Venezuela, much of Africa between the Sahara and the Kalahari deserts, and the monsoon regions of Asia. Most tropical annual crops are grown in this region [60]. The remaining areas of the tropics have dry climates where there is either a short wet season (<4.5 months) or two or less humid months in the case of the tropical deserts.

A major feature of tropical climates is their constancy of temperature. The mean monthly temperature variation is 5°C or less between the average of the three warmest and the three coldest months. This applies to the tropical highlands which differ from the lowlands by having lower overall temperatures [60]. In addition to favourable temperature regimes for crop growth, the tropical regions generally receive more solar radiation than temperate regions during the year [46]. The combination of long, humid growing seasons, year-round solar radiation and favourable temperatures would suggest that the tropical latitudes should have around twice the yield-producing potential for food crops per hectare than temperate areas [19].

Table 1. Distribution of highly-weathered, acid soils and less weathered soils in the tropical regions of the world[c] (from Sanchez and Salinas, 1981)

Continent	Highly weathered soils[a]		Less weathered soils[b]	
	Area (10^6 ha)	(%)	Area (10^6 ha)	(%)
America	822	55%	991	45%
Africa	451	39%	692	61%
Asia	301	37%	509	63%
Australia	8	4%	216	96%
TOTAL	1582	43%	2088	57%

[a] Includes soils which belong to the orders Ultisols and Oxisols of the U.S. Soil Taxonomy;
[b] Includes soils in orders Entisols, Alfisols, Inceptisols, Vertisols, Aridisols, Mollisols, Andisols, Histosols and Spodosols;
[c] Excludes areas in Africa where the growing season is less than 150 days.

Such estimates of potential production differ greatly from actual reality, due in part, to the low fertility status of many of the soils that occur in the tropics.

Soils of the tropics

Around 40 per cent of the land surface of the tropics consists of highly weathered, acid soils which are classified mainly as Oxisols and Ultisols (Table 1). In the continent of Africa, more than 50% of the surface is occupied by acidified Alfisols and Entisols. Soils in these four orders will provide a focus for this review as they are the soils in which PRs are potentially effective. The Oxisols and Ultisols have generally been considered marginal for crop production yet they represent a large area of potentially arable land. Pressure will therefore develop to use this land for food production because of the growth in human population in many tropical countries [22]. Tropical America contains the largest areas of these soils which comprise more than one half of the region, whereas they occupy around a third of the tropical parts of Asia and Africa (Table 1).

The important chemical features of the Oxisols, Ultisols, Alfisols and Entisols result from the fact that they are highly weathered. The Oxisols and Ultisols in particular contain an abundance of variable charge colloids, have a low soil pH in water which is generally less than 5.0, and a low CEC which is usually <10 cmol (+) kg^{-1} with low base saturation and high aluminium saturation (often above 40%). The excessive weathering in these soils has reduced the total P levels in the soil and the high content of iron and aluminium oxides and exchangeable aluminium result in high P sorption capacities, leading to low concentrations of plant available P in the soil solution [60]. The overall effect then of their weathered nature is that they provide a very infertile medium for plant growth particularly for food crops that are not well adapted to acid soils. The main constraints for plant growth are toxicities of aluminium and manganese, and deficiencies of calcium, magnesium and phosphorus [60].

In the more humid parts of tropical Africa, the Alfisols have been formed from granite and sandstone but prolonged pedogenesis has obscured the influence of these parent materials on these soils. Excessive leaching and cultivation have accelerated the depletion of bases. The textures of both the Alfisols and the Entisols range from sandy to sandy loam. The absence of large amounts of colloidal material in these sands creates an ideal environment for greater than expected effectiveness of PRs even for annual crops [53].

Tropical farming systems

Farming systems vary widely in the humid and seasonal tropics. By far the most widespread form of land-use is the practice of shifting cultivation which occurs on almost half of the tropics in both forested and savannah areas [60]. Here subsistence farmers cut and burn a small area to grow several crops, before abandoning the area when soil fertility declines or when weeds or other factors reduce yields. More permanent food cropping activity is carried out on about 17 per cent of the tropics, which includes small-scale lowland rice cropping and upland cropping based on corn, beans, sorghum, millet etc. Livestock grazing on tropical grasslands occurs on 11 per cent of the land, while probably the most productive enterprises in the udic climates are the plantation crops such as sugar cane, coffee, cacao, rubber, bananas and pineapple, which occur on less than 5 per cent of tropical land. Despite the variety of landuse activity there are still vast areas of unused yet potentially arable land in the tropics [42]. This is partly due to inadequate knowledge of how to manage the highly weathered Oxisols and Ultisols.

Fertilizer effectiveness of phosphate rocks in the tropics

The extent to which PRs have a direct role to play as P inputs in management systems for crop production on acid tropical soil depends on their agronomic effectiveness relative to other available P fertilizers and the relative costings of alternative products. Because added fertilizer P reacts with soils and continues to be available over time the effectiveness of PRs will be considered in terms of both their initial effects and their residual effectiveness over time.

Initial response of PRs

Phosphate rocks are effective as an initial application in a tropical farming system if they release P into the soil solution at a rate that enables crop plants to take up this dissolved P fast enough to grow satisfactorily and produce adequate yields. Phosphate rock characteristics, environmental conditions, crop type and management practice all impinge on the P supply/demand balance and hence the effectiveness of a given PR in a given crop management environment.

A schematic diagram which lists the factors that influence P supply from dissolving PRs on the one hand, and the ability of the plant roots to take up dissolved P from the PR on the other, is presented in Figure 1. The effectiveness of the PR is dependent on the extent to which the P uptake rate required for satisfactory plant growth K_2, is maintained by the dissolution rate K_1. The following discussion will outline how PR characteristics, soil properties, climate, plant effects and management practices influence K_1, and how some soil properties, plant factors and some management procedures modify K_2.

Factors influencing rate of P release from the PR particle (K_1)

PR characteristics. The realisation that PRs differ widely in their chemical reactivity or solubility in acidic solutions and that this was related to their mineralogy and chemistry [47] was a major advance in our understanding of PR effectiveness. It was shown that the reactivity of sedimentary apatites which are the major source of commercial PRs [49] results from the degree to which isomorphic substitution of phosphate by carbonate has occurred within the apatite crystal structure. Increasing carbonate substitution in PR increases the rate at which P is released from PR in the soil as it facilitates the breaking down of the lattice structure of the apatite crystal (See also Bolan *et al.*, Hagin and Harrison and Chien in this issue). This is a key factor in determining the effectiveness of a PR. The most reactive PRs are those having a molar PO_4/CO_3 ratio less than 5 [35]. As the extent of carbonate substitution in an apatite molecule is difficult to measure, rapid empirical dissolution tests with dilute acids and chelating agents have been developed to indirectly measure chemical reactivity of PRs. Of these the 2% formic acid extraction appears to be the most useful [35]. Unfortunately many of the PR sources in tropical countries have been shown to be relatively unreactive in numerous agronomic trials [32]. The only PRs from tropical deposits that can be classified as highly reactive are the Bayovar PR from Peru and the Bahia Inglesa PR from Chile [36]. In tropical Africa, Matam PR from Senegal, Tilemsi PR from Mali, Tahoua PR from Niger and Mingingu PR from Tanzania are classified as being of medium reactivity [50]. The number of moderately reactive PRs in tropical Latin America is also

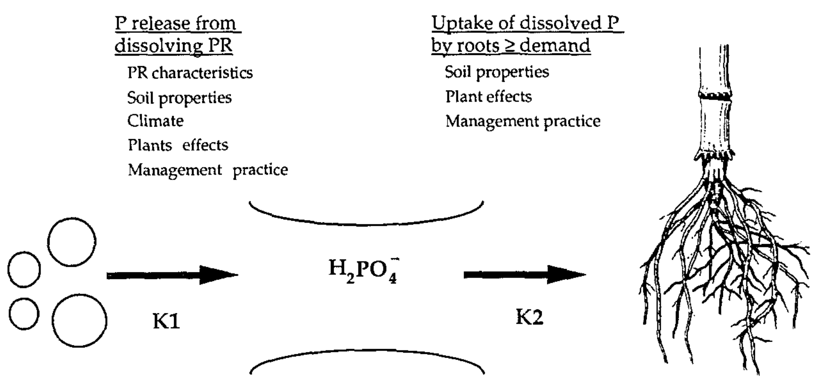

Fig. 1. Schematic diagram representing the flux of soluble P from dissolving PR particles into the soil solution (K_1) and the uptake of this P by plant roots, at rates that are sufficient for adequate plant growth (K_2). Factors that influence these flux rates are listed in the figure.

limited to a few deposits such as Huilia from Columbia [48].

The PR dissolution process is a reaction that occurs at the surface of the PR particle [4]. Increasing the particle size by fine grinding will increase the surface area of PR particles exposed to the soil and therefore increase the rate of P release from the PR, but fine grinding is not a substitute for reactivity. Reducing PR particles to a size less than 100 mesh (150μm) by grinding is generally not warranted as finer particles do not increase effectiveness greatly [43, 58]. The use of finely ground PRs may result in handling problems for mechanised agriculture, but would pose fewer problems for the more labour intensive farming practices used in tropical agriculture.

Soil properties. The dissolution of Sechura (Bayovar) PR, one of the most reactive carbonate apatite located in the tropics, can be described [32] by the equation:

$$Ca_{9.03}Na_{0.74}Mg_{0.13}(PO_4)_{4.88}(CO_3)_{1.12}F_{1.73}(OH_{0.72}) \rightleftharpoons {}_{9.03}Ca^{2+} + {}_{0.74}Na^{+} + {}_{0.13}Mg^{2+} + {}_{4.88}PO_4^{3-} + {}_{1.12}CO_3^{2-} + {}_{1.73}F^{-} + {}_{0.72}OH^{-}$$

The driving force for the dissolution of this carbonate apatite is the neutralisation reaction between soil H-ions and the PO_4-ions, CO_3-ions, F-ions and OH-ions resulting from dissolution, which are neutralised to H_2PO_4-ions, $H_2O + CO_2$, HF, and H_2O respectively [12]. Thermodynamic considerations indicate that these reactions occur spontaneously as the apatite dissolves [10]. The ability of the soil to provide H-ions to drive the dissolution process is therefore essential for PR effectiveness. Many field and laboratory observations confirm that low soil pH [6], with a high pH buffer capacity [41] and also a high rate of soil acid generation [1] all contribute to enhanced PR dissolution. Acid tropical soils certainly have the ability to provide H-ions to promote PR dissolution.

The law of mass action [2] would indicate from the equation above that PR dissolution would also be favoured by soil conditions that maintain low concentrations of Ca and P in the soil solution. Lower levels of exchangeable Ca associated with a reduced Ca saturation of the soil's cation exchange capacity (CEC), which in turn would lower Ca concentrations in the soil solution, were associated with increased rates of PR dissolution in one incubation study [51]. Low levels of exchangeable Ca certainly occur in acid tropical soils, but this is associated with a low CEC; the CEC sink for Ca in Oxisols and Ultisols would be appreciably less than in soil used in the incubation study above. What can provide a substantial sink for Ca in tropical soils is the hydrolysis of soil organic matter, which provides chelating substances that can also reduce the activity of Ca-ions in the soil solution [11]. Reported differences in PR effectiveness in two Ultisol soils where the main soil difference was the level of soil organic matter [15], was attributed to the chelating effect of Ca. Organic matter levels in recently cleared tropical soils are generally quite high and are comparable with those in temperate soils [60]. However the rate of organic matter decomposition in the tropical environment is rapid and levels decline quickly once the soil is cultivated.

Whereas high Ca concentrations in the soil solution can depress PR dissolution in moderately acid soils [43], high concentrations of inorganic P in the soil solution, that would depress PR dissolution, are not generally found in agricultural soils. High soil P regimes would appear to have a lesser effect than those of Ca in depressing PR dissolution [51]. This is attributed to the substantially lower P concentration, compared to that of Ca, in the solution due to the greater reactivity of phosphate ions with soil colloids. However, soil P sorption capacity does affect PR dissolution rates. As the P sorption capacity increased in a group of Oxisol soils that had similar pH values, the dissolution rate of PRs placed in incubated samples of those soils increased [62]. Similar results were reported for a group of New Zealand soils [63]. This effect of P sorption has been attributed to the removal of phosphate ions from the soil solution by rapid sorption with Fe and Al compounds [16].

Effect of climate. Rainfall is important for PR dissolution because PRs will not dissolve in dry soils [59]. Moisture films surrounding the PR particle are required to enable the products of dissolution such as Ca-ions to diffuse away from the dissolving surface and to permit the inwards diffusion of H-ions towards the surface, and to enable their associated neutralisation reactions with anions released from the PR to occur. Incubation studies confirm that PR dissolution declines as the soil moisture content is decreased [29]. Similarly data from field observations in Senegal, Africa [32] indicate that the yield response of field crops to applied PRs is linearly related to the mean annual rainfall between 500 and 1300 mm. Moisture supply should not be a limitation of PR dissolution in the humid tropics nor should it depress dissolution during the wet season of the seasonal tropics. In addition, high annual rainfall in the humid tropics combined with the stable aggregates of tropical Oxisols [60] would result in substantial water movement through the soil. The high leaching indices would promote PR dissolution by facilitating the removal of the products of dissolution away from the surfaces of the PR particles. This may provide the principle mechanism for removing calcium from the system.

Temperature has been found to have no significant effect on PR dissolution in soil [14]. The implication has therefore been made that the availability of P released form PRs in tropical soils may be less affected by temperature than the P released from water-soluble fertilizers [32]. This would tend to improve the effectiveness of PRs in warm environments, relative to soluble P forms. Such an outcome would depend on the extent to which P sorption reactions were operating in the soil as temperature does have a marked effect on the rate of P sorption by soil [3].

Plant effects. Actively growing plant roots can have a stimulating effect on PR dissolution in a number of ways. For example, the acidification of the rhizosphere, where H-ions build up in the rhizosphere surrounding root surfaces, will result in an increase in the rate of dissolution of adjacent PR particles [44]. Root exudation of H-ions results from the excess uptake of cations over anions by the roots [5]. This will occur when legumes actively fix N_2 or when plants take up and assimilate predominantly ammonium N [7]. Other plants exhibit this response as a result of P deficiency [34].

Plants can also promote dissolution by producing a high root density in the vicinity of PR particles [44]. The mechanism whereby high rooting density *per se* stimulates PR dissolution is probably related to the lowering of the concentrations of Ca-ions and H_2PO_4-ions in the solution surrounding the surfaces of PR particles. A number of workers have suggested that high Ca uptake patterns are responsible for improved responses of certain plants to applied PRs [18, 25].

Management practices. Phosphate rock dissolution in soil can be influenced by management practice in a number of ways. Several examples are discussed here and the reader is referred to earlier reviews for a more complete coverage [32, 43]. One important practice is the flooding of lowland soils for rice culture which is widespread in tropical Asia. Factors which govern the dissolution rate of PRs under reduced conditions in a paddy soil are not fully understood. One might envisage that the general rise in soil pH following innundation, associated with the microbially mediated reduction of Fe (III) compounds [45] might depress the dissolution of PRs. Reports of the favourable performance of reactive PRs relative to soluble P sources in a network of international trials that measured the effectiveness of different P forms in flooded rice soils [32] however, suggest that flooding did not substantially reduce PR dissolution. Reasons have been advanced by Kirk *et al.* (1991) to explain why PR effectiveness may be quite satisfactory in flooded soils [45]: they argue that rice roots will acidify surrounding soil, that dissolved organic matter may chelate Ca and P in the flooded soil solution, and that there would be a lag phase following flooding before the soil pH increases during which time significant amounts of PR, applied pre-flooding, might dissolve. The application of the PR post-flooding would reduce its effectiveness [15] because of the post-flooding rise in soil pH.

The method of PR placement in the soil also influences the rate of P release from the PR. Numerous studies have shown that broadcasting and incorporating the PR in the surface soil will result in greater PR effectiveness than placing the PR in a concentrated band in the soil [43]. Banding PR will therefore reduce K_1 (Fig. 1). This can partly be attributed to the depression in PR dissolution resulting from overlapping diffusion zones around the closely spaced PR particles [4]. The build up in the products of dissolution at the surfaces of these particles would limit dissolution. This effect has been clearly demonstrated in incubation studies [37].

The use of lime on acid soils is another practice that will lower K_1 as it reduces PR dissolution rates. Liming will both reduce the supply of H-ions and increase the supply of Ca-ions in the soil solution [32]. Both of these effects will result in a decrease in the dissolution rate. The use of liming materials has been recommended as a practice to decrease Al saturation and increase Ca and Mg movement in the subsoil of tropical Oxisols and Ultisols [61], particularly if food crops that are sensitive to Al toxicity are to be grown. The outcome would be a lower rate of dissolution of PRs applied to these lime-amended soils. One solution to the negative interaction between lime and PR dissolution is to apply the PR in advance of the lime. This would allow significant amounts of PR to dissolve before the pH and the calcium status of the soil are raised by lime application [61].

Factors affecting plant acquisition of P from dissolved PR

Soil properties. Although PR dissolution may be increased by a high P sorption capacity of the soil, a number of studies indicate that PR effectiveness is lower in such soils [31, 33, 39]. Hammond *et al.* (1986) speculated that the poor performance of PRs in such soils was due to poor root development during the early stages of crop growth because of P deficiency; the majority of the P released from the dissolving PR is removed from the soil solution by P sorption processes and is therefore not available for uptake by the young plant [32]. This negative outcome for the plant is the direct result of the dominating effect that P sorption processes have on soil solution P concentrations: the relatively slow rate of PR dissolution is unable to increase the P concentration in the soil solution long enough to satisfy plant requirements. This result has major implications for the high-P sorbing tropical soils. Such soils are not very suitable for the direct application of finely ground PRs.

Plant effects. Phosphate rocks are generally more effective when applied to long-growing crop species such as the tropical plantation crops, sugar cane ratoon crops, and perennial pastures, than to short-term annual crops such as wheat, maize or millet [15]. Numerous research findings indicate that annual crops require a high rate of P supply during their rapid vegetative growth phase, and that this need is more readily met by the P supply characteristics of water-soluble P fertilizer [54]. The rapid establishment of a root system by seedlings of annual crops is sensitive to P availability: a perennial crop or pasture, on the other hand, has an established high root density in the surface layers of the soil. Their annual P requirements are also taken up over a considerably longer period of time, although short-term seasonal requirements may still exceed the P supply characteristic of a PR. The lower overall rate of P demand by these perennial plants increases the likelihood that P release form dissolving PRs will be sufficient to maintain plant P uptake rates that are adequate for plant growth. Such plants would have a low K_2 rate (Fig.1).

Plants with higher root densities in the surface layers of the soil in which the PR is located would be expected to acquire dissolved P from the PR at a higher rate, because there would be a greater likelihood of a root encountering localised 'high concentration pockets' of soluble P adjacent to the PR. This proposition is supported by evidence in greenhouse pot trials where the effectiveness of the reactive Bayovar PR was greater with the high-rooting-density ryegrass than with wheat or maize, which had lower root densities [15]. It is also likely that plants which are heavily infected with mycorrhizae are better able to acquire dissolved P from PR because of the greater volume of soil into which the mycorrhizal root system can extend, compared to non-mycorrhizal roots. Positive benefits have been reported from the addition of mycorrhizal innoculum to sterilized tropical soil in which moderately reactive PR had been mixed [65].

Management practices. A number of management practices will increase the rate of recovery of dissolved P from PRs. It has been highlighted in earlier reviews on PR effectiveness that the availability of P from PR depends on the probability of plant roots encountering the localized 'low concentration pockets' of soluble P around the dissolving PR particle [32, 43]. This probability will be increased if the PR is broadcast and incorporated into the surface soil layers.

Another management practice that will increase the rate of uptake of P from PRs is to apply the PR to the soil well in advance of the time of planting the crop [23]. This enables more dissolved P from the PR to accumulate in the soil so there is a greater P supply in the soil when the crop is sown. However this strategy will be unsuccessful in tropical soils that are high P-sorbing because the P released from the PR before sowing will be retained by the soil and will not be available for later uptake by the crop seedlings [15].

Residual effectiveness of PRs over time

A feature of the performance of the less reactive PRs in tropical acid soils is that their agronomic effectiveness relative to that of a water soluble fertilizer improves appreciably with time. This is illustrated by the data in Figure 2 which show effects of the low reactivity Araxa PR and single superphosphate (SSP) on the dry matter yield

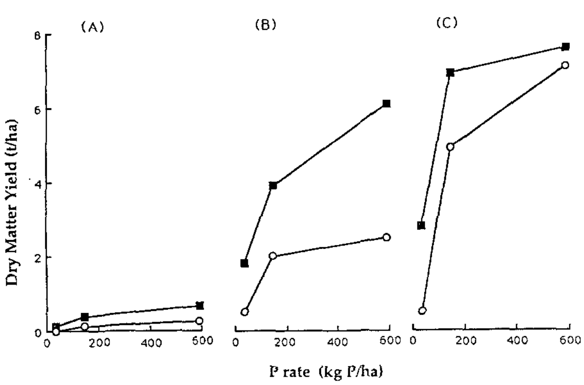

Fig. 2. Yield response of *Brachiaria decumbens* (A) 3 months, (B) 10 months and (C) 13 months after the application of a range of rates of single superphosphate (■) and the low reactivity Araxa PR (○) applied to a Brazilian Oxisol. (After Fenster and Leon, 1978).

(DM) responses of the pasture grass *Brachiaria decumbens* that was grown on a Brazilian Oxisol that had a water pH and an Al saturation of 4.9 and 79% respectively in the 0–10 cm soil surface layer [24]. Substitution values of this igneous Brazilian PR for superphosphate (P rate of SSP/P rate of PR) at the maximum yield for the PR increased from around 0.13 to 0.15 at the two early harvests to around 0.5 after one year. In a separate study, the substitution values of Pesca PR (low to moderate reactivity) and the moderately reactive Huila PR for TSP were calculated from the yield response data of *Brachiaria decumbens* that was grown on a Columbian Oxisol (water pH and Al saturation in the 0–10 cm soil surface of 4.9 and 82% respectively) [24]. These values increased from around 0.2 and 0.4 at the first harvest when the maximum yield was 2 t DM ha^{-1} to 0.8 and 1.1 by the second harvest when yields had increased to over 3 t ha^{-1}.

The superior 'residual effects' of finely ground PRs, compared to water soluble fertilizers, in these tropical soils result from relative increases over time in the concentration of plant available P in the soil solution with the PR treatments. This is attributed to the continuing dissolution of the PR compared to the declining availability of P from the residues and reaction products of the water soluble P sources over time. The improvement in the residual effect of PRs compared to water soluble P sources does not mean that they will necessarily out-yield, or even yield as well as the water soluble source [43]. This is certainly the case with unreactive PRs applied to annual food crops growing in tropical soils.

Guide-lines for the use of phosphate rocks in the tropics

Guide-lines for the use of PRs in tropical agriculture hinge around two questions. These are the suitability of the soil environment for PR dissolution and how reactive the PR must be for the specified cropping situation. In the past the basic premise has been that PRs are recommended if they are agronomically as effective as alternative forms of P fertilizer from the time of application. However if major economic savings result from using either an imported reactive PR or an indigenous PR that is less reactive, in place of a water soluble source, then lower yield outcomes might be acceptable. Lower initial yields from a PR may also be acceptable if the improved residual effect (see Fig. 2) of a PR gives a comparable yield outcome over a multiple cropping period, to that from a soluble fertilizer. This also may be a satisfactory cost option. Alternatively, if internal freight costs are high, then a more concentrated water soluble fertilizer, which might be as effective as an imported reactive PR, might provide cost savings [55].

A set of suggested guide-lines for PR use has been developed for humid tropical conditions where Oxisols and Ultisols predominate. These are summarised in Figure 3. The feasibility of using a directly applied PR, and the required reactivity of that PR, are determined by considering the soil environment and the type of plant that is to be used in the agricultural enterprise. The suitability of the soil environment for the effective performance of the PR (K_1) will determine if the required rate of P demand (K_2) can be met.

The above guide-lines are based on published research findings on PR performance in a range of tropical farming systems on Oxisols and Ultisols. The effects of PR reactivity have been reported on yields of annual food crops and pastures on very acidic Oxisols and Ultisols and

Rate of P demand from dissolving PR	Suitability of humid tropical soil for PR effectiveness: HIGH (high K_1) [low pH, (<4.8), low Exc. Ca low to moderate P sorption]	→ LOW (lower K_1) [higher pH (>5.2) high P sorption]
LOW (low K_2)	Required PR reactivity rating	
Plantation crops: rubber, oilpalm	LOW	MEDIUM
Perennial pasture, sugar cane	MEDIUM	HIGH
Low P demand food crops: upland rice/cassava	MEDIUM	u/s
High P demand food crops: wheat/potatoes	HIGH	u/s
↓ HIGH (high K_2)		

Fig. 3. Guide-lines for determining the reactivity of PRs for use in the humid tropics, based on the suitability of the soil for PR effectiveness and on crop type. (u/s indicates that all directly applied PRs are unsuitable).

less acidic, higher P sorbing Andepts in South America [13, 24, 30, 32]. Other findings were that the widespread use of low reactivity PRs occurs successfully with plantation crops in South East Asia [19], and that an unreactive local PR was found to be ineffective on tropical pastures in Australia [26]. Similarly the disappointing yield responses of annual food crops to low reactivity, indigenous PRs in Africa and Asia were noted [32].

Liming and the use of PRs in the tropics

The use lime to reduce soil acidity is widely recommended as a management practice for tropical soils [60, 61]. This is particularly important if there is the need to grow crops that are sensitive to the Al toxicity that may prevail in acid tropical soils. An additional cost in using lime is the reduction in the effectiveness of PRs applied to the same soil. An approach already discussed is to apply the PR well in advance of the application of lime, so long as the soil's P-sorption capacity is not excessive. We suggest that the use of lime on tropical soils needs to be carefully reconsidered in instances where cost-effective PR options are available.

There is an increasing body of evidence indicating that Ca deficiency is a greater constraint in many topical soils than Al toxicity for the growth of crops with some degree of acid-soil tolerance. Levels of exchangeable Ca in Oxisols and Ultisols are very low, and range from 0.1 to 0.7 cmole (+) kg^{-1} in the topsoil of tropical savannas in South America [61]. Calcium levels in the subsoil are generally lower and in some cases undetectable in Oxisol subsoils [57]. The low Ca concentrations in soil solution extracts from tropical soils in northern Australia and the low ionic ratio of Ca to total cations would suggest that Ca supply would limit growth of many species [27]. It has since been suggested that Ca deficiency is the primary constraint of root growth in unfertilised acid tropical soils of Australia, even though the pH is low and the Al saturation is high [21]. This has been confirmed in some tropical soils in South America from plant growth studies with *Centrosema* [38] and wheat [28]. The immobility of Ca in the phloem of the plant [66] means that Ca must be taken up at the tips of growing roots; it cannot be translocated to the growing points of subsoil roots from the upper portions of the root system. Given that Ca is a major constraint, the question that must be asked is whether lime is always the most appropriate carrier to supply Ca to the subsoils of acid tropical soils. Alternative Ca sources are gypsum and PRs.

Phosphate rocks are now being considered as a Ca fertilizer as well as a potentially cost-effective P source. As Ca is released when PRs dissolve it follows that the ability to supply Ca would be related to PR reactivity, and this has now been confirmed [36]. Not only does PR dissolution release Ca-ions but it also has the beneficial effect of consuming soil acid, particularly if the PR contains appreciable amounts of free carbonate. Although there may not be marked increases in pH following PR applications there may be significant effects on exchangeable Al [12, 20, 67]. The extent to which a PR application will ameliorate soil acidity on low CEC tropical soils will depend on the reactivity of the PR, its content of free carbonate, and the rate of application.

Future use of phosphate rocks in the tropics

The extent that the direct use of finely ground PR will increase in the tropics will primarily depend on price of PR relative to alternative sources and the cost of the fertilizer relative to crop prices. There are good reasons, such as their low cost and their ability to dissolve in acid tropical soils, why the use of these materials will increase. However, the uneven distribution of PR deposits in the tropics, particularly in South East Asia [17] and the fact that a disproportionate number of PR sources are not particularly reactive will limit their use. The situation may change to some extent in the future as many of the PR deposits have not been adequately characterised, particularly in Africa, where about 70% of the total estimated world reserve of PR is located (Piero C. Personal communication).

There are only a limited number of tropical situations where an indigenous PR would be sufficiently reactive for it to be used as an effective, initial application of fertilizer P for annual food crops. The use of Bayovar PR on corn/soybean/rice rotations on acidic Ultisols in the upper Amazon basin of Peru, and the use of Huila PR for upland rice on Oxisols located on the Llanos of Columbia [32] and the use of Tilemsi PR for cotton, sorghum, corn and millet [40], would be the best examples available. Alternative more energy-intensive strategies, such as the use of some imported (or locally produced) water-soluble P forms, or imported acid, would be required to enable indigenous PRs to be used effectively for food production in most tropical countries. The addition of water soluble P forms to PRs to improve their effectiveness is the subject of a major review [32] and is discussed elsewhere in this issue [8, 56]. It is likely that this will occur and that there will be increased use of PRs in conjunction with some water soluble P sources in the tropics [61].

Annual fertilizer use is a mere 12 kg per ha of arable land and land under permanent crops in sub-Saharan Africa. Poor market infrastructure for both inputs and farm products hinder the increased use of inputs such as fertilizers. In the severely P-deficient soils of this region fertilizer P is needed not only to increase crop production but also to maintain much needed vegetation on the soil surface thereby slowing down the rate of soil erosion and soil degradation [52]. The use of even the most unreactive indigenous PRs on acidic soils in the region, as an investment for soil fertility restoration, should be encouraged. This, however would require that we re-evaluate our standard criteria for promoting the use of PR for direct application to include not only benefits in crop yield, but also the benefits in maintaining the soils P reserve. Small initial increments in yield may be ideal for small nation states with no market outlets. Modest yield increases do not saturate the rudimentary marketing channels. On the contrary, the small monetary returns may initiate the slow process of transforming the subsistence-type agriculture into a market-oriented agriculture.

Expanded use of directly applied PRs is likely to occur for tropical crops that have a lower rate of P demand. This will be the case for the expanding areas of perennial plantation crops that are now starting to produce. The use of more reactive PRs for sugar cane production in the tropics to provide both P and Ca will also increase [21]. Similarly the ever increasing areas of tropical pastures that are being sown on land cleared from rainforest, will provide a large market for medium to high reactivity PRs. It may well be that these PRs will be used to reclaim degraded tropical land that was previously cleared from rainforest and then over-run by weeds such as *Imperata cylindrica*, as the soil's fertility declined rapidly following clearing. The combination of dry season burning, a heavy initial application of reactive PR, and the use of the leguminous creeper *Mucuna coccichinensis*, has produced promising results in Indonesia [64]. The PR application in this instance represents a capital investment to overcome nutrient deficiency and ameliorate soil acidity.

The reality is that most acid tropical soils are inherently infertile and therefore unproductive. Inputs are required to minimize these constraints if these lands are required to produce food for the expanding human population. Phosphate rocks are potential inputs that produce a number of beneficial outcomes in these soils: they should considered increasingly in the future.

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