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Management and conservation of tropical acid soils for sustainable crop production

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FOREWORD

According to FAO estimates, only 11% of the Earth's surface area is currently cultivated (1406 Mha) and about 24% (3.90 Mha) is potentially arable, most of which, 2500 Mha, is composed of acid soils with 1700 Mha located in the humid tropics. Thus, tropical acid soils, mainly Ultisols and Oxisols, represent the largest remaining potential for future agricultural expansion.

Forests of the tropics are invaluable ecosystems of global, regional and local importance, particularly in terms of protection and conservation of biodiversity and water resources. The indiscriminate conversion of tropical forests into agricultural land as a result of intense human activities — logging and modern shifting cultivation — continues to cause soil erosion and degradation. However, the acid savannahs of the world, such as the cerrado of Brazil, the Llanos in Venezuela and Colombia, the savannahs of Africa, and the largely anthropic savannahs of tropical Asia, encompass vast areas of potentially arable land. The acid soils of the savannahs are mostly considered marginal because of low inherent fertility and susceptibility to rapid degradation. These constraints for agricultural development are exacerbated by the poverty of new settlers who try to cultivate such areas after deforestation. Low- or minimum-input systems are not sustainable on these tropical acid soils but, with sufficient investment and adequate technologies, they can be highly productive. Thus, there is a need to develop management practices for sustainable agricultural production systems on such savannah acid soils.

The Soil and Water Management and Crop Nutrition Sub-programme of the Joint FAO/IAEA Division of Nuclear Techniques in Food and Agriculture strongly supports an integrated approach to soil, water and nutrient management within cropping systems. In this context, nuclear and related techniques can be used to better understand the processes and factors influencing the productivity of agricultural production systems, and improve them through the use of better soil, water and nutrient management practices. A panel of experts actively engaged in field projects on acid soils of savannah agro-ecosystems in the humid and sub-humid tropics convened in March 1999 in Vienna to review and discuss recent research progress, along the following main lines of investigation: (i) utilization of acid tolerant and P-efficient plant genotypes, (ii) addressing issues of soil acidity and infertility, and (iii) management and conservation of acid soils. The state of the art reports presented at the meeting are contained in this publication, which, as the first comprehensive treatment of the subject, is expected to serve as an invaluable source of reference to underpin future research on management practices for sustainable crop production systems on tropical acid soils. The responsible IAEA officer was F. Zapata of the Joint FAO/IAEA Division of Nuclear Techniques in Food and Agriculture. The assistance of A.R.J. Eaglesham in the preparation of this publication is gratefully acknowledged.

EDITORIAL NOTE

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SUMMARY

As a consequence of the world's burgeoning population, there is need to increase and sustain food production. This can be achieved through intensification, diversification and specialisation of agricultural production systems on existing cultivated land and/or by expansion of the land under cultivation. The greatest potential for expanding agricultural land lies in the humid tropics, mainly in rainforest and savannah zones that are dominated by acid, infertile Ultisols and Oxisols. The largest extent of these tropical acid soils occurs in Latin America (in which 81% of the soils are acidic), Africa (56%) and Asia (38%). The development of the humid tropics is a controversial subject because the need to expand the agricultural frontier is in direct conflict with the need to preserve the tropical rainforest ecosystem. Deforestation and inappropriate soil-management and conservation practices associated with traditional shifting cultivation are accelerating the degradation of the natural resource base. The problems of acidic soils are likely to be exacerbated by increasing CO_2 levels in the atmosphere, use of ammonium-based nitrogenous fertilisers, continuous removal of farm products and nitrate leaching. It is critically important that the required increased food production be achieved without further degrading the resource base. Much of that food must come from agro-ecologies that are capable of sustainable agriculture but which are currently poorly productive.

Of greater production potential are the lands within the savannah agroecosystem. The savannahs are located in the sub-humid tropical zone, and comprise large areas of the agricultural land in many countries of Africa and Latin America. In terms of agro-climatic conditions, the savannahs are suitable for rain-fed agriculture. Brazil's cerrados, for example, already supply a considerable portion of that country's agricultural produce. In Africa, the savannahs have historically produced all of the sorghum, millet, cowpea, much of the maize, yams and groundnuts, and, more recently, large amounts of cassava, soybean, cotton and upland rice.

In view of these considerations, several international agricultural research centres (IARCs) have focused their activities on identifying technologies suitable for the savannah regions. IFDC has carried out extensive research on fertiliser management on the acid savannah soils of Africa and Latin America. IITA, CIMMYT and CIAT have given special attention to the improvement of maize for savannah conditions. Recently, an EU-funded project focussed on maize and mechanisms of tolerance to Al with the aim of developing user-friendly sustainable technologies to mitigate soil acidity. CIAT has also developed new agropastoral systems for the savannahs that can improve soil fertility. ICRISAT has major programmes on sorghum, millet and groundnuts. IITA has active programmes on soybean and cowpea, and ICRAF has studied the potential for agroforestry systems.

WARDA is working extensively on upland-rice production suited to the humid forest and savannah regions. In addition, networks have been created to integrate national efforts into regional programmes to improve the flow of technology from the IARCs into the regions. As a result of all these efforts, many technologies are available for the savannahs. However, there are significant gaps in our understanding of optimal methods for development and transfer of technologies to farmers. As a result, agricultural production in the savannahs remains far below its potential.

In summary, bridging the gap between potential and actual production of the savannahs will require improved technologies to intensify crop production while conserving the resource base. This would be a major contribution to food security in sub-Saharan Africa and Latin America.

The results of the deliberations of the consultants are summarized as follows:

(1) The key issue is to develop integrated soil-, water- and nutrient-management practices to increase and sustain productivity of the acid soils of the savannah ecosystem in the humid and sub-humid tropics of Africa and Latin America. Research should focus on the following:

- Identification of adapted genotypes and comparison of their usefulness with susceptible lines in terms of P efficiency and Al tolerance,

- Plant residues, green manures, phosphate rock and amendments such as lime to improve nutrient availability and to alleviate Al toxicity,
- Analyses of the dynamics of carbon, nutrients and water in various soil- and crop-management systems, and
- The development of guidelines for improved soil, water and nutrient management.

(2) Nuclear techniques provide a powerful tool for gaining better understanding of the mechanisms and processes that influence the dynamics of water and nutrients for developing improved soil-, water- and nutrient-management practices to increase and sustain agricultural productivity. Nuclear techniques that have potential utility include the soil-moisture neutron probe, ^{18}O for soil-water studies, ^{15}N for measuring N dynamics (N recovery from organic residues and chemical fertilisers, biological N_2 fixation, N transfer, N-fertiliser balance, etc.) in soils, crops and water, ^{32}P for evaluating soil-P dynamics and the agronomic effectiveness of P fertilisers, in particular phosphate-rock-derived products, ^{13}C for measuring soil organic matter dynamics, root studies, drought stress, and water-use efficiency, and ^{137}Cs for measuring soil erosion at the landscape level.

(3) An eco-regional approach should be utilised, identifying specific benchmark sites as focal points for strategic research and development activities. Selected sites should:

- Be representative of the main problems of acid soils, with potential for intensification and operating with existing farm practices (on-station and on-farm studies),
- Be well characterised in terms of soil type, depth, water table, and available climate data,
- Presently have, or have plans for, cropping-system experiments on productivity enhancement and natural-resource conservation, e.g., should include combinations of crop rotations with ground covers and/or minimum or no-tillage, improved fallows, forage or grain legumes,
- Have related work on acid-soil-tolerant germplasm enhancement.

(4) The first approach should be to increase agricultural productivity of tropical acid soils through the use of adapted genotypes, the amelioration of soil acidity and infertility and better management of soil, water, and nutrients. The achievement of sustainable cropping systems in the savannah zones is a long-term issue, necessitating better understanding of soil organic matter, carbon, nutrient and water dynamics in these systems. The adoption of improved and more-profitable technologies by the small farmers to obtain increased yields is a pre-requisite for long term sustainability of new cropping systems in tropical acid soils.

INTEGRATED MANAGEMENT OF TROPICAL ACID SOILS

MANAGEMENT AND CONSERVATION OF ACID SOILS IN THE SAVANNAHS OF LATIN AMERICA: LESSONS FROM THE AGRICULTURAL DEVELOPMENT OF THE BRAZILIAN CERRADOS

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Abstract

Acid-soil savannahs represent most of the remaining land suitable for agricultural development in the world. Considered as marginal lands, they are of low inherent productivity for agriculture, and susceptible to rapid degradation. The vast Brazilian "cerrados" were opened up some 30 years ago, and today they supply a considerable portion of the country's agricultural commodities. Monocultures of grain crops and pastures are proving to be unsustainable under today's conditions, and alternative production systems are being developed and implemented that incorporate improved production technologies and conservation of the natural resources. No-till, minimum tillage and integrated crop-livestock systems are proving to be successful in terms of farmer adoption. However, there is a need to elucidate the principles and functioning of these systems in order to assess their suitability for long-term sustainability of marginal savannah lands. The challenges that remain to ensure that these lands are developed in a sustainable manner include social, cultural and economic aspects, a favourable policy environment and a clearer understanding of sustainability and its measurement. In this article we review the lessons learned from the cerrados experience. Future research should include the development of new crop options with tolerance of acid soils, a better understanding of water and nutrient cycles, the development of principles of soil organic matter and crop-residue management, and the biological management of soil fertility.

1. INTRODUCTION

The burgeoning world population, with the addition of over 80 million people per year, will place great demands on the existing agricultural resource-base and will exert increasing pressure to exploit any remaining lands with potential for agriculture. At the same time, there is an increasing awareness of need for careful stewardship of the world's agricultural lands, which are already suffering significant degradation [1].

In Latin America, the vast savannah areas of Brazil (207 Mha), Venezuela (28 Mha), Colombia (17 Mha), Bolivia (14 Mha) and Guyana (4 Mha) constitute around 50% of the world's savannahs. They have been described as one of the last agricultural frontiers [2]. Their sum exceeds the agricultural area currently under irrigation worldwide, 255 Mha [3].

The Brazilian "cerrados" are the largest and most developed savannahs in Latin America. Before the mid-1960s, most of the cerrados were used only for extensive cattle ranching on native pasture of low carrying capacity. During the 1970s, the introduction of exotic pastures was the main land-use change. The initial lush pastures soon were degraded from lack of adequate management, including maintenance fertilisation [4]. Today, there are approximately 50 Mha of these introduced pastures, mainly *Brachiaria* species, with as much as 50% in some state of degradation [5]. The region gradually began to see the introduction of grain crops, coffee, fruit crops, and reforestation [6]. Soybean was the main grain crop followed by maize. However, as with pastures, these monocrops proved to be unsustainable as a result of inadequate management, inappropriate tillage practices, increased pest and disease problems and soil-fertility decline [7]. Because crop monocultures and introduced grass pastures have become increasingly unsustainable under current practices, alternative

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systems such as agropastoral, silvoagropastoral, minimum and no-tillage, and perennial cropping systems have emerged.

In this article we describe and review the lessons learned during the development process in the cerrados, highlighting the constraints and the technological and management options to overcome them. Such lessons, together with a better understanding of the driving forces behind land-use change, may serve as valuable background for the exploitation of other similar areas in Latin America [8] and certain parts of Africa [9].

2. CONSTRAINTS TO AGRICULTURAL PRODUCTION

2.1. Soil acidity and nutrient status

Most soils of the cerrados are highly weathered Oxisols (46%), Ultisols (15%) and Entisols (15%), with limitations for crop production in terms of low inherent fertility. Lopes and Cox [10] published a survey of 518 top-soil samples, collected from under natural vegetation in central Brazil, covering 33% of the cerrados. Forty-eight percent of the samples had a pH in water lower than 5.0, and 50% were between pH 5.0 and 5.9. This indicates that these soils are predominantly acid, emphasizing the need for adequate liming as the first management practice for cultivation of non-acid-soil-tolerant species.

2.2. Organic matter

The levels of organic matter in cerrados soils range from 70 to 660 g kg^{-1}, which are considered medium to high. Under monocropping that includes conventional tillage and the use of lime and fertilisers, mineralisation and depletion of organic matter is very fast and can reach low levels after 5 to 6 years or less, especially in sandy soils. Silva et al. [11] for example, found that losses of organic matter in the top 15 cm layer in West Bahia under soybean monocropping were, 80, 76 and 41% of the initial values in soils with less than 150, 150 to 300, and more than 300 g kg^{-1} of clay, respectively. According to these authors, the half-life of soil organic matter was 2.1, 2.3 and 2.9 years, respectively.

2.3 Phosphorus

Phosphorus is the most-deficient nutrient in the cerrados. Ninety percent of the samples in the survey of Lopes and Cox [10] had less than 2 mg P dm^{-3}. The problem is complicated as a result of the high P-fixing capacity of these soils [12].

2.4. Calcium and magnesium

The great majority of cerrados soils have extremely low levels of exchangeable Ca and Mg. The survey of Lopes and Cox [10] indicated that 96% of the samples had less than 1.5 cmol Ca dm^{-3} and 90% could be classified as low in exchangeable Mg (< 0.5 cmol Mg dm^{-3}). The great majority of these soils had less than 0.4 cmol Ca dm^{-3} and less than 0.2 cmol Mg dm^{-3}, emphasizing the importance of Mg and dolomitic lime in savannah production systems in order to correct soil acidity and supply sufficient Ca and Mg for crops.

2.5 Potassium

Although responses to potash fertilisers have not been as common or as pronounced as those obtained with lime and P, it is important to ensure that adequate rates of K are supplied in order to obtain medium to high yields.

2.6 Effective CEC and Al saturation

The majority of the soils sampled by Lopes and Cox [10] had between 0.25 and 1.0 cmol Al dm^{-3}, medium levels, and only 15% were considered high in Al. However, since the levels of Ca and Mg are extremely low, exchangeable Al is the dominant cation in these soils even when exchangeable acidity levels are not very high. The effective CEC (the sum of Al + Ca + Mg +K) is low with most soils having less than 4.0 cmol dm^{-3}. These extremely low levels of effective CEC reflect the high degree of weathering of cerrados soils. Very few negative charges exist at the natural pH values, which, together with the low levels of basic cations, results in only a small reserve of nutrients for cultivated crops. Most of the effective CEC is occupied by exchangeable Al, hence Al saturation is high. The productivity of the majority of cultivated crops sensitive to Al^{3+} is decreased in soils with more than 20% Al saturation. Most of the cerrado soils are above 40% Al saturation, a level at which the majority of cultivated plants start to suffer Al toxicity [13].

2.7 Nitrogen and sulphur

According to Malavolta and Klieman, [14], only 32% of cerrado soils are deficient in N. These authors calculated an annual availability of 135 kg N ha^{-1}, assuming a medium level of total N of 90 g N kg^{-1} and a mineralisation rate of 5% per year. However, hydric stress, low pH and generalised deficiencies of nutrients limit the mineralisation process. Therefore, large responses to N applications have been observed for a range of crops in this region [15–21].

Sulphur deficiency tends to be pronounced over time as a result of considerable losses by annual burning of the natural cerrado vegetation and the use of concentrated fertilisers that, in general, do not contain S. Several experiments have shown positive responses to S in these soils [22–27]. Couto and Ritchey [28] suggested a rate of 15 to 30 kg S ha^{-1} $year^{-1}$ to supply the needs of the majority of cultivated crops. A level of 10 mg dm^{-3} seems adequate to define high availability of S.

2.8. Micronutrients

A tentative interpretation made by Lopes and Cox [10] suggests 1 mg Zn dm ^{3} as a critical level for cerrados soils. The great majority of the samples had levels of 0.5 to 0.8 mg Zn dm^{-3}, indicating that this micronutrient is a limiting factor for growth and development of many crops in these soils.

While research related to Cu availability is still incipient, good yields in several crops in the region have been observed without use of Cu fertilisers [29, 30]. Specific studies suggest a critical level of 0.8 mg Cu dm^{-3}.

Induced deficiencies of Mn are common due to over-liming and/or inadequate depth of incorporation. By using 5.0 mg Mn dm^{-3} as the critical level, Cox and Kamprath [31] observed that only 37% of the samples were below this value. This suggests that the majority of these soils are well supplied with extractable Mn. Similarly, these soils are well supplied also with extractable Fe.

Boron (B) can be a limiting nutrient, mainly in sandy and low organic matter soils. McClung et al. [32] observed increases of 80 to 90% in cotton yields, and Silva and Andrade [33] observed yield increases, and reductions in male sterility, in wheat as a result of additions of B. Deficiencies in these cases seem to be more related to high demands of certain crops (cotton, coffee, cauliflower, cabbage and other brassica species) than to a low natural availability. [29, 30]. A level of 0.5 mg B dm^{-3} extracted by hot water can be used as an approximate critical level [34, 35].

With respect to Mo, the great majority of experiments have not shown positive responses [15, 36–38]. However, Couto et al. [27] observed that the use of Mo increased dry matter yields of pasture grasses associated with legumes. Adequate liming of these soils seems to be a management practice that liberates sufficient Mo for most crops, if adequate amounts already exist.

Problems of Mn and Fe toxicity are restricted to small areas, generally associated with continuous and excessive rainfall and/or poor local drainage conditions.

2.9. Water stress

One of the greatest limitations for food production from non-irrigated agriculture in the cerrados is the high probability of dry spells ("veranicos") during the rainy season. Duration, period and the number of veranicos vary from year to year. Taking into account climatic data of 42 years, Wolf [39] estimated the average occurrence of veranicos at 8-days duration three times per year; he concluded also that only 1 year in thirteen had an adequate distribution of rainfall. The problem is further aggravated by low water-retention capacity of these soils. Reichardt [40] estimated the average storage at 6.9 mm H_2O per 10 cm of soil depth in sandy soils, and 11.1 mm H_2O per 10 cm for the other textural classes.

Assuming an homogeneity of physical properties with soil depth and, also, a loss of soil water by evapotranspiration of 6 mm day^{-1}, Reichardt [40] calculated that, in soils with less than 180 g clay kg^{-1}, a crop with roots exploring the 0–30 cm layer would not have available water after 4 days without rain. (Table I). He mentioned also that even clay soils behave similarly to sandy soils in terms of water retention.

Another important factor related to water stress in cerrado soils is the presence of chemical barriers that restrict root penetration of cultivated crops. These natural chemical barriers are the result of Al toxicity and low exchangeable Ca down the soil profile. Ritchey et al. [41] indicated that root development is restricted when exchangeable Ca is below 0.15 cmol dm^{-3} in the sub-soil and when Al saturation is close to 80%.

2.10. Soil compaction

Annual tillage operations with disk ploughs and heavy tandem disks**,** have resulted in the development of a compacted layer that drastically reduces root penetration. This compaction, to a depth of 10 to 15 cm, limits uptake of water and nutrients from the sub-soil, making crops much more susceptible to water stress during veranicos.

TABLE I. AVAILABLE WATER STORAGE FOR CERRADO SOILS IN CENTRAL BRAZIL WITH SANDY AND LOAMY SAND TEXTURAL CLASSES (<180 g kg^{-1}); RESIDUAL STORAGE (mm) AFTER n DAYS WITHOUT RAINFALL AND EVAPOTRANSPIRATION OF 6 mm DAY^{-1}. ADAPTED FROM REICHARDT [40]

Depth (cm)	Max'm storage (mm)	n=2	n=4	n=6	n=8	n=10	n=12	n=14	n=16
0–10	6.9	0	0	0	0	0	0	0	0
10–20	13.8	1.8	0	0	0	0	0	0	0
20–30	20.7	8.7	0	0	0	0	0	0	0
30–40	27.6	15.6	3.6	0	0	0	0	0	0
40–50	34.5	22.5	10.5	0	0	0	0	0	0
50–60	41.4	29.4	17.4	5.4	0	0	0	0	0
60–80	55.2	43.2	31.2	19.2	7.2	0	0	0	0
80–100	69.0	57.0	45.0	33.0	21.0	9.0	0	0	0
100–120	82.8	70.8	58.8	46.8	34.8	22.8	10.8	0	0
120–140	96.6	84.6	72.6	60.6	48.6	36.6	24.6	12.6	0

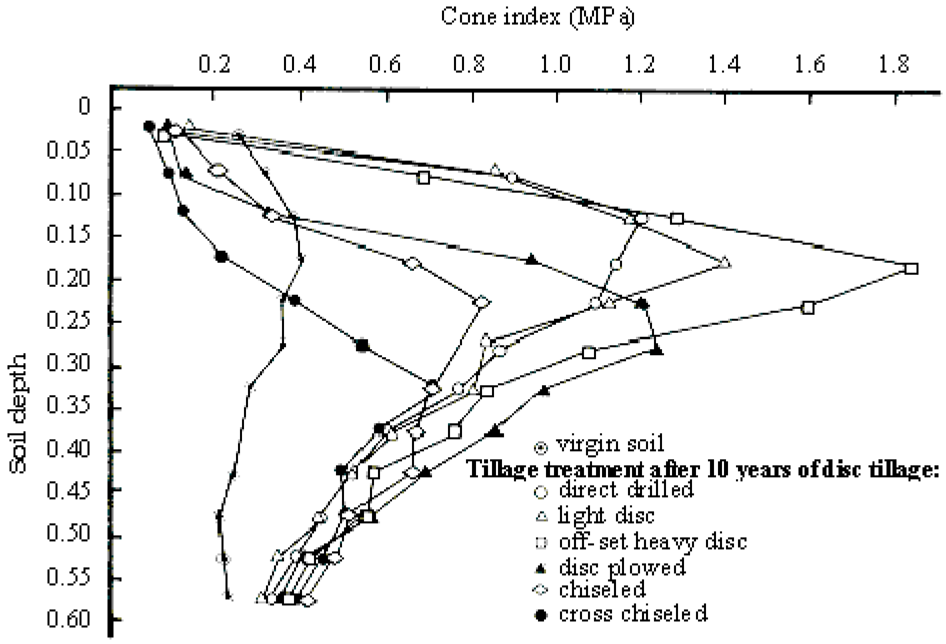

FIG. 1. Mechanical impedance profiles of six tillage treatments on a Typic Haplustox at Minas Gerais, Brazil, compared to native soil conditions [42].

Using an Oxisol with 430 g clay kg^{-1}, cultivated for ten consecutive years with a heavy tandem disk, Stoner et al. [42] found a high compaction level (Cone index of 1.4 Mpa) as compared to 0.4 Mpa for the natural soil condition (Fig. 1). Additional soil tillage in the eleventh year with disks aggravated the problem, with compaction reaching 1.8 MPa.

Knowledge of clay content is essential for identifying areas of greater or lesser susceptibility to soil compaction and restriction of crop-root development. Surface samples with 160, 530 and 700 g clay kg^{-1} soil, artificially compacted to give bulk densities of 1.0, 1.1, 1.2, 1.3 and 1.4 Mg m^{-3}, were evaluated in relation to root development for seedlings of corn, soybean, wheat and common bean [42]. The roots of all four species showed normal development in the sandier soils (160 g clay kg^{-1}), even at a bulk density of 1.4 Mg m^{-3}. In the clayey Oxisol (530 g clay kg^{-1}), roots penetrated at all bulk densities (from 1.0 to 1.4 Mg m^{-3}). However in the very clayey Oxisol (700 g clay kg^{-1}), serious restriction to root penetration was observed with all four species.

Restriction of root development was greatest for common bean, diminishing in the order bean > corn > wheat > soybean. The most problematic soil was the very clayey Oxisol, which impeded bean-root penetration under humid conditions with a bulk density of 1.1 Mg dm^{-3}, a level frequently observed in farmers' fields [42]. The main conclusion of this research was that the higher the clay content, the greater the soil susceptibility to compaction and reduction in root development.

2.11. Soil erosion

Excessive tillage operations with disk equipment even in level areas of the cerrados leads to loss of soil structure and the formation of compacted layers at 10- to 15-cm depth, that can result in reduced water infiltration and considerable soil loss by run-off and erosion.

Rainfall erosivity, characterized by the index EI_{30} (kinetic energy of rainfall in 30 min), is quite intense in the cerrados, increasing the breakdown of surface soil aggregates, sealing the soil surface, reducing infiltration and increasing run-off [43, 44]. Dedecek et al. [44] showed that losses of soil and water in a Dark-Red Latosol (Oxisol) with 5% slope were higher for the bare soil and corn under conventional tillage, compared with soybean under no-till, and pasture (Table II). These findings emphasize the need for the maintenance of soil cover and the avoidance of long periods of bare soil as a first step to reducing erosion in the cerrados. Even in this Dark-Red Latosol, which was considered to be highly resistant to erosion according to the evaluation by the authors, soil losses under no-till were 5 t ha^{-1} [45].

3. TECHNOLOGIES FOR ALLEVIATING SOIL ACIDITY AND LOW FERTILITY

3.1. Liming

Several papers have summarised positive effects of lime use in the cerrados [46–48]. In addition to correcting soil acidity, reducing Al toxicity, increasing levels of Ca and Mg that are inherently low, increasing biological activity and the efficiency of fertilisation with macronutrients, liming these soils has other key beneficial effects [48, 49]:

– Increasing pH-dependent charges and, by consequence, the “available” CEC,
– Diminishing the P-fixation capacity by precipitating exchangeable Al as $Al(OH)_3$,
– Stimulating root development at depth depending on rate, depth of incorporation and time after application.

The average rate of lime use in this region is 3 t ha^{-1} (range 1–5), incorporated as deeply as possible by disk ploughing or tandem-disk harrowing (in general 0–20 cm). This procedure is generally used for annual grain crops, for the establishment of perennial crops and for some pasture species.

When micronutrient deficiencies are adequately corrected, additional benefits can be obtained by using high rates of lime that result in pH values above 6.0. Such values are achieved generally by utilising the increase-base-saturation method [50]. Independent of the method used, it is necessary to adjust the rates according to the RPTN (Relative Power of Total Neutralization) of the lime, which includes the $CaCO_3$ equivalent and the reactivity of the lime. Residual effects of these rates, in general, vary from 3 to 5 years.

The concept of liming in no-till or minimum-tillage agriculture differs from that used with conventional tillage. Before initiating no-till or minimum tillage, it is necessary to use an adequate rate of lime, in order to increase base saturation of CEC at pH 7.0 to 70%. Lime should be incorporated as deeply as possible and targeted for residual effect by using a coarser lime [51]. After this preparatory period, one third or one half of the lime requirement can be applied in clayey and sandy soils without ploughing [52].

TABLE II. LOSS OF SOIL AND WATER FROM A DARK-RED LATOSOL WITH 5% SLOPE, UNDER VARIOUS COVERS (AVERAGE DATA OF 6 YEARS) [44]

Erosivity index	Bare soil	Corn	Rice	Soybean	Soybean no-till	Pasture
		Conventional				
	Soil loss (t ha^{-1})					
($t\ ha^{-1}\ mm^{-1}\ h^{-1}$)						
805	53	29	8	9	5	0.1
	Water loss (mm)					
rainfall (mm)						
1,243	293	264	257	180	168	15
	Infiltration (%)					
	76	79	79	86	87	99

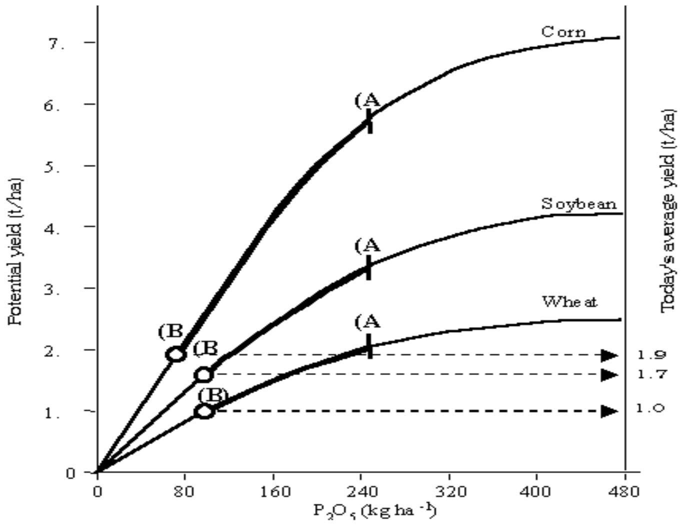

FIG. 2. Potential (A) and average production (B) for corn, soybean and wheat, as a function of "build-up" of phosphate fertilization, under rainfed conditions in the central cerrado region [57].

3.2. Amelioration of sub-soil acidity

The existence of chemical barriers (Al toxicity and low exchangeable Ca), associated with low available-water-retention capacity of these soils, mean that only a small volume of soil can be explored by the root system. Corrective alternatives exist: deeper lime incorporation, and possible phosphate fertilisation, or downward movement of Ca and Mg through the profile. The first practice is limited by the high costs of deeper lime incorporation and the second by slow vertical movement of Ca and Mg.

Gypsum, a by-product of phosphoric-acid production, has been promoted for amelioration of sub-soil acidity [53]. The most direct effect of gypsum on the sub-soil, after surface broadcasting, is increase of Ca, and a reduction in exchangeable Al down the profile. Increased rooting depth is observed, with beneficial implications for water and nutrient use in the sub-soil.

Several studies have been conducted to estimate gypsum applications for specific soil conditions. The first guidelines for gypsum applications to improve rooting in the subsoil were developed by Lopes [48]. The conditions were: exchangeable Ca ≤ 0.3 cmol dm^{-3} and/or exchangeable Al ≥ 0.5 cmol dm^{-3} and/or > 30% Al saturation of the effective CEC. It should be stressed that these components (Ca, Al and %Al) must be evaluated not only in the surface soil layer (0–20 cm), but also to depths of 20 to 40, 40 to 60 and down to 60 to 80 cm for perennial crops [48, 54].

The effects of gypsum depend upon soil texture, level of organic matter, proportion of Ca in relation to other cations and crop species [55, 56].

3.3. Phosphorus capitalisation or "build-up" via fertiliser application

Increasing the stock of P, via fertiliser application, in soils with extremely low levels of extractable P and high P-fixing capacity, is a crucial step in achieving adequate and economic yields in the short term. The importance of an adequate "build-up" of P via phosphate fertilisation can be observed in Fig. 2. Research has indicated that, with adequate rates of phosphate fertiliser, yields of wheat, soybean and corn can be more than doubled, compared with small maintenance rates of fertiliser [57].

TABLE III. AGRONOMIC EFFICIENCY INDEX (AEI %) OF PHOSPHATE FERTILISERS IN A CLAYEY OXISOL UNDER CERRADO VEGETATION IN CENTRAL BRAZIL, CALCULATED BY P ABSORPTION DATA OVER 5 YEARS WITH ANNUAL CROPS FOLLOWED BY 3 YEARS WITH *ANDROPOGON* PASTURE [62]

Phosphate fertiliser	200 kg total P_2O_5 ha^{-1}			800 kg total P_2O_5 ha^{-1}		
	Annual crops	*Andropogon*	Total	Annual Crops	*Andropogon*	Total
	AEI (%)					
Triple superphosphate	100	100	100	100	100	100
Hyperphosphate (Gafsa)	93	110	104	106	106	106
Thermophosphate-Mg	92	142	113	110	119	114
Thermophosphate-IPT	45	84	60	88	98	92
Pirocaua	76	97	87	81	84	82
Araxá[a]	27	69	41	47	74	58
Patos[a]	45	81	59	56	91	70
Abaeté[a]	21	86	43	47	71	56
Catalão[a]	8	36	17	26	43	33

[a]Brazilian phosphate rocks.

Several studies in the cerrados evaluated methods, sources and rates of P fertilisation, and state-of-the-art papers have been published [46, 48, 58, 59]. When new areas of the cerrados are utilised for grain-crop production, broadcast "build-up" corrective phosphate fertilisation, followed by maintenance fertilisation in bands, has been recommended [48, 60]. The most common method to estimate the rate for "build-up" P fertilisation is to apply 1.5 to 2.0 kg P ha^{-1} per each 10 g clay kg^{-1} soil, followed by normal annual maintenance P-fertiliser use, in order to achieve good yields 3 to 4 years after clearing the area [48].

Considerable research effort has been made in the past 20 years to evaluate the effectiveness of Brazilian phosphate rock in comparison with triple superphosphate and Gafsa phosphate rock [61]. In a study by Goedert and Lobato [62] with a clayey Oxisol at the Cerrado Research Center, Planaltina, Brasilia, Brazilian rocks had low agronomic efficiency index (AEI) values (Table III). However, for *Andropogon* grass, cultivated for 3 years after annual crops, AEI % of these Brazilian phosphate rocks, except for Catalão, was considerably higher. The high AEI % for Gafsa phosphate, triple superphosphate and thermophosphate-Mg is a good indication that these P fertilisers are adequate sources for "build-up" of P capital in the cerrados.

In recent years, a few highly reactive phosphate rocks (North Carolina, Arad, Daouy, Gafsa) have been evaluated. Preliminary results indicate that both commercial (coarser) and finely ground types are adequate for building up P levels in these soils when applied by broadcasting and incorporated through tillage (Table IV).

3.4. "Build-up" of potash via fertiliser application

A corrective broadcast application of potash fertilisation is recommended for soils with more than 200 g clay kg^{-1} soil and low exchangeable K. For soils with less than 200 mg clay kg^{-1}, a complete correction is not recommended because low CEC in these soils can exacerbate loss of K by leaching [34].

Corrective potash fertilisation can be made gradually through annual applications of K_2O at rates above those recommended for maintenance, applied in the planting furrow. In successive years, tillage (ploughing and disking) mixes the residual K, resulting in an adequate level of exchangeable K in the plough layer after 4 to 5 years [34].

TABLE IV. AGRONOMIC EFFICIENCY INDEX (AEI %) OF TRIPLE SUPERPHOSPHATE (TSP), NORTH CAROLINA PHOSPHATE ROCK, COMMERCIAL (NCC) AND VERY FINELY GROUND (NCG), BROADCAST AND BANDED, FOR SOYBEAN IN A CLAYEY OXISOL. ADAPTED FROM REIN [63]

Year	Broadcast[a]			Banded[b]		
	TSP	NCC[c]	NCG[d]	TSP	NCC	NCG
1992	100	63	96	100	30	42
1992/93	100	138	112	100	96	91
1993	100	167	114	100	108	77
Average	100	123	107	100	78	70

[a]160 kg of total P_2O_5 ha^{-1}, broadcast in the first year.
[b]Average of 40 and 80 kg of total P_2O_5 ha^{-1}, banded every year.
[c]80% between 0.15 and 0.42 mm diameter.
[d]More than 70% with less than 0.075 mm diameter.

TABLE V. RATES OF K_2O (kg ha^{-1}) RECOMMENDED FOR TOTAL AND GRADUAL "BUILD-UP" POTASH FERTILISATION FOR SOYBEAN IN THE CERRADOS. ADAPTED FROM SOUSA [34]

Interpretation	Level of exchangeable K (mg dm^{-3})		"Build-up" fertilisation	
	clay < 200 g kg^{-1}	clay ≥ 200 g kg^{-1}	Total: if clay ≥ 200 g kg^{-1}	Gradual
			--------- K_2O (kg ha^{-1})-------	
Low	< 15	< 25	100	70
Medium	16–30	26–50	50	60
Good[a]	> 30	> 50	0	0

[a]After achieving this level, maintenance fertilisation rate is 20 kg K_2O t^{-1} ha^{-1} soybean produced.

The recommended rates for total and gradual "build-up" potash fertilisation for soybean crops in the cerrados as a function of clay content and K availability, is presented in Table V. Adaptations of these recommendations can be made for other crops in the region. The main source for Brazilian agriculture is KCl.

3.5. "Build-up" of micronutrients via fertilisation

Since there few studies have been reported on micronutrients, farmers adopt an "insurance" strategy. The recommended rates (kg ha^{-1}) include 6 of Zn, 1 of B, 1 of Cu and 0.25 of Mo, by broadcast distribution, repeated every 4 to 5 years. One quarter of this rate is recommended for annual distribution in the furrow [64].

4. LAND-MANAGEMENT SYSTEMS

4.1. Native pastures

Until 30 years ago, native pasture was the most common land-use system in the cerrados. The main management practice was annual burning, to eliminate dry, non-palatable native pasture at the end of the dry season and to stimulate the growth of more palatable new material. The two main factors responsible for the low herbage quality and animal performance under these conditions were lack of humidity in the soil during the dry season and low soil fertility.

4.2. Improved pastures

Introduced pastures were established usually after a pioneer crop of upland rice in recently cleared cerrado, using low rates of lime and fertilisers. It is estimated that about 48 Mha of improved pastures now are planted, mainly with grasses introduced from Africa, such as *Brachiaria* and *Andropogon* spp. [5]. In spite of the low native soil fertility, the resulting pastures are lush and productive during the early years after planting [4]. However, pure grass pastures often decline in productivity after 4 to 10 years of grazing, a phenomenon that occurs more rapidly on sandy soils [5, 65]. It is estimated that more than 50% of the area of improved grass pastures in the cerrados are, to some degree, degraded [5]. Declines in grass and animal productivity are followed by the invasion of non-palatable weed species and appearance of bare areas in the sward. Often there are marked increases in termite populations and numbers of mounds [65].

The causes of pasture degradation are numerous and complex [4]. However, N deficiency has been implicated as a main factor. Pure-grass pastures under intensive grazing pressure usually become deficient after 2 or 3 years [4]. This has been associated with losses of N from the system by volatilisation, leaching from urine spots and immobilisation in stable organic matter pools formed from grass residues in the soil [66]. Also, lack of maintenance fertilisation, and pest and disease pressures may be important contributors to pasture degradation.

The use of legume-based pastures has been shown to reverse rapid decline of soil fertility and to contribute to improved dry-season forage quality and availability [64]. Locally adapted legumes and grasses are now becoming available, which should lend greater persistence and productivity. A key factor for the persistence of grass/legume pastures is adequate grazing and maintenance fertiliser management [67].

4.3. Annual crops — conventional tillage

Monocropping of annuals in the cerrados contributes around 28% of the total grain production of Brazil, 43% of the soybean, 3% of the wheat, 14% of the common bean and 9% of the sugar cane, and is considered moderately successful. However, extensive monocropping is often accompanied by inappropriate tillage operations, consisting mainly of excessive numbers of passes of disc ploughs that result in decreased productivity, increased production costs and soil degradation via organic matter loss, soil compaction, and erosion. Additionally, weed invasion and pest and disease problems exacerbate productivity losses.

4.4. Annual crops — minimum or no-till

Probably more important than the “cerrado revolution” that occurred in the 1970s is the “no-till revolution” that started in the 80s in Brazil and exploded in the 90s. No-till increased from 150 kha in 1980 to 1 Mha in 1990, reaching nearly 10 Mha in 1998. It is estimated that 2 Mha of annual grain crops in the cerrados now are grown under no-till [68].

The first attempts to apply no-till in the cerrados failed because the hot, dry winter did not allow the development of traditional winter crops. From this experience, a variant evolved with the absence of a cover winter crop. One step forward was the use of minimum tillage to plant crops into perennial grasses. The main advantage of this technology was the possibility of using conventional planters, leaving the soil surface soft and easy to plant [69].

A major breakthrough in the evolution of the system was the introduction of a “safrinha” that consists of a second crop after the main crop in the same year. This strategy increases financial returns, enhances the production of crop residues to be left on the soil surface and reduces rates of herbicide use. Besides these effects, a safrinha can improve forage availability for livestock during the dry season and increase recycling of nutrients by bringing them to the surface, thus reducing loss by leaching [68].

TABLE VI. QUANTITY OF NUTRIENTS RECYCLED BY SEVERAL CROPS IN THE CERRADOS [70]

Crop	Dry matter	Nutrients recycled (kg ha^{-1})				
	(t ha^{-1})	N	P_2O_5	K_2O	Ca	Mg
Millet	12.0	206	60	350	53	32
Soybean	4.0	42	11	64	35	26
Wheat	3.5	34	11	58	7	4
White oat	2.5	18	16	60	13	3

A second major breakthrough in the improvement of no-till in the cerrados has been the introduction of African millet *(Pennisetum typhoides)*, which is highly resistant to drought, adapted to low-fertility soils and has a high capacity to produce biomass. The water requirements for millet are small compared to those for other crops. In addition to its adaptation to low fertility, African millet has a rooting system able to penetrate into high-Al, low-Ca sub-soils, thereby facilitating deep nutrient capture and recycling (Table VI). Further, millet is easy to establish and manage; it produces seedlings of high vigour and can be planted using several alternative methods, such as rows, broadcast and even aerial sowing. It has little susceptibility to diseases and pests, is an excellent feed for animals and has low risk as a weed species [70].

Although no-till and minimum-tillage management practices are recent in the cerrados, several variations have been described in detail by Landers [68], a summary of which follows, for rain-fed systems.

4.4.1. No-till in the straw

Before initiating no-till, it is necessary to “build-up” soil fertility over a period that normally takes 3 to 4 years under conventional tillage. The second step is to generate a large amount of straw as a winter cover crop. In some cases the seed is planted into cut straw of the preceding crop. A non-selective herbicide is applied in winter to eliminate weeds before planting.

The most promising combinations for adequate straw production for summer planting include the sowing of millet with the first summer rains, followed by the main crop with no-till and generation of straw with corn, millet or sorghum from a follow-up safrinha after the main crop. For farmers more interested in soybean, a deep ploughing and adequate soil “build-up” in the first year then crop cycles of soybean/sorghum (or millet) for several years is recommended. Using this system for four consecutive years, yields of soybean above 4 t ha^{-1} have been obtained [71]. These yield levels are similar to those of obtained on the better soils of the world.

4.4.2. No-till without winter fallow

This system is characterized by the absence of a safrinha after the main rain-season crop. In this situation, weeds, mostly grasses produced from seeds of the same year, are the main straw producers. This option is efficient when the weed species are easy to control. It has been used in Santa Helena de Goiás, GO, to plant no-till corn and soybean on weed winter-fallow straw on clayey soils with high fertility, for more than 5 years. The weeds grow as fallow during the winter dry period, then are allowed to germinate and are controlled with herbicide.

4.4.3. No-till with a living cover crop.

Under this system, crops are planted into a living cover crop of a legume. It requires control of legume re-growth with 2,4-D during the first 40 days of corn development. After that stage, Paraquat can be used. Perennial soybean (*Glycine javanica*), kudzu (*Pueraria phaseoloides*), centrosema (*Centrosema* spp.), Siratro (*Macroptilium purpureum*), and *Arachis pintoi*, have been used with relative success. The cycle ends when a grass/legume pasture is established. *Calopogonium* and Siratro have been planted under rice straw and used later as forage crops for beef cattle.

4.4.4. No-till and conventional tillage on the same farm

This system is practised when there has been a substantial delay in planting and germination of weeds in areas already prepared with conventional methods. Operations of tandem disking and levelling are substituted by herbicide use when there is a perception that the area to be planted exceeds the farm capacity. The farmer selects areas infested predominantly with weed grasses, in order to obtain more straw for erosion protection and to reduce further weed-seed germination.

The main advantages of this combined system are reduction in production costs and avoidance of preparation operations with wet soils, which are detrimental to soil quality and to the environment. Under this system, conventional planters can be used since the soil is well prepared and soft.

4.4.5. Intermittent no-till

Surface compaction due to machinery transit under humid conditions, or weed infestation that is difficult to control, can contribute to reversion to conventional tillage practices. Surface compaction is easily eliminated with minimum tillage by use of a chisel plough down to 20 to 25cm depth. However, there are circumstances when no-till has to be combined with deep ploughing. Landers [68] suggested its use as follows:

- When the crop is very sensitive to small changes in soil compaction, as in the case of rice [71],
- When there is need to control persistent weeds and pests in an economical way,
- As a precautionary measure against disease propagation by the straw, where the disease epidemiology requires this procedure, or in cases where it is not clear,
- To eliminate soil compaction resulting from excess machinery traffic on moist soil, especially in the cases of silage production and irrigation,
- To dilute the effects of high rates of lime applied to the soil surface.

4.5. Minimum tillage

This system represents minimum disturbance of the cover crop and of the soil, leaving as much straw as possible on the surface. When utilised in combination with pre-plant chemical weed control, minimum tillage represents an option between conventional tillage and no-till. This system is adequate for erosion control where there is no compacted layer, and it is a preliminary step towards the adoption of no-till. Some variations of minimum tillage have been discussed by Landers [68].

4.5.1. No-till and minimum tillage, annual crops, under irrigation

There are farmers using no-till and minimum tillage with annual crops under irrigation. The main difference when compared to rain-fed conditions is the security against water stress during short dry periods in the rainy season, and the elimination of the deleterious effects of the dry season. Under irrigated conditions with two or more crops per year, it is possible to generate a considerable quantity of straw.

The continuous use of no-till under irrigation requires a higher level of technical knowledge and experience, with detailed attention to:

- Soil humidity when operating the machinery,
- Crop successions to avoid pest built-up,
- Close monitoring of the soil and nutritional levels of the plants,
- The selection of herbicides and other cultural practices that do not allow problematic weeds to reach harmful levels,
- The avoidance of residual effects of pesticides in the cropping sequence.

4.6. Perennial crops

Perennial crops, occupying around 2 Mha of the cerrados, include banana, coffee, rubber, citrus, cashew, pineapple, mango, avocado, passion fruit, Barbado cherry and sour-sop (*Annona muricata*). Forestry is mainly pine and eucalyptus. Coffee is grown on around 1 Mha, mainly in the southern state of Minas Gerais [7],

4.7. Integrated crop/pasture systems

In recent years, considerable research effort has focussed on crop/pasture rotations, also termed ley farming. This integrated approach may contribute more to the ecological and economic sustainability of crop- and livestock-production systems in the humid and sub-humid tropics than any other single innovation. Inclusion of no-till or minimum-tillage management of the annual crops may further improve the system's sustainability.

The advantages of ley farming are derived mainly from synergism between the annual and perennial components of the system [4, 72, 73]. Problems inherent with each component can be solved by rotating. Vera et al. [74], Thomas et al. [75] and Spain et al. [4] cited the following advantages:

- Enhanced soil fertility,
- Increased biological activity,
- More-efficient nutrient cycling,
- Enhanced soil physical properties,
- Controlled weeds, insects and diseases,
- Improved dry-season feed quality and availability,
- More-effective soil and water conservation and use,
- Economically more resilient than separate enterprises.

The argument for crop/pasture rotations in the cerrados is strengthened by the presence of extensive areas of degraded pastures, most of which are on arable soils in areas also being exploited for grain production. At the same time, many grain producers are facing increased costs of production and declining yields due to soil degradation, mainly from compaction, weeds, insects and diseases.

Several technologies for crop/pasture rotations have been developed and are used extensively by farmers in the cerrado region. One of them is the Barreirão System [76], developed by farmers to establish pastures with a pioneer crop of upland rice. Other options include corn, sorghum and millet with pastures [76, 77]. Advantages include:

- Reduced requirements for machinery,
- Correction of acidity according to the needs of the plant species,
- Reduction of termite mounds and weeds,
- Reduction of water-stress risk,
- Extended growth of forages during the dry period,
- Partial or total return on investment costs in a short period,
- Ease of implementation, if machinery and technical support are available.

Methods of reversing pasture degradation through the integration of grain crops, mainly soybean, have been developed by the Foundation for Research and Technology Diffusion of Mato Grosso do Sul State. These involve the integration of degraded pastures (*Brachiaria decumbens, Brachiaria brizantha, Panicum maximum* cv. Tanzania *and Panicum maximum* cv. Mombaça) with annual crops, under no-till. In addition several combinations of commercial crops, green manures and perennial pasture species have been used to implement crop rotations in integrated crop-livestock systems. A summary of this technology is available [78], as are evaluations of herbicides for desiccation of these pasture species [79–84].

Mato Grosso do Sul is in the southern temperate region in Brazil, therefore, it is possible to extrapolate the cover-crop data to the southern cerrados. A series of practical extension publications provide guidelines for management of these crops in this region [85–89].

One of the most successful examples of crop-livestock integration has been developed at the Santa Terezinha Farm, near Uberlândia, MG [90]. Briefly, beef-cattle production, which was the only activity of the farm in 1978, has been gradually replaced by crop/pasture rotations. The main rotation system consists of 2 years of soybean followed in the third year by corn planted simultaneously with pasture grass. After harvest, the pastures are ready for grazing and remain green throughout the dry season, thus supplementing forage availability for the herd during the most critical period of the year (May to September). As soil fertility was improved due to the fertiliser applied to crops, the more rustic grasses *Brachiaria decumbens, Brachiaria ruziziensis* and *Brachiaria humidicola* were replaced by better and more demanding grasses, such as *Panicum maximum* (cvv. Vencedor, Tanzania and Centenário) and *Brachiaria brizantha* cv. Marandu.

The control of pastures for the planting of crops was initially achieved by conventional tillage at the end of the rainy season. The farmer is now moving towards direct planting of crops into chemically controlled degraded pastures. His goal is to take advantage of the improved soil fertility and minimize tillage operations.

The main advantages of the rotation system used at Santa Terezinha Farm can be seen in the increased carrying capacity of the pastures (Table VII), improved soil structure and increased grain yields. In spite of the significant achievements at Santa Terezinha Farm, the introduction of high quality forage species that are more demanding in terms of fertility and management is leading to rapid decline in pasture productivity. Nitrogen deficiency is causing a rapid degradation of *Panicum maximum* pastures.

TABLE VII. CHANGES IN PASTURE AREA OVER TIME IN SANTA TEREZINHA FARM, UBERLÂNDIA, MG, AS CONSEQUENCE OF THE INTRODUCTION OF CROPS AND CROP/PASTURE ROTATION [90]

Year	Planted pastures[a] (ha)	Pastures after crops (ha)	Total area (ha)	Herd size	Stocking rate (animals/ha)
1983	1,014	0	1,014	1,094	1.1
1984	970	0	970	1,069	1.1
1985	858	60	919	1,025	1.1
1986	647	80	727	804	1.1
1987	521	176	697	862	1.2
1988	293	296	589	821	1.9
1989	205	377	582	846	1.4
1990	115	493	608	892	1.4
1991	15	632	647	891	1.4
1992	0	412	412	1,150	2.8

[a]Planted after cerrado clearing.

TABLE VIII. TODAY'S PRODUCTION OF CEREALS AND MEAT IN THE CERRADO, SCENARIO FOR FOOD PRODUCTION USING AVAILABLE TECHNOLOGY IN THE AREA ALREADY OCCUPIED, AND SCENARIO FOR FOOD PRODUCTION USING AVAILABLE TECHNOLOGY IN THE POTENTIAL AREA OF THE CERRADOS [5]

Activities	Area ($\times 10^6$ ha)	Productivity (t ha^{-1} $year^{-1}$)	Production ($\times 10^6$ t)
Today's production of cereals and meat			
Crops (rain fed)	10.0	2.0	20.0
Crops (irrigated)	0.3	3.0	0.9
Meat	35.0	0.05	1.7
Total	45.0	–	22.6
Scenario for food production using available technology in the area already occupied			
Crops (rain fed)	20.0	3.2	64.0
Crops (irrigated)	5.0	6.0	30.0
Meat	20.0	0.2	4.0
Total	45.0	–	98.0
Scenario for food production using available technology in the potential area			
Crops (rain fed)	60.0	3.2	192
Crops (irrigated)	10.0	6.0	60.0
Meat	60.0	0.2	12.0
Perennial crops	6.0	15.0	90.0
Total	136	–	354

5. CHALLENGES AHEAD TO ACHIEVE SUSTAINABLE PRODUCTION SYSTEMS

The opening of the cerrados for crop and livestock production has shown clearly that even marginal soils can be successfully incorporated into the production process by using adequate management and technology. The adoption of these technologies has resulted in substantial gains in production with increases predicted from further exploitation of the potential area (Table VIII). However, the apparent lack of long-term sustainability of these systems has led to a series of alternative management options that are thought to be better adapted to today's and tomorrow's needs.

As with all new technologies and management options, there are some difficulties and obstacles to their widespread adoption in other areas. These result from three fundamental points:

- Social, economic and cultural aspects at the farmer and community levels that can hinder the required change in thinking and/or adoption of more sustainable management practices,
- A favourable policy environment is needed during the transition periods of technological change,
- The need to standardise sustainability concepts and to develop quantifiable parameters of sustainability.

Below we briefly discuss these aspects.

5.1. Social, economic and cultural aspects

A better understanding of the driving forces behind land-use change at the farm and other levels is required in order to ensure that new technological and management options are appropriate and are acceptable to farmers. For example, the conventional wisdom that farmers will not adopt resource-management technologies that require long-term investments needs re-examination following the finding that soybean farmers in the cerrados do invest in no-till systems for erosion control and longer-term benefits [91]. In this case, the private sector played a major role in the dissemination of no-till systems.

The concept of integrated crop-livestock systems appears to be sound from the economical and ecological aspects. However it was reported that over 60% of farmers surveyed in three watersheds of the state of Minas Gerais planted pastures only on areas they considered unsuitable for crops [91]. These examples emphasise the need for better communication and collaboration amongst farmers, researchers and policy makers. Recent emphasis on the need for "farmer first" and "farmer participatory research approaches" within the research community is a welcome sign that progress is being made. The publication by the American Society of Agronomy of a book on no-till agriculture authored by a Chilean farmer and based solely on his experiences [92] is another indicator of a willingness to break down traditional barriers between the scientific community and agricultural practitioners.

5.2. Favourable policy environment

Just as the opening up of the Brazilian cerrados was stimulated by government programmes and subsidies, it is likely that new technologies and management options will require more-favourable policy environments to be successful. "Magic bullet" remedies are rare, especially when dealing with the complexities of sustainable agriculture. Better dialogue amongst farmers, researchers, extension workers and policy makers is essential and requires much more effort from the research community.

5.3. Sustainability and its measurement

Among the several definitions of sustainable agriculture, one of the most acceptable is that of the FAO [93]: "Sustainable agriculture should involve the successful management of resources for agriculture to satisfy changes in human needs while maintaining or enhancing the quality of the environment and conserving the natural resources." The key issue in this definition is the quality of the environment and, in terms of this paper, we refer to soil quality. According to Eswaran et al. [94], the aspects of soil quality that are important for sustainable agriculture are many, but can be reduced to ten points: (i) available water-holding capacity; (ii) nutrient-retention capacity — cation exchange capacity; (iii) nutrient availability — pH, base saturation, P and K; (iv) nutrient fixation; (v) chemical constraints — acidity, sodicity, salinity; (vi) physical constraints — low hydraulic conductivity, permeability, high bulk density, crusting; (vii) effective soil volume — depth to root-restricting layer, stoniness, structure; (viii) surface tilth; (ix) erodibility; and (x) water-logging.

Until and unless such soil-quality standards are established, it will be difficult to monitor soil degradation and consequently evaluate the effects of management. These standards provide a basis for evaluating changes in soil conditions due to management, provide the tools for monitoring changes, provide the basis for legislating soil stewardship, provide means of signalling potential problems in order to trigger research or development activities, and provide the criteria for evaluating agricultural systems for sustainability [94].

For the specific case of the cerrados, many of the possible quality patterns (chemical, physical, biological, etc.) are not yet quantified with a scientific basis to give sufficient support for discussions concerning directions for sustainable management. Besides a need to develop further the scientific components there is also a need to relate them to components that farmers can use and understand.

More effort is needed to document farmers' knowledge and perceptions of soil quality. Scientific and local knowledge need to be brought together to develop land-quality monitoring systems that can be implemented and interpreted by the land users themselves.

6. CONCLUSION AND RECOMMENDATIONS FOR FURTHER RESEARCH

There has been a considerable research effort in the past three decades to solve the problems of low inherent soil fertility, high soil acidity, P-fixation, Al toxicity and low Ca availability in the sub-soils of the cerrados that limit root development. The basis for the chemical management of these soils has been established through relatively high rates of lime and fertiliser application. This knowledge allowed the incorporation of millions of hectares into the agricultural-livestock-forestry production sector, transforming marginal areas into a highly productive land.

Most of the research findings were adequately transferred to a significant number of farmers in the form of practical bulletins and other extension mechanisms that revolutionised soil-fertility management. However, this revolution has been questioned in recent years as not being adequate in terms of the medium- to long-term sustainability. Most of the research on the evaluation of losses of sustainability has involved classical aspects such as a decrease of soil organic matter, intensification of soil erosion and the formation of compacted layers. There is need for the establishment of "early warning" indicators, biological indicators, and integrative indicators that incorporate chemical, physical and biological components in order to gauge system productivity, resilience and sustainability. Integrative indicators should be based primarily on indicators that farmer use.

The search for more-sustainable systems of agriculture-animal husbandry-forestry on these soils has led to considerable effort to introduce no-till and minimum tillage for grain-crop production, sometimes integrated with improved pastures. The observed increases in no-till and minimum tillage in the last decade, reaching almost 30% of the grain-crop area of the cerrados in 1997, is evidence of a change in thinking among farmers.

Although there has been considerable effort in research, teaching and extension for the development of better technologies by various national and international institutions, the true "explosion" in technology implementation was more a result of effort of the farmers themselves. Farmer-to-farmer communication and farmer cooperatives were the main driving forces behind the transfer and adaptation of the experiences obtained in the southern temperate region in Brazil.

The good results obtained at farm level from the integration of grain crops with improved pastures is strong evidence that this integration is not only feasible but highly recommendable in order to achieve more sustainable production systems.

Improved pastures, mainly with *Brachiaria* species, are, by far, the most extensive use of these soils as a replacement for the native cerrado vegetation. The fact that nearly 50% of the improved pastures already show some level of degradation is of major concern. Policy incentives are needed to stimulate adoption of crop/pasture systems or other means of intensification of production.

Perennial crops represent a minor cropping system in the region, in comparison with grain crops and improved pastures. Several perennial systems (coffee, rubber, fruit trees, and reforestation with pines and eucalyptus) constitute some of the successful experiences on large farms in the region. Integrative systems that involve perennial crops with annual crops and/or improved pastures are only beginning to receive attention from researchers, with respect to sustainable production on these soils.

The higher average yields for several crops obtained by some growers in the region, as compared to the average yields for the region as a whole, is strong evidence that technology information is available and already being used by the best farmers. In this sense, it is important to develop strategies to ensure that farmers have access to these technologies, that the implementation of the technologies is encouraged, and that the continued opening of new areas of native cerrados with low yields is discouraged.

Finally the 30-years experience of soil and crop management of the cerrados may be of invaluable importance for similar areas in Latin America and in Africa that have acid, highly weathered, low fertility, high P-fixing-capacity soils. However careful analysis of biophysical and socio-economic factors of these similar areas is essential before there is any effort to transfer the "cerrados technology." The use of relatively high amounts of inputs such as lime and fertilisers and the favourable policies and subsidies available in Brazil at the time of the "opening up" of the cerrados are unlikely to apply elsewhere. In addition, the majority of farmers in tropical savannahs do not have ready access to inputs and machinery, especially in Africa. Recent changes towards no-till and minimum tillage with reduced inputs and improved efficiency in Brazil are, however, relevant to other savannah areas.

This knowledge needs to be incorporated into a strategy that combines the selection of crop species tolerant to the constraints of acid soils with the definition and application of agroecological principles. The latter involves technologies of integrated pest management (IPM) and integrated nutrient management (INM). An example of INM involves the use of grass/legume pastures for the improvement of P acquisition and cycling in pasture and crop/livestock systems in the Colombian savannahs [95, 96]. Besides improving P cycling, the legume component brings other benefits such as increased N input and cycling via biological N_2 fixation, and increased soil organic matter [75, 97]. Increasing the soil organic matter will be an important factor in improving productivity of acid soils without large inputs of fertilisers. In addition to helping to reduce Al toxicity, organic matter can improve soil physical, chemical and biological components [98].

Further efforts should be made to characterise the climates and soils of potentially similar areas, as it should not be forgotten that the details of these components are not available for many areas of the tropics [99]. Each potentially similar area will have its own particular set of socio-economic and biophysical characteristics that need to be understood at the local level. The development of a set of technological and management principles has emerged from the cerrado experience. These can be used to produce simple decision-support tools for the available production options, but, to become relevant and significant, they must be firmly grounded in local experience.

7. FURTHER TOPICS FOR RESEARCH IN THE SAVANNAHS AND THE ROLE OF ISOTOPES

Based on experience in the cerrados, we present a list of topics that requires further research for the improved management of acid-soil savannahs:

- There is a need to develop more crop options, e.g., sunflower, quinoa, pigeon pea, multi-purpose legumes with better stress adaptation (water and acidity, nutrient acquisition),
- The fate of herbicides and environmental risks of increased use with increasing no- and minimum till,
- Water and nutrient flows/cycles in the improved production systems need quantifying in order to improve nutrient-use efficiency and to reduce costs via less use of machinery and chemical inputs (e.g., the role of plants such as forage legumes in acquiring unavailable P sources),
- Soil organic matter management in the improved production systems e.g. optimisation of immobilisation/mineralisation, role of physical nature of soil organic matter and decomposition/nutrient release, etc.,
- Stubble/residue management, is it science or an art? Farmer knowledge needs to be collated and related to scientific principles,
- The control of soil biological processes, e.g. for nutrient cycling of P and N, mycorrhiza and rhizobium studies, agrochemical residues, soil structure, pests and diseases,
- Policies addressed at potential problems in nutrient cycles, e.g. nutrient mining, returns of nutrients to the land, scales involved in on-farm, off-farm, urban areas, etc.,

– There is a need to address how small-scale farmers can be helped versus large farmers,
– Research is needed on how to give farmers better access to information on crop options, especially higher value crops, post-harvesting technologies, agro-processing and market opportunities.

Isotopes can play an important role in the improvement of soil nutrient and water management in the acid savannahs via their use in the following researchable topics:

– Estimating water and nutrient balances in the new systems, e.g., N and P,
– Identifying inefficiencies in nutrient-cycling processes and developing guidelines for increased nutrient-use efficiency and reduced costs,
– Monitoring the transfer of biologically fixed N to the soil and other plants,
– Assessing the risks of groundwater contamination from nutrients and agrochemicals.
– Determining the release and fate of nutrients from ground covers and pasture, crop and animal residues and developing guidelines for residue management,
– Determining the dynamics of soil organic matter and C,
– Quantifying soil erosion in various land-use systems.

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THE ROLE OF TOLERANT GENOTYPES AND PLANT NUTRIENTS IN THE MANAGEMENT OF ACID SOIL INFERTILITY IN UPLAND RICE

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Abstract

As in other parts of the humid tropics, acid-related problems are the major constraint to crop production on low-activity clay soils in the humid and sub-humid zones of West Africa. The upland ecosystem of West Africa is very important to rice production. About 70% of upland rice is grown in the humid zone of the sub-region. To increase and stabilize rice productivity of the acid uplands at reasonable levels, a strategy is needed that integrates the use of tolerant cultivars with soil and plant-nutrient management. Research conducted on Alfisols and Ultisols of the humid-forest and savannah zones in West Africa showed that upland rice is a robust crop, possessing a wide range of tolerance to acid-soil conditions. Recent research at WARDA showed also that acid-soil tolerance can be enhanced through interspecific *Oryza sativa* × *O. glaberrima* progenies, which not only possess increased tolerance of acid-soil conditions, but also have superior overall adaptability to diverse upland environments in the sub-region. Our research on the diagnosis of acid-soil infertility problems on the Ultisols and Alfisols of the humid savannah and forest zones indicates that P deficiency is the most important nutrient disorder for upland rice. In the forest zone, response to N depended on the application of P. In the savannah and forest-savannah transition zones, N deficiency was more important than P deficiency. Among other plant nutrients, the application of Ca and Mg (as plant nutrients) did not appear initially to improve the performance of acid-tolerant upland rice cultivars. The results from a long-term study on an Ultisol with four acid-tolerant rice cultivars, revealed that they differed in agronomic and physiological P efficiencies, and the efficiencies were higher at lower rates of P. The amounts of total P removed in three successive crops were similar for all four cultivars although P-harvest index was 10 to 12% higher in the P-efficient than the inefficient cultivars. The differences observed in the P efficiency of the cultivars may be due to variability in internal efficiency of utilization of P. Overall, our research showed that rice productivity on the acid uplands can be improved by exploiting synergy between genetic tolerance and new P-management practices.

1. INTRODUCTION

Upland rice is the staple food of a hundred million people including some of the poorest in the world [1]. The upland ecosystem in West Africa is very important to rice production [2]. It is estimated that 70% of that upland rice is produced in the humid zone of the sub-region, primarily on Alfisols and Ultisols. While Alfisols dominate the savannah, transition (between forest and savannah) and dry forest zones, Ultisols and some Oxisols dominate the humid zones. In the high-rainfall Ultisol areas excessive weathering, leaching of bases and acidification make low fertility the major constraint to crop growth [3].

World wide, acid-related soil infertility is the major constraint to crop production on low-activity clay soils in the humid and sub-humid tropics. The nutrient-element problems commonly encountered are Al and Mn toxicity, and P, K, Ca and Mg deficiency, and toxicity × deficiency interactions [4, 5].

In the context of West African agriculture, we do not visualize farmers using amendments to ameliorate soil constraints – they face such difficulties in obtaining fertilisers to meet the nutritional needs of their crops. Under prevailing conditions, the most appropriate strategy is to develop cultivars of rice that are adapted to harsh rain-fed environments where soil acidity and P deficiency are the major factors limiting yields.

Interest in selecting and breeding of cultivars for adaptation to specific conditions was re-kindled by recent success at the West Africa Rice Development Association (WARDA) in producing fertile progenies between *Oryza sativa* and *O. glaberrima*. These possess desirable traits of both species, e.g. the superior yield and responsiveness to inputs, such as nutrients, of *O. sativa*, and the general hardiness, drought and acid-soil tolerance, and competitiveness against weeds, of *O. glaberrima* [6, 7]. In the long term, however, an integrated approach, in which genetic tolerance and plant-nutrient management are integrated, seems likely to be more practical and sustainable.

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This paper reviews recent research that relates to acid soils and P-deficiency tolerance of upland-rice cultivars, including interspecific *O. sativa* × *O. glaberrima* progenies recently developed at WARDA. Results of research to clarify the role of plant nutrients, such as P, Ca and Mg, in reducing acid-soil infertility and genotypic differences in P-responsiveness and P-efficiency, are discussed. It is concluded that management of P nutrition of plant types that are adapted to acid-soil environments will make major contributions towards increasing yields and yield stability of upland rice.

2. CHARACTERISTICS OF WEST AFRICAN SOILS

2.1. Genesis, distribution and inherent chemical fertility of soils

The inherent fertility of soils in West Africa is closely related to the bedrock material from which they are derived. Because parent materials are not uniformly distributed and the climatic conditions under which weathering takes place are diverse, inherent fertility varies considerably [8–11]. And, as a result of intense leaching and weathering, many of the soils in the humid zone of West Africa have an acidic reaction and low inherent fertility with regard to major nutrients, especially N and P, and to micro-nutrient elements. Also, because of intense weathering, the clay mineralogy is dominated by kaolinite, and varying amounts of Fe and Al oxides. The soils are of low and variable cation exchange capacity (CEC) and accumulated organic matter is the main source of CEC and nutrients, especially N [8, 12, 13].

TABLE I. PHYSICAL AND CHEMICAL CHARACTERISTICS IN THE SURFACE (0–20 cm) SAMPLES OF ULTISOLS AT THE MAN SITE IN CÔTE D'IVOIRE USED FOR EVALUATING UPLAND RICE CULTIVARS FOR TOLERANCE OF ACID-SOIL CONDITIONS AND P DEFICIENCY, AND PLANT-NUTRIENT STUDIES, 1992–98

Soil characteristic	Range
Clay (g kg^{-1})	220–250
Sand (g kg^{-1})	450–490
Silt (g kg^{-1})	290–300
pH (H_2O)	4.6–5.0
pH (KCl)	3.9–4.3
Organic C (g kg^{-1})	13.0–15.0
Total N (mg kg^{-1})	850–950
CEC (cmol kg^{-1})	4.5–5.9
Total P (mg kg^{-1})	145–165
BRAY 1 P (mg kg^{-1})	3–6
KCl extr. Al (cmol kg^{-1})	0.65–1.15
DTPA extr. Zn (mg kg^{-1})	0.4–1.5
Exchangeable cations (cmol kg^{-1}):	
K	0.15–0.24
Ca	0.50–1.12
Mg	0.26–0.58

TABLE II. PERFORMANCE OF TWENTY-FOUR UPLAND-RICE CULTIVARS, BY GRAIN YIELD, GRAIN-YIELD EFFICIENCY INDEX (GYEI) AND RELATIVE YIELD (RY), ON AN ULTISOL AT MAN, CÔTE D'IVOIRE, 1993

Cultivar	Yield ($t\ ha^{-1}$)	GYEI[a]	RY[b]
WAB 32-133	1.46	0.91	0.71
CNA 4136	1.48	0.92	0.72
WABC 165 (check)	2.05	1.27	1.00
WAB 33-25	1.55	0.96	0.76
WAB 33-17	1.19	0.74	0.58
WAB 56-39	1.73	1.07	0.84
WAB 96-13-1	0.32	0.20	0.16
IDSA 46	1.66	1.03	0.81
TOX 1011-4-A2	1.20	0.75	0.58
WAB 56-50	2.57	1.60	1.25
IRAT 144	2.68	1.66	1.31
WAB 32-46	1.09	0.68	0.53
WAB 99-1-1	1.18	0.73	0.58
WAB 32-55	2.02	1.84	0.99
WAB 181-18	1.85	1.15	0.90
IRAT 112	1.19	0.74	0.58
IDSA 10	2.04	1.27	1.00
IDSA 27	1.53	0.95	0.75
WAB 56-125	2.09	1.30	1.02
WAB 56-104	2.66	1.65	1.30
ITA 257	1.36	0.84	0.66
WAB 99-14	0.86	0.53	0.42
IAC 164	1.87	1.16	0.91
WAB 32-80	1.10	0.68	0.54

[a]Grain yield of the cultivar/mean yield of cultivars.
[b]Grain yield of the cultivar/yield of the check cultivar.

The soils in West Africa, particularly those south of 12°N are derived mostly from basement-complex rocks and the rest of the soils in the sub-region are from a range of sedimentary rocks. The basement complex is a varied formation of metamorphic and igneous rocks, consisting of schists, phyllites, granites, gneisses and occasional intrusions of more basic rocks. Generally, these produce soils of inherent fertility that is relatively higher than those generated from the sedimentary rocks. Both granite and schists weather to produce soils that are moderately fertile, except when they are developed under high rainfall, i.e. conditions that prevail in the humid and sub-humid zones [10, 14]. However, the most fertile soils of the basement complex are those developed over the more basic rocks such as hornblende, schist and gneiss, and the basic igneous intrusions. On the other hand, soils developed over shale, sandstone and mudstone are sandy in surface texture, and generally low in nutrient reserves [8, 10].

Among the various soil types, Alfisols predominate in the West Africa savannah, a region with annual rainfall of 800 to 1,500 mm in one (mono-modal) or two (bimodal) distinct seasons. They have a coarse-textured surface horizon, are low in silt, have low CEC and a relatively high base saturation compared to other soil orders of the sub-region [15]. Ultisols are also found extensively in the high rainfall regions of West Africa, e.g. in the coastal areas of Cameroon, Nigeria, Liberia, Côte d'Ivoire and Sierra Leone [16, 17]. According to Lal [15], Oxisols are predominant in the equatorial zone where rainfall is high. They have low CEC, have less than 40% base saturation, and are relatively infertile. Vertisols are widespread in semi-arid tropical Africa; in West Africa they are found mainly in the Accra plains of Ghana. Inceptisols and Entisols are perhaps the most fertile groups in tropical Africa; located along the flood plains of major rivers and valley bottoms, they are utilised for rice production because of the favourable moisture regime in the wet season [15].

The chemical environments in upland or aerobic soils are distinctly different from those of submerged soils, and several chemical constraints, especially those related to soil reaction and plant-nutrient availability, are more severe in the upland systems of humid West Africa [18].

The pH values of the soils used for upland-rice cultivation under rainfed conditions in the West African sub-region are generally in the acidic range, as a result of high rainfall and resultant leaching of bases from the profile. The soils of the wet forest zone, where annual precipitation is more than 1,750 mm – along the coastal regions in Guinea, Sierra Leone, South and West Côte d'Ivoire, south-west Ghana, south and east Nigeria – are thoroughly leached, very acidic with pH values from 4.0 to 5.0 and very low base saturation. In the semi-deciduous forest zone, where annual rainfall is between 1,150 and 1,750 mm, the soils are less leached and only slightly acid in reaction (pH 5.5 to 6.0) with moderate base saturation. In the savannah region, where the annual rainfall is less than 1,200 mm, leaching is less and the soils have pHs from near neutral to slightly alkaline [19]. Soil reaction affects nutrient availability and their balance in roots and shoots [20]. Strong acidity and low effective CEC restrict higher productivity of low activity clay soils [17, 21, 22]. Recent research has also indicated the importance of silicon (Si) deficiency for upland rice grown on highly weathered Ultisols and Oxisols in West Africa and South America [23, 24].

3. TOLERANCE OF ACID UPLAND SOILS

Since 1992, a large number of upland rice cultivars, including interspecific progenies, have been evaluated for tolerance to acid-soil conditions at "hot spot" sites in the field. Important physical and chemical characteristics of the soils (Ultisols or Ferric Acrisols) at the experimental site at Man in the humid forest zone of Côte d'Ivoire are summarized in Table I. The soil analyses were done as described by Sahrawat et al. [25]. On average, the site receives about 1,700 mm of rainfall annually.

In all experiments, the cultivars under evaluation received uniform application of 60 kg N, 36 kg P and 36 kg K ha^{-1}. The experiments were conducted in the wet season (June to October). Results from an evaluation of twenty-four cultivars in 1993 showed a wide range in grain yields, from 0.32 to 2.68 t ha^{-1}. Grain yield efficiency index (GYEI = grain yield of the cultivar/mean grain yield of the cultivars) and relative yield (RY = grain yield of the cultivar/grain yield of the check cultivar) values varied from 0.20 to 1.66, and from 0.16 to 1.31, respectively (Table II).

TABLE III. FREQUENCY DISTRIBUTION IN THE GRAIN YIELDS OF ONE HUNDRED AND TWENTY UPLAND-RICE CULTIVARS ON AN ULTISOL AT MAN, CÔTE D'IVOIRE, 1994

Grain yield (t ha^{-1})	Number of cultivars
0.00	10
0.36–0.99	30
1.00–1.50	40
1.51–2.00	21
2.10–2.50	12
2.51–3.00	7

TABLE IV. SOIL FERTILITY-RELATED CONSTRAINTS, AND CULTIVAR REQUIREMENTS, FOR UPLAND RICE IN THE HUMID ZONE OF WEST AFRICA

Constraints	Humid forest	Forest/savannah transition
Soil acidity	+++[a]	+[b]/++[c]
P deficiency	+++	+, depends on N supply
N deficiency	depends on P supply	+++
Shortened fallow	acidity, P deficiency	severe N deficiency
Plant type	acidity tolerant, P-efficient, weed-competitive	mild acidity tolerance, N-efficient, weed-competitive

[a]Of major importance. [b]Important. [c]Locally important.

TABLE V. EFFECTS OF Si AND Mg ON THE PERFORMANCE OF UPLAND RICE ON AN ULTISOL AT ONNE, NIGERIA, 1986 WET SEASON [27]

Treatment	Grain yield ($g\ m^{-2}$)	Discolouration index
None[a]	234[b]	66
Mg[c]	204	66
Si[d]	248	43
Mg + Si	314	42
$LSD_{0.05}$	44	7

[a]All plants received uniform applications of N, P and K.
[b]Means for cvv. ITA 212, OS 6, FARO 27.
[c]At 22.5 kg ha^{-1} as magnesium sulphate applied in two splits, 21 and 69 days after sowing.
[d]At 188 kg ha^{-1}as sodium silicate.

In 1994, one hundred and twenty upland-rice cultivars were evaluated on an Ultisol at the Man site. Grain yields varied from 0 to 3.0 t ha^{-1}. Ten cultivars failed to yield, whereas nineteen produced between 2.1 and 3.0 t ha^{-1} of grain. Frequency distribution in grain yield is shown in Table III.

In 1994, one hundred and twenty cultivars of upland rice were evaluated on an Ultisol at the Man site in Côte d'Ivoire. Grain yields varied from 0 to 3.0 t ha^{-1}. Ten cultivars failed to yield grain, whereas nineteen produced between 2.1 and 3.0 t ha^{-1} of grain. Frequency distribution in grain yield is shown in Table III.

A large number of *O. sativa* × *O. glaberrima* were evaluated for their performance at Man in 1996 and 1998. Some showed promise in that they out-yielded not only the *O. glaberrima* check cv. CG 14, but also the *O. sativa* check cv. WAB 56-104 (Figs. 1 and 2). In the 1996 season, grain yields of the interspecific lines varied between 0.68 and 2.47 t ha^{-1}. In 1998, another set of interspecific progenies produced grain yields varying from 0.50 to 3.50 t ha^{-1}. These results clearly indicate that the development of interspecific progenies has enhanced the rice plant's adaptability to typical upland, acid-soil conditions (low in bases and P supply), in this case in a humid-forest Ultisol.

In the 1997 and 1998 wet seasons, eleven promising interspecific cultivars were tested in Guinea, which has the largest area of upland rice in West Africa, in a farmer-participatory varietal selection project on farmers' fields [26]. Of these, WAB 450-I-B-P-38-HB and WAB 450-I-B-P-160-HB have been proposed by the national programme for release to farmers. Thus, the new plant type, adapted to the acid uplands, along with proper crop and nutrient management, may provide the basis for a sustainable rice-production system.

4. ROLE OF PLANT NUTRIENTS IN REDUCING ACID-SOIL INFERTILITY

In upland Ultisols and Oxisols in the tropics rice faces a complex of nutrient disorders caused by acid-soil conditions and low fertility. Apart from direct nutritional effects, acidity and low soil fertility also influence growth and yield through the incidence of diseases, such as grain discolouration characterized by brown or black spots on the husk [27]. At times, it is difficult to separate nutritional and pathological effects.

In West Africa, a number of fertility diagnostic studies in the field involving nutrient-omission experiments have clearly demonstrated that:

– Nitrogen and P deficiencies are the major factors affecting upland rice,
– More importantly, P deficiency is more important than N deficiency in the humid forest zone, whereas the reverse is true in the savannah and forest-savannah transition zones; because of intense leaching in the humid forest zones, the soils are acutely deficient in P, and N response of crops such as upland rice depends on the application of P [19],
– As a general rule, P deficiency becomes increasingly important from north to south in West Africa.

A generalized conceptual analysis of plant-nutrient problems in upland acid soils by agroecological zone, and the associated requirement for an upland rice plant type, is summarized in Table IV.

Yamauchi and Winslow [27] studied the effects of nutrient supplies on the performance of upland rice on Ultisols in Nigeria's humid zones. Applications of N, P, K, Mg and Si were necessary to produce high dry matter. Magnesium and Si were involved in protection against grain-discolouration disease and their application increased the grain yields of three varieties by an average of 34% (Table V).

Sahrawat et al. [28] studied the role of P, Ca and Mg in ameliorating acid-soil-related fertility problems in upland rice (cv. WAB 56-50) on an Ultisol in the humid forest zone of Côte d'Ivoire. Application of P alone [50 kg P ha^{-1} as triple superphosphate (TSP)] or in combination with Ca (50 kg ha^{-1}) and Mg (50 kg ha^{-1}) significantly increased yields and agronomic and physiological P efficiencies, and improved the harvest index of the crop (Tables VI and VII). Application of Ca or Mg alone, or together, had no significant effects on yield, elemental composition of plant tops at tillering (Table VIII), or the uptake of macro- and micro-nutrients at harvest (Table IX). It was concluded that P deficiency was the most important nutrient disorder in the Ultisol studied, and that applications of Ca and Mg were initially less important to growth, yield, and plant-nutrient status of this acid-tolerant variety.

We have observed that upland rice is a robust crop, genetic tolerance of which can be utilized to select cultivars that can grow normally on acid upland Ultisols and Alfisols. Applications of P and N to such cultivars can contribute to increased yields and to yield stability of cropping systems as a whole. The use of suitable legume fallows can be utilized to improve the N economy of the intensified upland rice-based systems of West Africa [29].

TABLE VI. EFFECTS OF P, Ca AND Mg ON YIELD AND HARVEST INDEX OF RICE CULTIVAR WAB 56-50 ON AN ULTISOL AT MAN, CÔTE D'IVOIRE, 1994 [28]

Treatment[a]	Grain yield (t ha^{-1})	Straw yield (t ha^{-1})	Harvest index (%)
Control[b]	2.02	2.14	48
P	3.14	2.99	51
Ca	2.11	2.43	46
Mg	2.28	2.86	44
P + Mg	2.87	2.72	52
P + Ca	2.79	2.79	51
Ca + Mg	2.12	2.28	48
P + Ca + Mg	2.98	2.81	52
$LSD_{0.05}$	0.364	0.712	6.7

[a]All plants received 100 kg N ha^{-1} and 80 kg K ha^{-1}.
[b]No P, Ca or Mg.

TABLE VII. AGRONOMIC P EFFICIENCY (APE) AND PHYSIOLOGICAL P EFFICIENCY (PPE) OF RICE CULTIVAR WAB 56-50 AS AFFECTED BY APPLICATIONS OF Ca AND Mg WITH P FERTILIZER AT MAN, CÔTE D'IVOIRE, 1994 [28]

Treatment[a]	APE (kg grain kg^{-1} P applied)	PPE (kg grain kg^{-1} P uptake)
P	22	482
P +	17	482
P + Ca	15	476
P + Ca + Mg	19	421
$LSD_{(0.05)}$	4	64

[a]All plants received 100 kg N ha^{-1} and 80 kg K ha^{-1}.

5. PHOSPHORUS RESPONSE AND P EFFICIENCY OF UPLAND RICE

Selection of cultivars of rice that acquire more P, or that have better efficiency of use of P, is a strategy for adaptation to harsh rainfed upland environments where acute P deficiency limits yields. In the highly weathered soils of the humid zone in West Africa, availability of P is reduced by the reaction of soluble P with Fe and Al oxides [30, 31].

Varietal differences in P efficiency are expressed when they are grown on acid, highly P-deficient soils. Despite a great deal of research on soil P worldwide, much still remains to be learned about practical aspects of management, and about P responsiveness and P efficiency of upland rice [32, 33]. Monde et al. [34] evaluated the performance of a hundred and forty-four local upland genotypes, collected in Sierra Leone, for tolerance of low available P by growing them on an upland Oxisol [pH (H_2O) 4.9; Bray-1 P 4.3 kg ha^{-1}; organic C 0.78%; CEC 10.2 cmol kg^{-1}) sandy loam in texture.

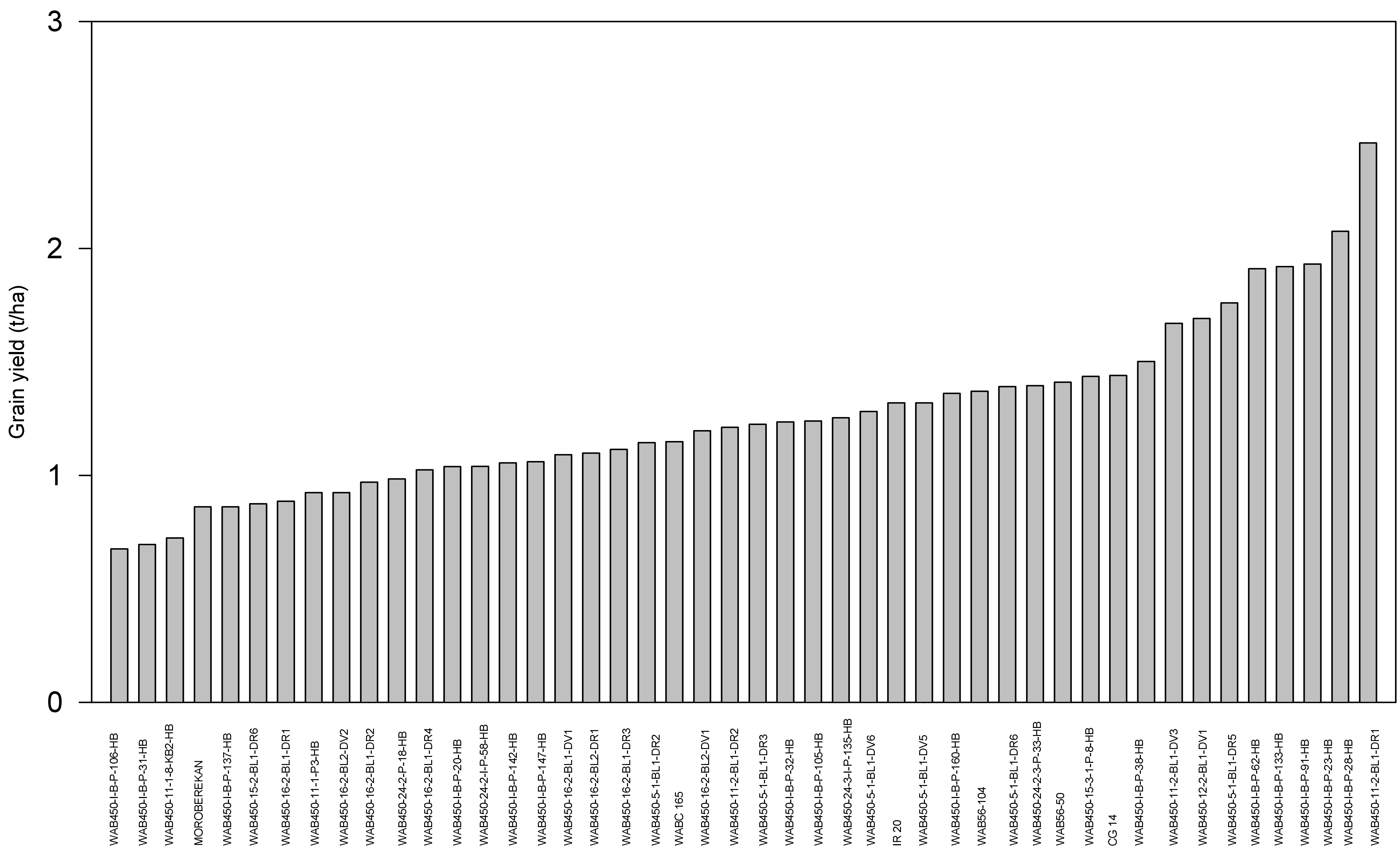

FIG. 1. Performance of 46 interspecific progenies grown on an Ultisol at Man,Côte d'Ivoire in 1996.

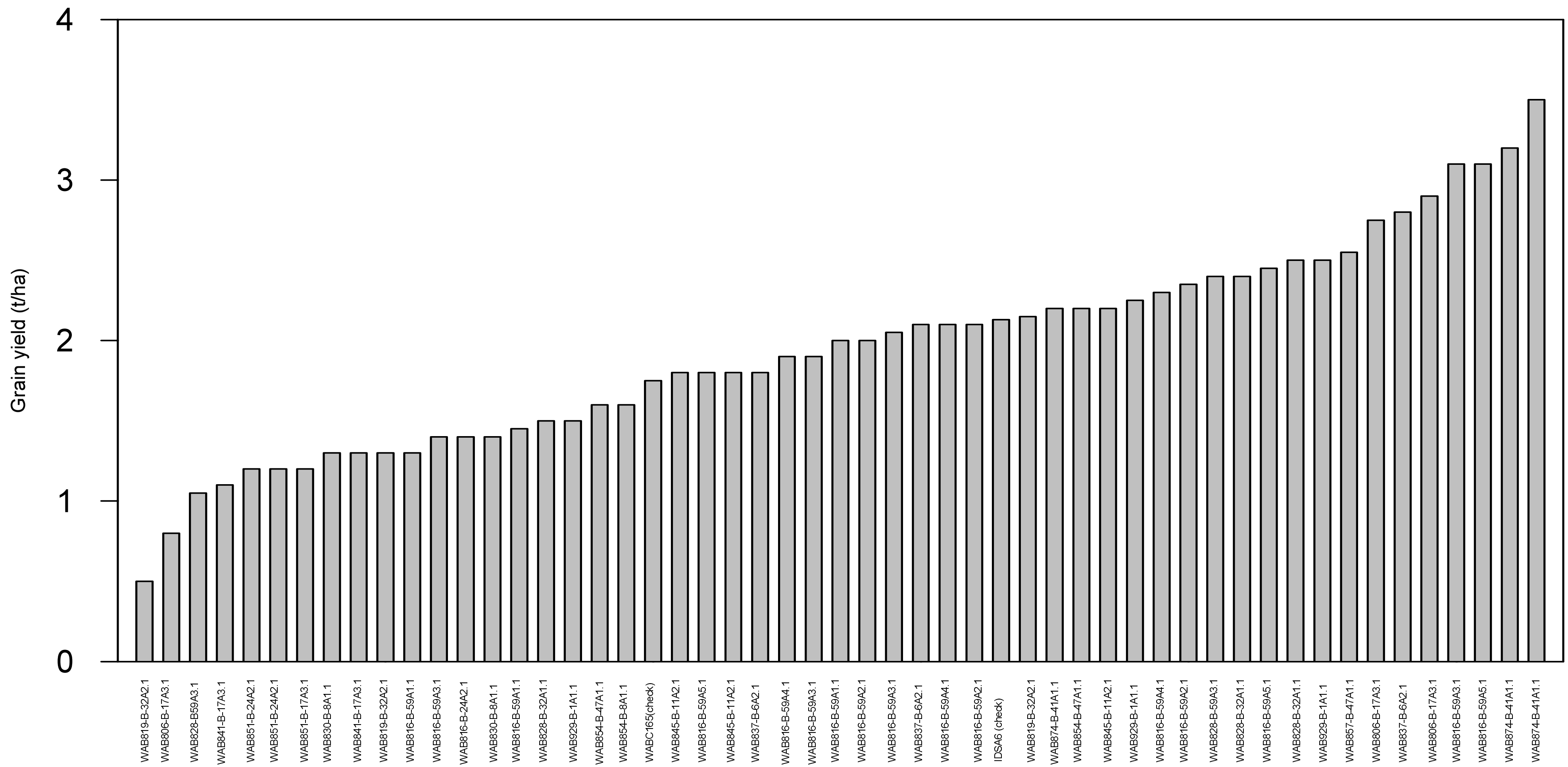

FIG. 2. Performance of 53 interspecific progenies grown on an Ultisol at Man, Côte d'Ivoire in 1998.

TABLE VIII. NUTRIENT ELEMENT CONTENT (mg kg^{-1}) IN SHOOTS OF RICE CULTIVAR WAB 56-50 AS AFFECTED BY APPLICATIONS OF P, Ca AND Mg AT TILLERING, AT MAN, CÔTE D'IVOIRE, 1994 [28]

Treatment[a]	N	P	K	Ca	Mg	Fe	Mn	Zn
Control[b]	30,400	2,000	26,800	3,400	2,700	306	528	34
P	27,800	2,300	31,300	3,000	3,000	330	628	28
Ca	28,900	2,000	30,500	3,100	3,000	269	441	35
Mg	29,400	2,000	29,100	3,200	3,300	294	556	27
P + Ca	31,500	2,100	28,100	3,300	3,000	205	570	32
P + Mg	1,000	2,150	27,600	2,900	2,700	267	539	33
Ca + Mg	30,800	2,000	30,100	3,400	2,900	271	644	27
P + Ca + Mg	29,500	2,300	28000	3,500	2,900	303	571	28
$LSD_{0.05}$	4,420	200	2,600	350	590	119	146	6

[a]All plants received 100 kg N ha^{-1} and 80 kg K ha.
[b]No P, Ca or Mg.

TABLE IX. NUTRIENT ELEMENT UPTAKE (kg ha^{-1}) IN THE BIOMASS OF RICE CULTIVAR WAB 56-50 AS AFFECTED BY APPLICATIONS OF P, Ca AND Mg, AT MAN, CÔTE D'IVOIRE, 1994 [28]

Treatment[a]	N	P	K	Ca	Mg	Fe	Mn	Zn
Control[b]	39.6	3.7	49.4	5.6	6.9	0.91	1.21	0.085
P	61.0	6.5	58.1	9.4	11.4	1.93	1.70	0.080
Ca	48.2	3.3	56.2	8.0	9.0	0.90	2.09	0.080
Mg	45.2	4.1	56.2	8.1	10.3	1.08	2.14	0.096
P + Ca	52.9	5.9	52.8	8.3	9.9	1.71	2.31	0.070
P + Mg	54.1	6.0	52.8	6.6	10.9	2.75	1.61	0.070
Ca + Mg	48.1	3.9	45.2	6.9	8.5	1.21	1.60	0.093
P + Ca + Mg	59.1	7.1	59.4	8.2	11.8	2.24	2.16	0.090
$LSD_{0.05}$	12.3	1.6	16.9	2.7	3.0	0.40	0.93	0.024

[a]All plants received 100 kg N ha^{-1} and 80 kg K ha^{-1}.
[b]No P, Ca or Mg.

The cultivars received 60 kg N, 25 kg P or as appropriate, and 32 kg K ha^{-1}. Among the cultivars tested, thirty *O. glaberrima* and ten *O. sativa* showed tolerance of low P, using as the criterion percent relative tillers, i.e. ratio of number of tillers with no P : number with 25 kg P ha^{-1} [35]. Tolerant cultivars achieved 90 to 100% relative tillers. The results showed that *O. glaberrima* varieties have greater tolerance for low available P. Tolerance for low available P was significantly correlated with tiller production (r = 0.80, n = 140), panicles m^{-2} (r = 0.58), panicle weight (r = 0.66) and grain P-content (r = 0.72).

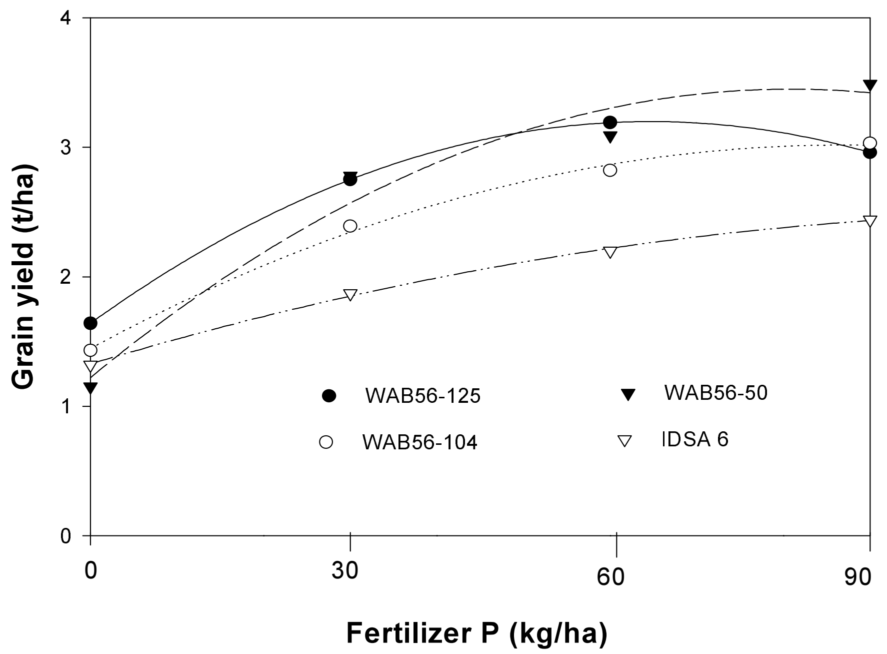

FIG . 3 . Relationships between grain yield and different fertilizer P rates of four upland rice cultivars on an Ultisol in 1992.

TABLE X. AGRONOMIC P EFFICIENCY (APE) AND PHYSIOLOGICAL P EFFICIENCY (PPE) OF FOUR UPLAND-RICE CULTIVARS AS AFFECTED BY P FERTILIZATION OF AN ULTISOL AT MAN, CÔTE D'IVOIRE, 1992 [33]

P rate (kg ha^{-1})	WAB 56-125	WAB 56-104	WAB 56-50	IDSA 6
		APE (kg grain kg^{-1} P applied)		
30	37	32	54	18
60	26	23	32	15
90	15	18	26	12
Mean	26	24	37	15
		PPE (kg grain kg^{-1} P uptake)		
30	542	542	588	537
60	508	519	571	504
90	461	507	517	411
Mean	504	523	559	484

Sahrawat et al. [33] conducted field experiments in 1992 and 1993 to determine P responses and efficiencies of four promising, acid-tolerant cultivars (WAB 56-104, WAB 56-125, WAB 56-50 and IDSA 6) on an Ultisol, low in available P, at Man. The cultivars were selected from a large number of entries tested earlier for acidity tolerance. Triple superphosphate was used, at 0, 30, 60 and 90 kg P ha^{-1} in 1992 and 0, 45, 90 and 135 kg P ha^{-1} in 1993. The four cultivars produced similar grain yields when no P was applied.

The WAB cultivars gave better responses than did IDSA 6 to increasing rates of P (Figs. 3 and 4). The agronomic and physiological P efficiencies were higher at lower rates of P, and higher for the WAB cultivars than for IDSA 6 (Table X). The poor P efficiency of IDSA 6 was due mainly to its lower harvest index (ratio grain yield : grain plus straw yield) which was improved relatively little by P fertilization (Fig. 5). Harvest index was significantly correlated ($r^2 = 0.626$, $n = 16$) to P harvest index (ratio of P in grain : P in grain plus straw) (Fig. 6). Therefore, harvest index may have utility as a simple criterion for selecting for P efficiency.

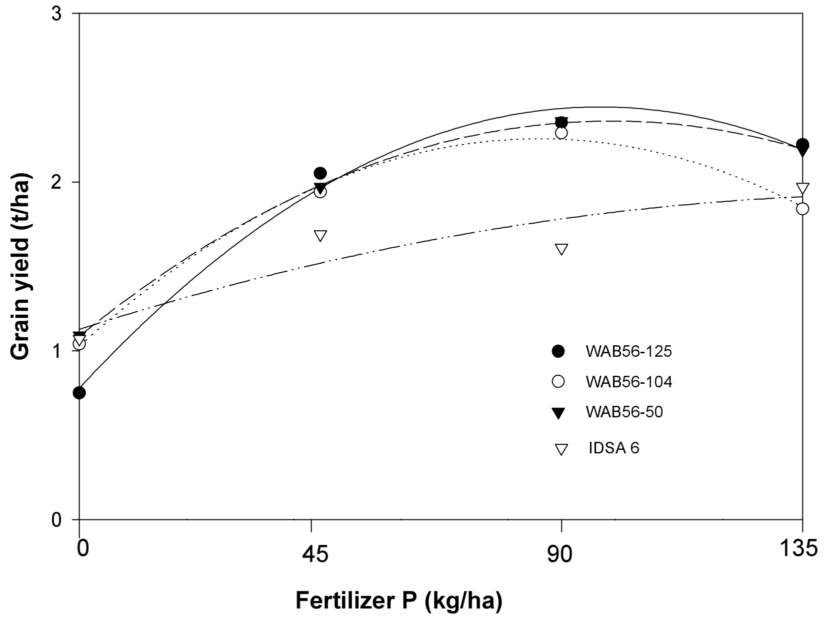

FIG. 4 . Relationships between grain yield and different fertilizer P rates of four upland rice cultivars on an Ultisol in 1993.

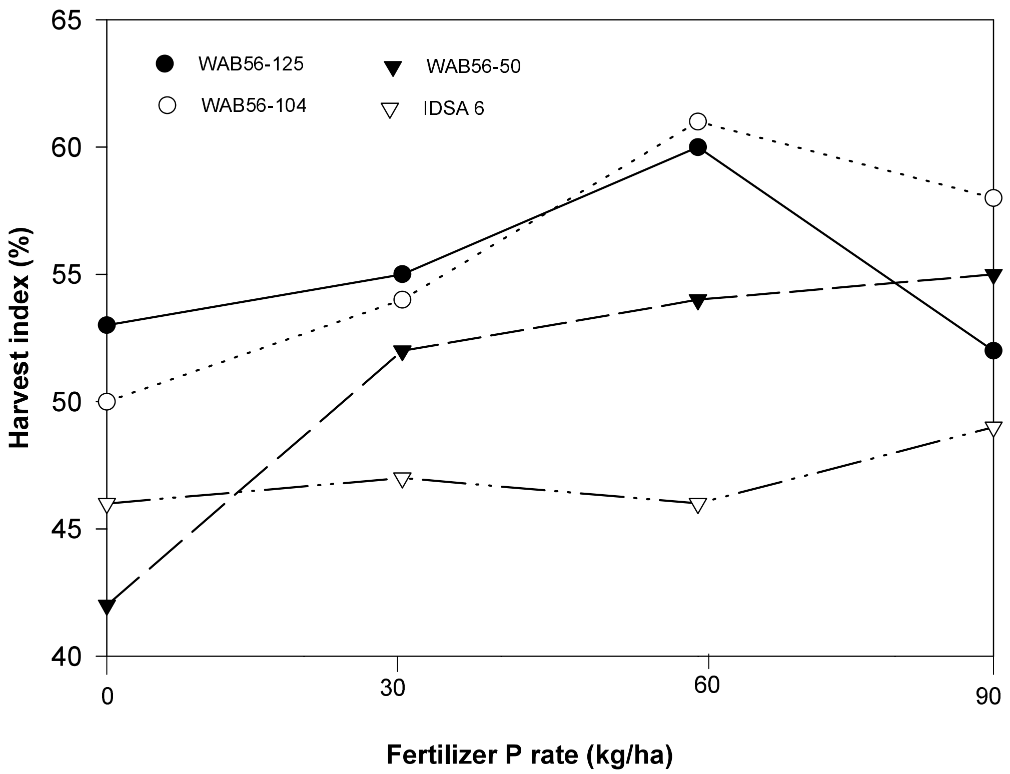

FIG. 5 . Relationships between harvest index and different fertilizer P rates of four upland rice cultivars in 1992.

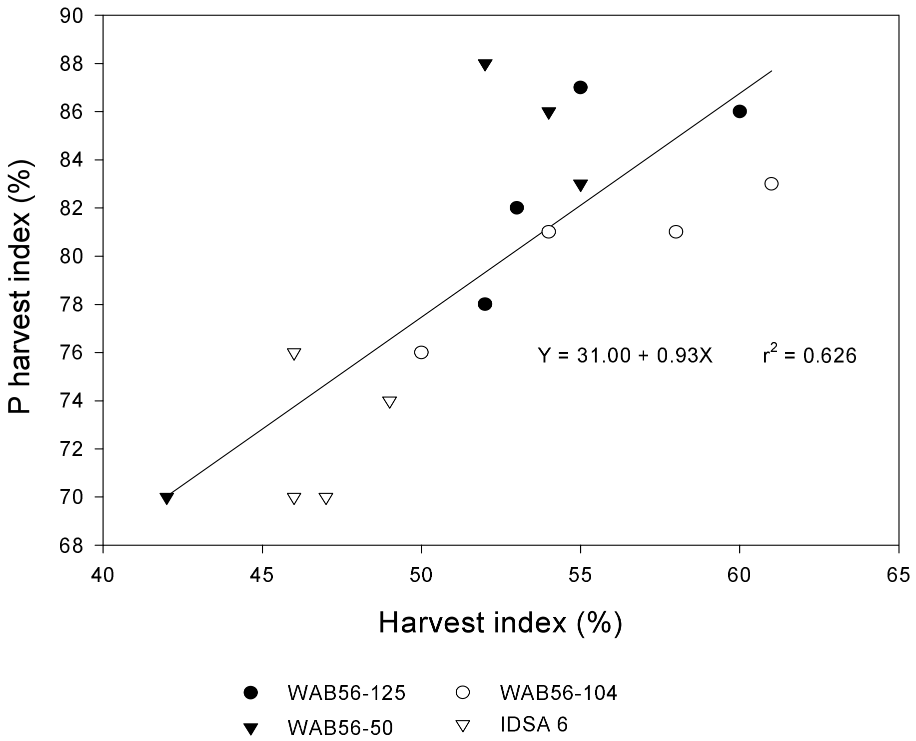

FIG. 6. Relationships between P harvest index and harvest index of four upland rice cultivars in 1992. Each point represents a mean value of four replications. The cultivars received four rates of fertilizer P at 0, 30, 60 and 90 kg P ha^{-1}.

In a 3-year (1993–95) study, Sahrawat et al. [36] determined the responses of the same four cultivars to 0, 45, 90, 135 and 180 kg P ha^{-1} applied only in 1993. The soil at the experimental site at Man was an Ultisol low in available P. Grain yields were significantly increased by applied P in 1993, and by the residual effects of the fertiliser in 1994 and 1995, although magnitude of the responses decreased with time. The WAB cultivars showed superior cumulative agronomic and physiological P efficiencies than did IDSA 6. The amounts of total P removed in three successive crops were similar for all four cultivars although P harvest indices were 10 to 12% higher in the WAB lines than in IDSA 6. The results revealed that the differences observed in P efficiency were due to differences in internal utilization efficiency.

In 1998, the three WAB cultivars were released by the national program in Côte d'Ivoire for cultivation by farmers in the upland ecology.

6. CONCLUSIONS

Rice is a unique crop in that it grows well submerged and in well drained upland soils. However, its performance under acid upland conditions is greatly affected by soil and environmental constraints. Water shortage and poor fertility, and lack of well adapted cultivars are the major factors constraining productivity and yield stability. Most farmers in tropical Africa cannot afford soil amendments to adapt the cultivars that have not been selected or bred for the local environments. The discussion in this paper highlights the need to exploit genetic tolerance in rice to select and develop cultivars that are well adapted to specific upland environments. We cannot over-emphasise the fact that upland rice is a robust crop, and tolerant cultivars can perform well in acid-soil conditions. It is argued that suitable crop and nutrient-management strategies are essential not only to exploit the full potential of genetic tolerance but, more importantly, to provide the bases for sustainable rice-production system. Phosphorus nutrition is of critical importance not only for food crops such as rice and others that are part of the system, but P input is also absolutely necessary for reaping the benefits of biological N_2 fixation in natural and managed fallows. Finally, the approach in which genetic tolerance and nutrient management are integrated appears both practical and sustainable.

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USE OF ACID-TOLERANT AND P-EFFICIENT PLANT GENOTYPES

FITTING MAIZE INTO SUSTAINABLE CROPPING SYSTEMS ON ACID SOILS OF THE TROPICS

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Abstract

One of the key elements of sustainable cropping systems is the integration of crops and/or crop cultivars with high tolerance of soil acidity and which make most efficient use of the nutrients supplied by soil and fertilizer. This paper is based mainly on on-going work within an EU-funded project combining basic research on plant adaptation mechanisms by plant physiologists, and field experimentation on acid soils in Brazil, Cameroon, Colombia and Guadeloupe by breeders, soil scientists and a agronomists. The results suggest that large genetic variability exists in adaptation of plants to acid soils. A range of morphological and physiological plant characteristics contribute to tolerance of acid soils, elucidation of which has contributed to the development of rapid techniques for screening for tolerance. Incorporation of acid-soil-tolerant species and cultivars into cropping systems contributes to improved nutrient efficiency overall, and thus reduces fertilizer needs. This may help to minimize maintenance applications of fertiliser through various pathways: (i) deeper root growth resulting in more-efficient uptake of nutrients from the sub-soil and less leaching, (ii) more biomass production resulting in less seepage and less leaching, with more intensive nutrient cycling, maintenance of higher soil organic-matter content, and, consequently, less erosion owing to better soil protection by vegetation and mulch.

1. INTRODUCTION

Agricultural systems may be described as sustainable if the management of the resources successfully meets human needs while maintaining or enhancing the quality of the environment and conserving natural resources. Among the major threats to sustainable soil productivity related to soil acidity are: (i) H^+, Al and Mn toxicities (ii) low availability (P, Mo) and supply of nutrients (N, Ca, Mg), (iii) high nutrient (base) losses. One of the key elements of sustainable cropping systems is the use of crops with high tolerance of soil acidity that make most efficient use of nutrients supplied by soil and fertiliser. Adaptation to soil acidity is defined as the ability of a genotype to provide a yield above the average population under conditions of sub-optimal soil pH.

The main objectives of the EU-INCO Programme ERBIC 18CT 960063, on which this presentation is mainly based, are, to advance breeding strategies and breed maize cultivars with improved adaptation to acid soils high in Al and low in P; to develop screening procedures for Al resistance and P efficiency in maize, based on an improved, in-depth knowledge of underlying physiological and molecular mechanisms; to improve the quantitative understanding of the comparative contributions of genetic and agronomic approaches to sustainable maize production on acid soils.

2. CHIEF CONSTRAINTS

2.1. Aluminium toxicity

Large variability in maize grain yield was found among genotypes, on a non-corrected acid soil as well as on a non-acid soil in Guadeloupe (Fig. 1) and in Cameroon (Fig. 2). Whereas the yields on the strongly Al-toxic and the non-acid soils were positively correlated in Cameroon, there was no relationship in Guadeloupe where the acid soil had less Al but more Mn. At both locations, one of the phenotypic characteristics that best correlated with adaptation to soil acidity was seminal root length (Fig. 3). Also, in Colombia, on a strongly acid, Al-toxic soil, root-length distribution down the soil profile revealed differences according to correction of soil acidity by liming and differences between adapted and non-adapted maize cultivars (Fig. 4).

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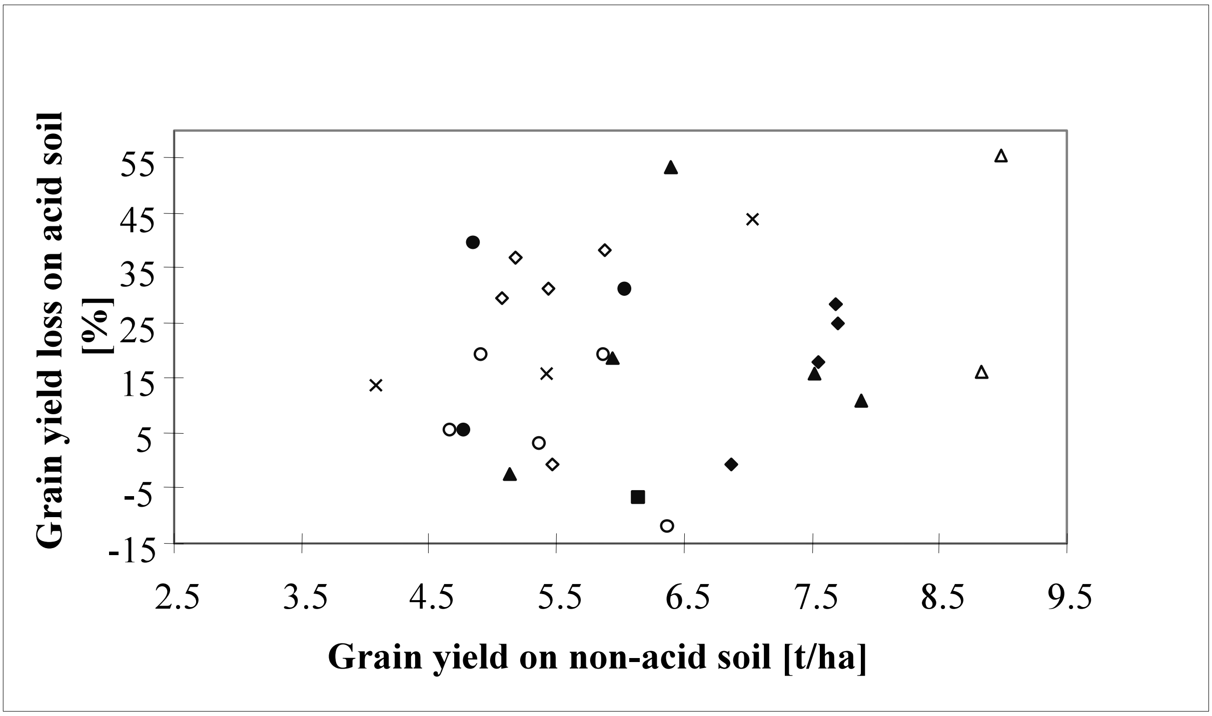

FIG. 1. Relationship between grain yield on non-acid soil (potential yield) and yield reduction of twenty-eight tropical maize genotypes grown on acid soil (C. Welcker, INRA-Guadeloupe, URPV).

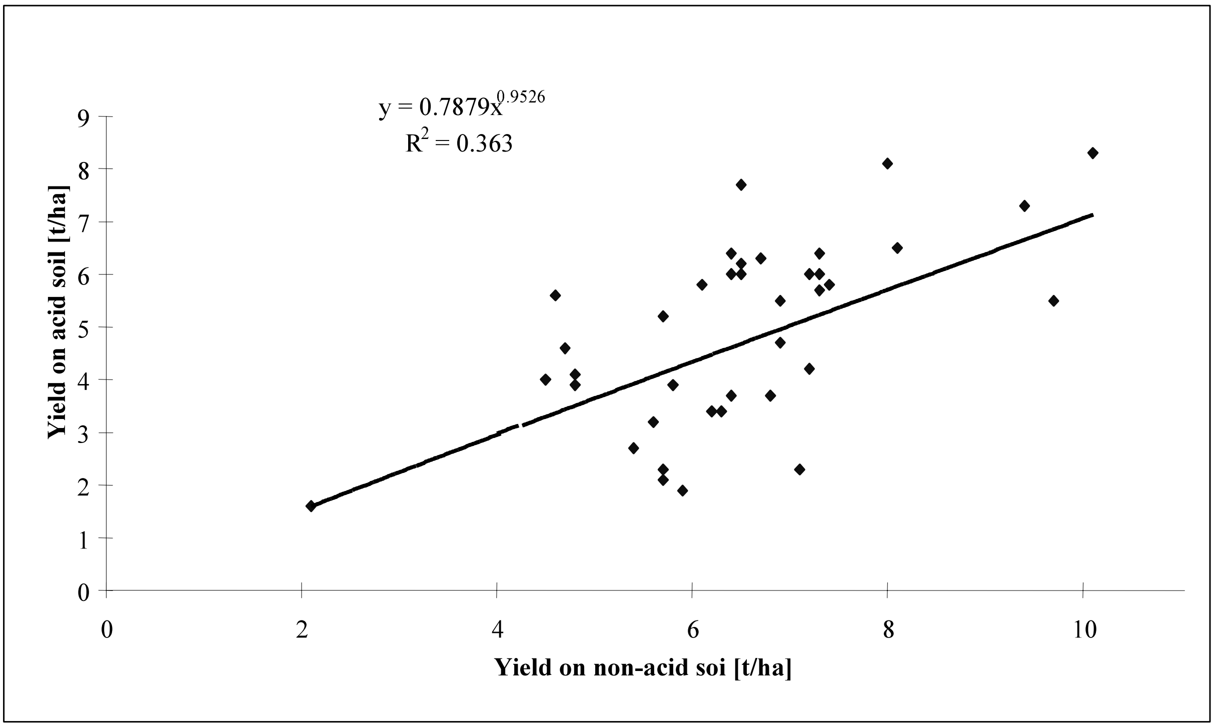

FIG. 2. Comparison of yield of maize cultivars grown on acid and non-acid soils (Ch. Thé, IRAD, Cameroon).

Inhibition of root growth typically indicates Al toxicity. The inhibition of root elongation by Al can be measured within minutes [1]; it is primarily due to accumulation in, and injury to, the distal part of the transition zone (1–2 mm from the apex) [2, 3]. Application of Al to this zone specifically and rapidly inhibits cell elongation in the elongation zone, although Al applied to this zone does not inhibit root elongation. Aluminium resistance appears to be related to the capacity to restrict Al uptake into this sensitive zone.

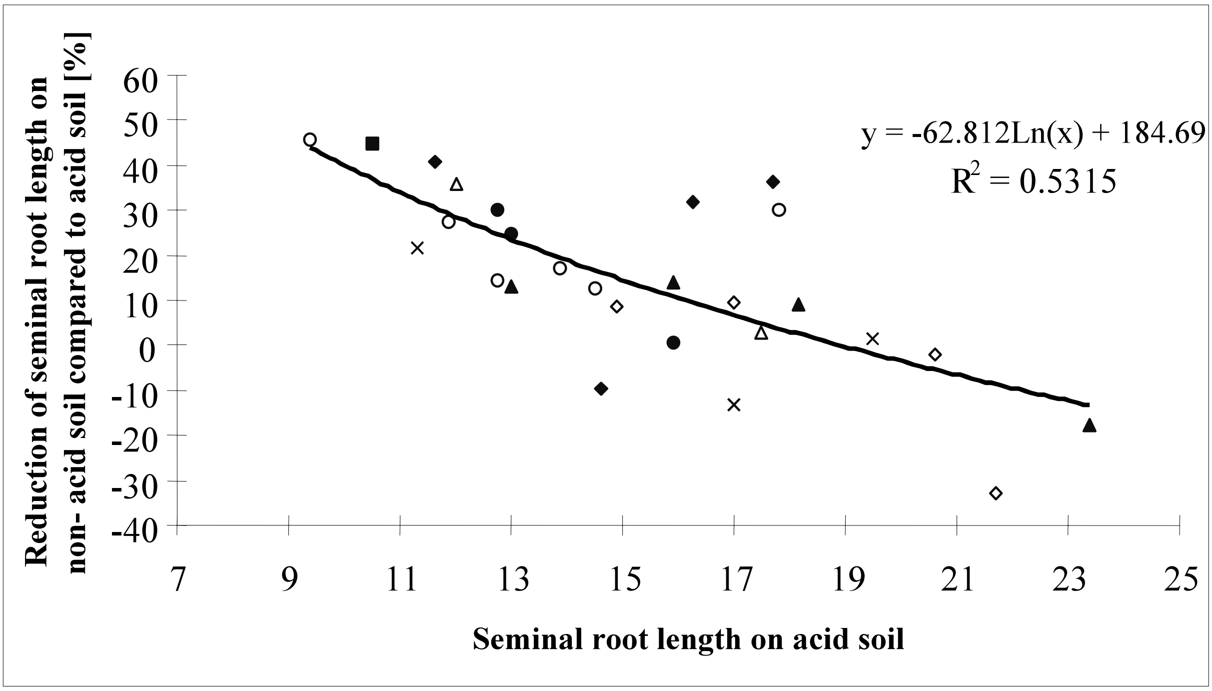

FIG. 3. Relationship between seminal root length of maize cultivars measured on acid soil and reduction of seminal root length on non-acid soil compared to acid soil (C. Welcker, INRA-Guadeloupe, URPV).

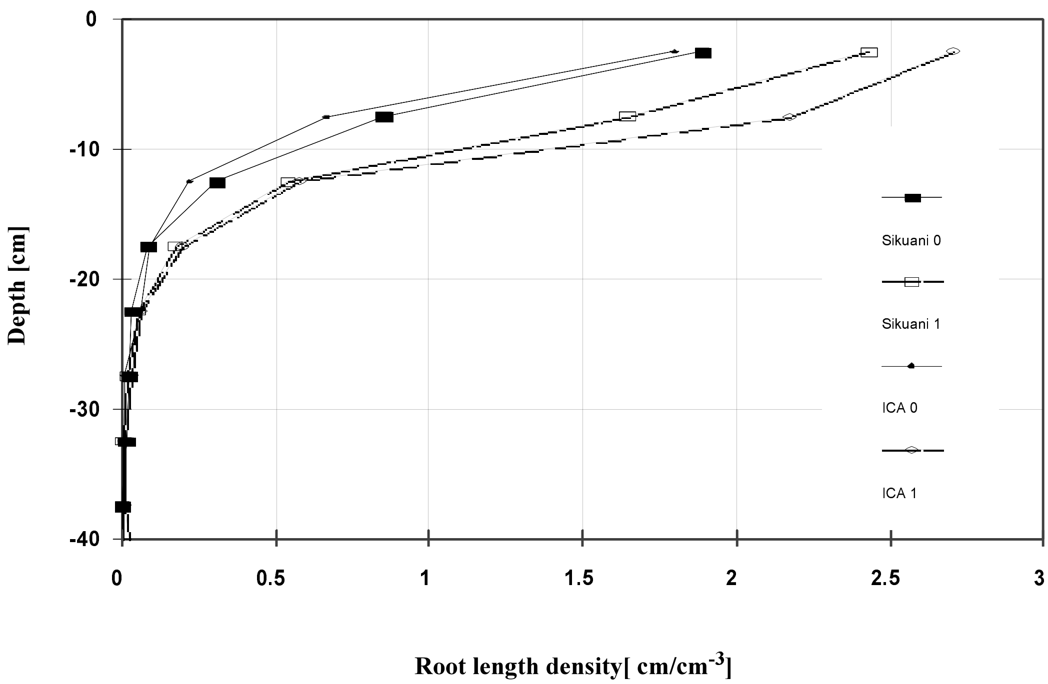

FIG. 4. Effect of maize cultivar and liming/P application on root distribution in the field experiment at CORPOICA, Colombia (J.-L. Chopard, CIRAD, France, L.A. Rojas and D. Roveda, CORPOICA, Colombia).

Based on this knowledge, a hematoxylin staining method for Al in root apices has been developed to screen rapidly for Al resistance. A rough pre-selection of genotypes appears to be possible, as has been shown for wheat [4].

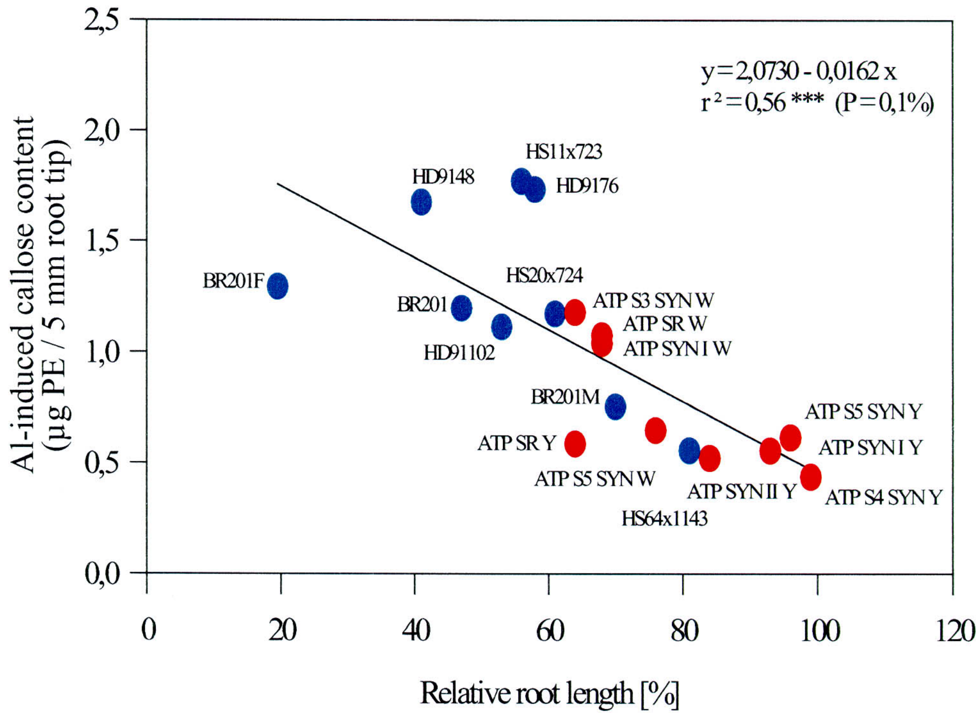

FIG. 5. Correlation between Al-induced callose contents and relative root length (RRL, +Al = 100%) of maize cultivars (RRL from CIRAD, Montpellier, France).

Induction of callose formation is a sensitive indicator of injury from Al [5], useful for comparing root apical zones [2] and maize cultivars differing in resistance (Fig. 5, [6]). This technique has been further developed into a non-destructive assay for screening for adaptation to acid soil on a single-plant basis within the CIMMYT maize-breeding programme at Cali, Colombia.

Screening maize seedlings for Al resistance with uniform exposure of the root system to Al, which does not occur under field conditions – in most cases the surface soil is less Al-toxic than the sub-soil – assumes absence of the Al-avoidance mechanism described for *Mucuna pruriens* [7]. This has been confirmed using a split-root approach (Fig. 6). Inhibition of root elongation was comparable when Al was supplied to half or the entire root system, and was independent of the P supply, with Al-sensitive and -resistant cultivars.

Evidence suggests that resistance to Al in maize is due to its exclusion from uptake into the root apex by sequestration with exuded citrate [8]. Our results show that toxicity can be modulated by the Al-binding characteristics of the pectic matrix of the root apoplast [9], suggesting an additional factor in the expression of resistance. The ameliorating effects of B [10] and Si [11], which are known to interfere primarily with cell-wall constituents, point in the same direction.

Reductions of crop yields on acid soils are due not only to direct toxic effects of Al, but also to indirect effects such as induced deficiencies of Mg and Ca. Decrease in the rhizobium/legume N_2-fixing symbiosis is possible as are lower use-efficiencies of water and P through less exploitation of the soil profile and possibly also through reduced water conductivity of the roots [12].

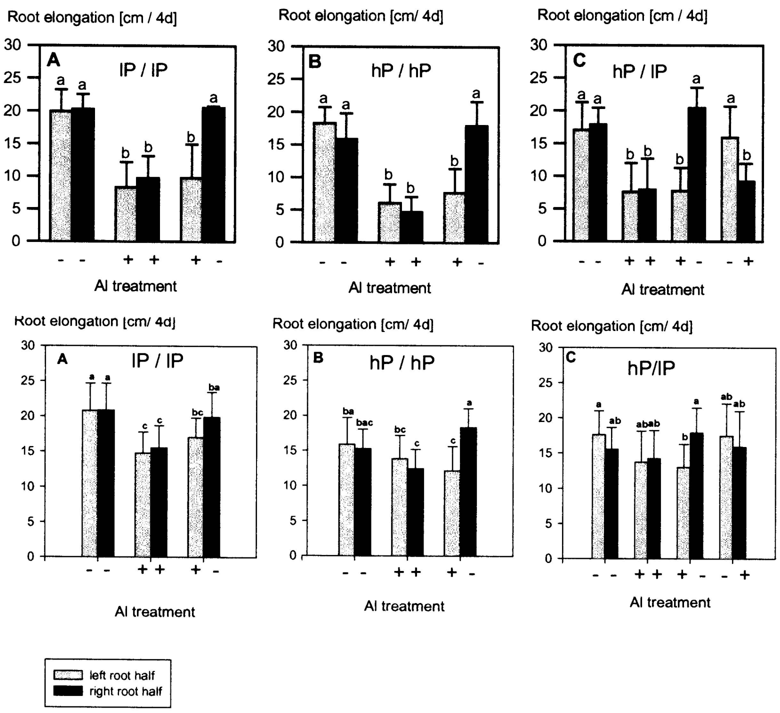

FIG. 6. Effect of Al and P supply on root elongation of maize cv. Lixis (upper) and BR201 (lower) in a split-root system.

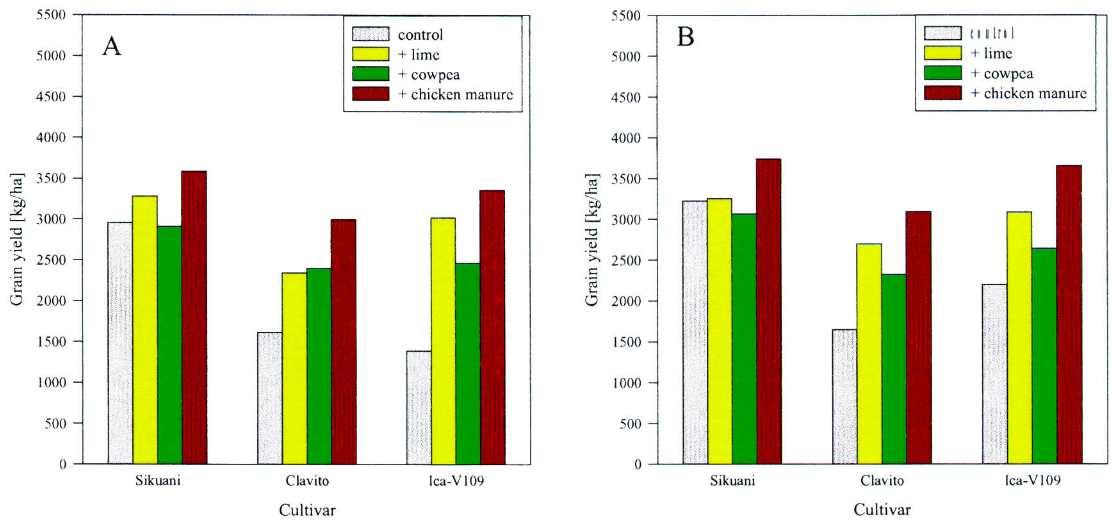

FIG. 7. Grain yields of three maize cultivars as affected by lime, cowpea green manure, or chicken manure; means of three seasons, A 25 kg P/ha, B 50 kg P/ha (L.A. Rojas et al., CORPOICA, Colombia).

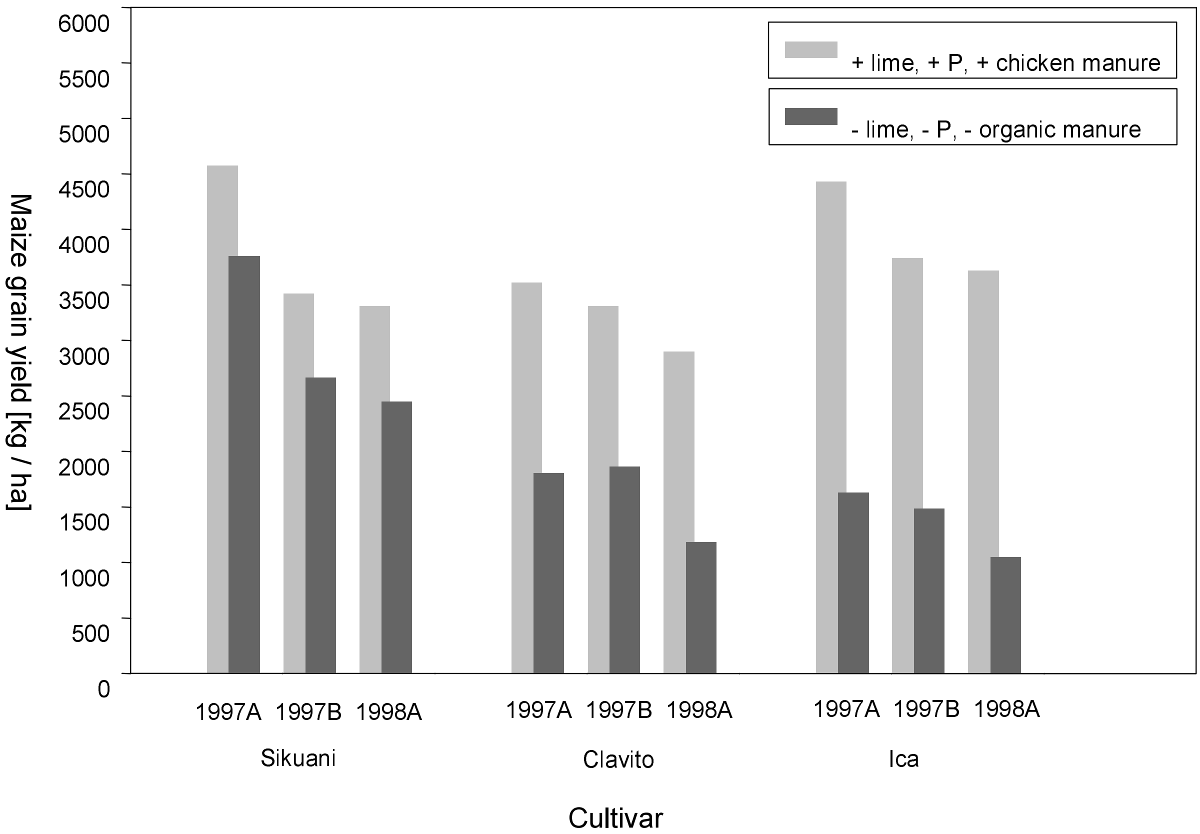

FIG. 8. Yields of three maize cultivars on an acid soil (Villavicencio) without and with correction of soil acidity.

The viability of the genetic approach to solving the problem of acid-soil infertility has been challenged repeatedly. Therefore, complex field experiments are being conducted by CORPOICA, Colombia, and IRAD, Cameroon, within the INCO programme, in order to establish the comparative contributions of genetic and agronomic approaches to sustainable maize production on acid soils. The superiority of maize cv. Sikuani, developed by CIMMYT for adaptation to acid soils of the Colombian Llanos, was clearly expressed when acidity was not corrected, independently of P supply (Fig. 7). Local, and, especially, improved non-adapted, cultivars strongly responded to lime and organic-matter application. Cowpea green manure was less efficient than chicken waste as a source of organic matter. After three seasons of cropping, yields of all cultivars declined independently of amendments, suggesting that maize monoculture is not sustainable at this location (Fig. 8). However, after only three seasons, preliminary conclusions may be premature. In Cameroon, on a highly Al-toxic acid soil, yields were low without amendments; however, acid-soil-tolerant cv. ATP-SR-Y clearly out-yielded non-adapted cv. Tuxpeno Sequia (Fig. 9). *Cassia* green manure was as effective in combating soil acidity as chicken manure. However, lime application was necessary to achieve optimum yields.

Data from Brazil suggest that optimum yields on acid soils can be achieved only with lime rates exceeding the need for Al detoxification [13]. This has been explained in terms of the important contribution of soil organic matter to the cation exchange capacity of these low-activity clay soils and its pH dependency [14]. However, maintenance of a higher soil pH requires not only continued applications of lime but also leads to accelerated decomposition of organic matter, resulting in increased CO_2 emissions and commensurate needs for inputs of C [15]. Too few quantitative data are available to reliably establish C balances of soils for different target pH values.

2.2. Phosphorus deficiency

On many acid soils, P deficiency is the second most important factor limiting maize yields, not only because of inherently low content, but especially because of non-availability to plants due to high P-fixation capacity. The use of P-efficient germplasm is not a long-term alternative to fertiliser application as it leads to mining of soil P and, ultimately, to destruction of soil fertility [16]. Although the process is likely to be slow since P uptake in traditional agriculture is usually low due to meagre yields [17, 18], agricultural productivity cannot be sustained without application of P to replace nutrients removed in the harvested product and by livestock.

Combined with strategic inputs, P-efficient germplasm will contribute to agricultural sustainability by: (i) reducing the need to adjust the soil-P status to higher levels to achieve similar productivity, a strategy that is also more demanding regarding maintenance levels of P; and (ii) increasing the efficiency of use of the applied P, which is a non-renewable resource [19]. Moreover, P-efficient crops would bring economic rates of applied P within the reach of small-holder farmers who might otherwise not use fertilisers.

Substantial genetic variation in P efficiency exists in maize, as was established in field experiments by EMBRAPA/CNPMS, Sete Lagoas, Brazil (Fig. 10). Generally, the factors that contribute to P efficiency are well established [20, 21], and can be divided into two components: (i) the efficiency of acquisition from the soil, and (ii) the efficiency of utilisation to produce yield. Phosphorus-uptake efficiency depends on traits such as root density and architecture, root-hair length and mycorrhizal infection that increases the interception of available P (which is largely immobile in soil), and root-induced changes of the rhizosphere through exudates that contribute to the mobilisation of less-available P sources. Phosphorus-utilisation efficiency depends on partitioning of P among plant parts, remobilization of P from vegetative to reproductive plant organs, and yield structure.

Whereas the principles are clearly established and plant species have been shown to adopt various strategies for P efficiency, the relative importance of these morphological/physiological traits is far from understood. Moreover, their compatibility with other plant traits required for high-yield capacity, such as N efficiency, drought resistance, disease and pest resistance, and competitiveness against weeds and companion crops in intercrops, has not been considered. For example, Lynch [22] demonstrated that higher P-uptake efficiency in *Phaseolus vulgaris* was associated with a more horizontally spread root architecture and higher density in the top-soil where available-P concentration is higher. However, such architectural adaptation of plants to low P supply reduces their capacity to acquire sub-soil water and N, reducing drought resistance and N-uptake efficiency while enhancing competitiveness for top-soil resources with crops grown in association.

Similar trades-off may result from increased P-utilisation efficiency through a higher P-harvest index (grain-P:stover-P ratio) producing more grain per unit of P taken up. A consequence of such an adaptation may be crop residues of low-P content that have less value as livestock fodder (important in small-holder farming systems) or as substrate for soil micro-organisms (important in the maintenance of soil fertility). On the other hand, a lower crop-residue decomposition rate may increase its value as mulch. While these considerations suggest the rather simple approach of increasing P-utilisation efficiency by selecting for low-P concentration in the grain, nutritive value of the grain would be decreased and seedling establishment in low-P soils may be adversely affected [23].

As indicated above, P efficiency is a multifaceted trait that is influenced a range of environmental factors. On one hand, this complicates the derivation of general conclusions from field screening, whereas, on the other hand, it makes field screening for this complex adaptation obligatory.

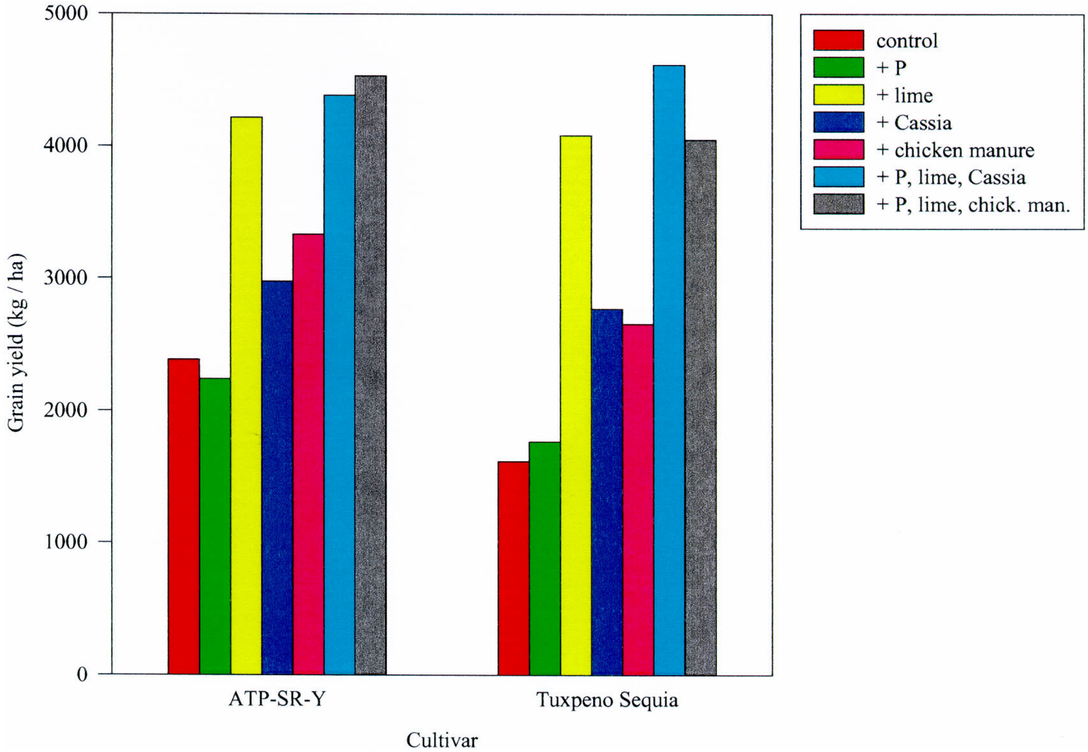

FIG. 9. Grain yields of two maize cultivars as affected by lime, Cassia green manure, and chicken manure (Ch. Thé, IRAD, Cameroon).

Although screening for P efficiency in the seedling stage using small pots filled with soil low in available P certainly reveals genetic variation in P uptake, agreement with field performance is often unsatisfactory [24]. A highly significant positive correlation between seed-P content and P uptake (Fig. 11) reveals the need for circumspection in interpreting P-uptake data. The quantification of P uptake and mobilisation, against a high background of seed P, may be achieved using isotope techniques [25, 26]. Pre-selection for P efficiency on the basis of physiological, morphological and molecular traits, therefore, is a prerequisite for more-efficient breeding for P efficiency.

Plant characteristics considered of primary importance for P efficiency are: (i) fine roots and high root density [27], (ii) long root hairs [28], (iii) P mobilization through root exudates [29], (iv) susceptibility to infection by mycorrhizal fungi especially in acid soils where root growth is inhibited [15], (v) reduced sensitivity to P deficiency in formation of yield components (flower initiation and grain set) [30], and (vi) less sensitivity in terms of leaf area and photosynthesis at early growth stages (also important for flower initiation and grain set) [31, 32]. Germplasm with desirable agronomic characteristics needs to be evaluated for these components; phenotypic markers for such traits need to be identified, and convenient screening techniques developed.

Although molecular markers have recently been used to support selection for P efficiency, their use for screening maize at this stage would be premature. Present investigations focus on acid phosphatases that are expressed under P deficiency [33]. However, the role of phosphatases in P acquisition is still uncertain [34]. In cropping systems in which P recycling from crop residues is significant, root-surface acid phosphatase cannot be excluded. Better understanding of the key plant characteristics for P efficiency and the role of P-efficient germplasm in sustainable crop production is necessary before costly molecular approaches can be used effectively. There is little doubt that morphological root characteristics are most important in determining the efficiency of uptake of nutrients of low mobility, such as P. Among those characteristics, root-hair length, which strongly and specifically responds to low P supply [35] is especially attractive because its contribution to P acquisition might be particularly energy-/C-efficient.

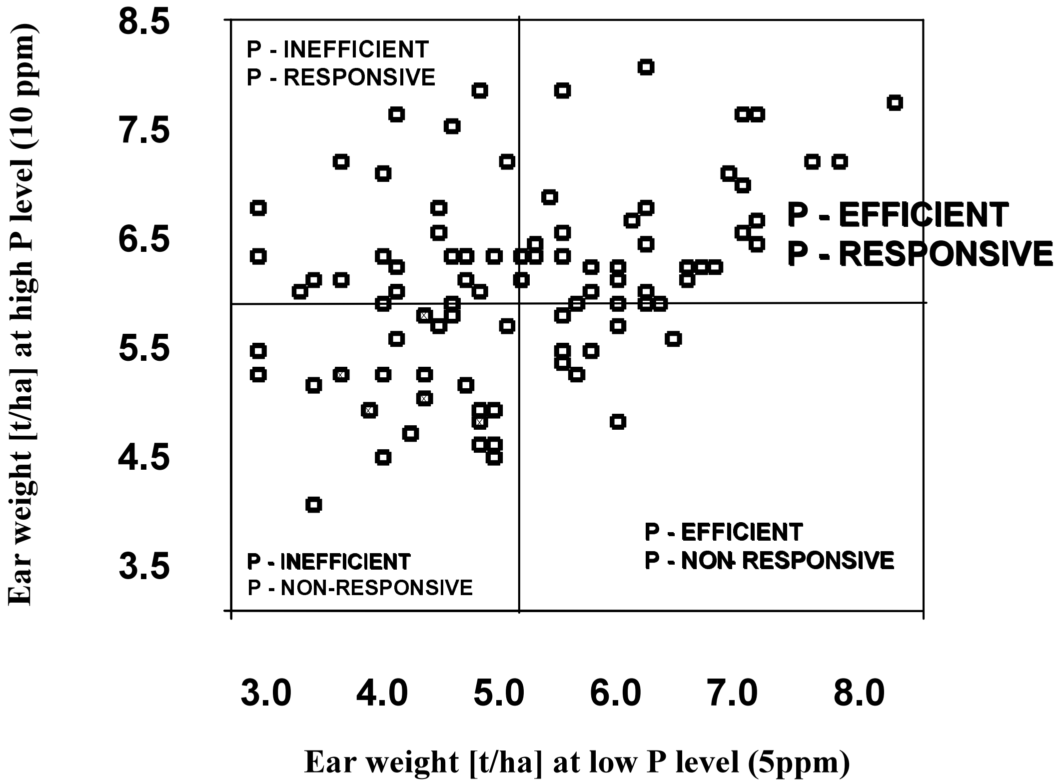

FIG. 10. Grain yields of one hundred maize hybrids at two levels of P (EMBRAPA/CNPMS, Sete Lagoas, Brazil).

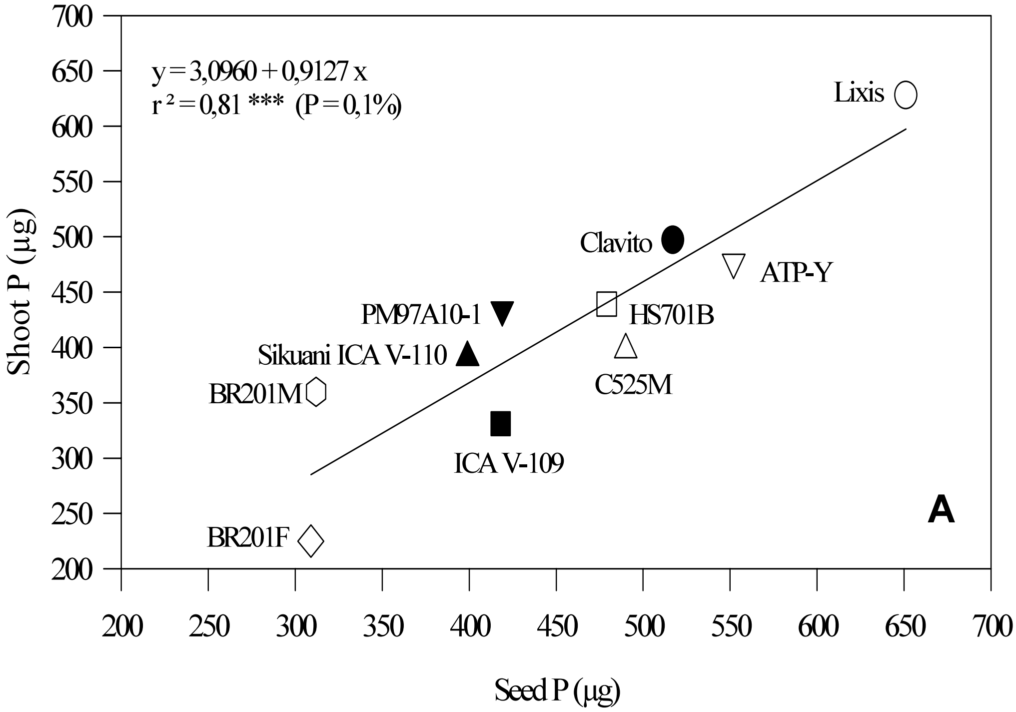

FIG. 11. Relationship between shoot-P uptake and seed-P content for ten maize cultivars grown in a P-deficient soil.

Some plant species, such as *Lupinus albus* [36] and *Cajanus cajan* [37], have evolved the capacity to mobilize sparingly soluble soil P by excretion of organic acids. We have indications that, in maize, genetic variation for excretion of protons (Fig. 12) and for mobilization of soil P through root exudates (Fig. 13) exists There is preliminary evidence that incorporation of such species/cultivars into mixed cropping systems or rotations may improve the P nutrition of less-P-efficient components [34, 38], increasing the overall P efficiency of that cropping system. This may be due to the P-inefficient component having access to mobilised fractions of P made available by the P-efficient component, or improved physical and biological soil characteristics leading to increased infection by mycorrhiza (Fig. 14).

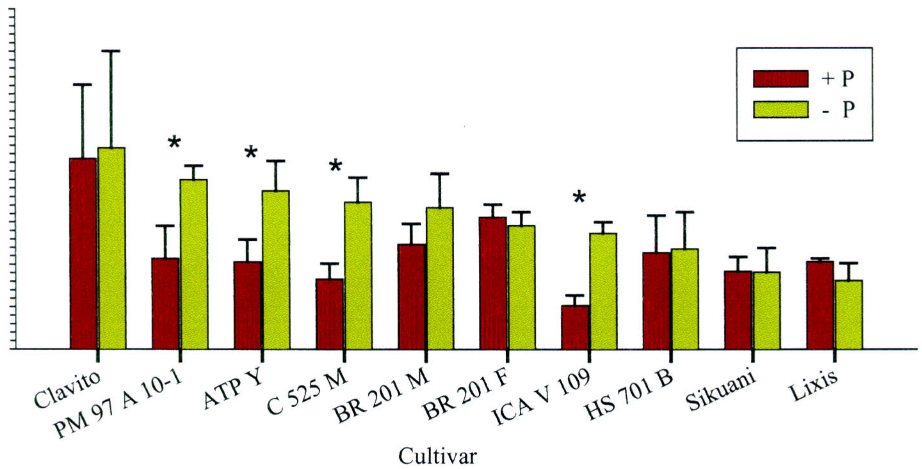

FIG. 12. Net proton excretion of maize cultivars as affected by P supply during preculture for 10 days in nutrient solution.

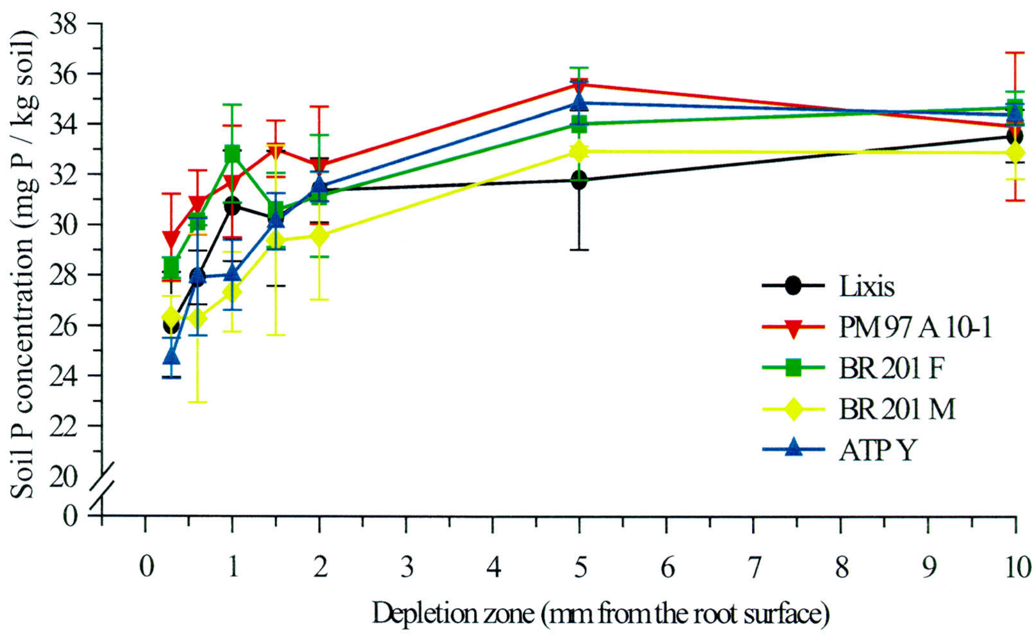

FIG. 13. Concentration of $NaHCO_3$-extractable inorganic soil P at the soil/root interface of maize cultivars grown.

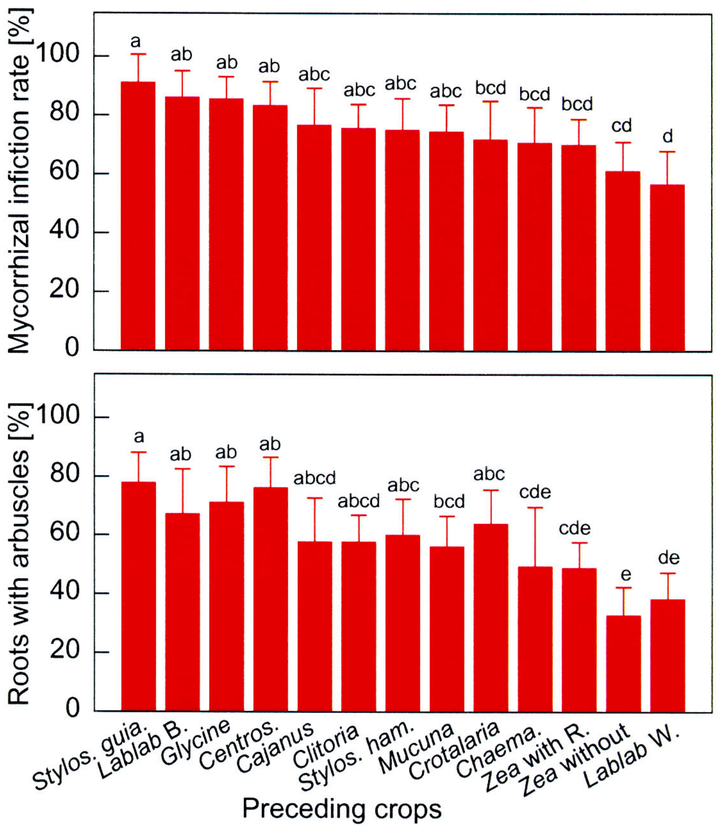

FIG. 14. Influence of preceding crops on mycorrhizal infection and roots with arbuscles in maize.

3. CONCLUSIONS

In conclusion, large genetic variability exists in the adaptation of plants to acid soil. There is a range of morphological and physiological characteristics that contribute to acid-soil tolerance. There is a need to better characterise these properties at the molecular level and to systematically select for them. Incorporation of acidity-tolerant species and cultivars will contribute improved nutrient efficiency to the cropping system as a whole, and thus reduce fertiliser needs.

The application of nuclear techniques may facilitate and enhance scientific progress especially in the following areas:

– Quantification of morphological root characteristics and rooting patterns,
– Water-use efficiency as affected by soil acidity and plant adaptation,
– Establishment of C and N budgets of cropping systems as affected by soil pH and crop management,
– Quantification of the P-mobilisation capacity of crops and cropping systems,
– Molecular characterisation of plant-adaptation mechanisms.

ACKNOWLEDGEMENT

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THE ROLE OF ORGANIC ACIDS EXUDED FROM ROOTS IN PHOSPHORUS NUTRITION AND ALUMINIUM TOLERANCE IN ACIDIC SOILS

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Abstract

Soil acidity is a major problem of large areas of arable land on a global scale. Many acid soils are low in plant-available phosphorus (P) or are highly P-fixing, resulting in poor plant growth. In addition, aluminium (Al) is soluble in acid soils in the toxic Al^{3+} form, which also reduces plant growth. There is considerable evidence that both P deficiency and exposure to Al^{3+} stimulate the efflux of organic acids from roots of a range of species. Organic acids such as citrate, malate and oxalate are able to desorb or solubilise fixed soil P, making it available for plant uptake. Organic acids also chelate Al^{3+} to render it non-toxic, and are, therefore, involved in Al tolerance mechanisms. In this review, we discuss the literature on the role of organic acids exuded from roots in improving plant P uptake and Al-tolerance in acid soils. Research is now attempting to understand how P deficiency or exposure to Al^{3+} activates or induces organic acid efflux at the molecular level, with the aim of improving P acquisition and Al tolerance by conventional plant breeding and by genetic engineering. At the agronomic level, it is desirable that existing crop and pasture plants with enhanced soil-P uptake and tolerance to Al due to organic acid exudation are integrated into farming systems.

1. INTRODUCTION

Soils that are naturally acid or have become acid through agricultural activities comprise large areas of arable land on a global scale [1]. Many are either naturally low in phosphorus (P) and require applications of P fertiliser to achieve economic yields, or are highly P-fixing so fertiliser P is “locked up” in the soil and unavailable to agricultural plants. Acid soils of notoriously high P-fixation capacity are the Alfisols, Andosols, Oxisols and Ultisols [2]. A further problem of acid soils is that the solubilisation of aluminium (Al) and manganese (Mn) into the Al^{3+} and Mn^{2+} forms can result in poor plant growth. Aluminium is much more detrimental than is Mn because it kills root tips, resulting in a stunted root system and greatly reduced uptake of water and nutrients [3, 4]. A combination of high P fixation and Al toxicity in acid soils can devastate crop production. The management of acid P-fixing soils in agriculture involves the application of P fertiliser, liming to raise the soil pH, implementation of practices that reduce inputs of acid, and the use of Al-tolerant plants. In many countries, however, the application of even moderate rates of P fertiliser and lime to acid P-fixing soils is not economical because of the large areas involved and/or the low input nature of agricultural production. Consequently, the inclusion of plants that can access poorly available soil P and that are Al-tolerant has an important role in sustaining agricultural production on acid soils.

Plant roots exude many compounds into the rhizosphere, including sugars, amino acids, phenolics, and organic acids [5]. Organic acids such as malate, citrate and oxalate are implicated in a variety of processes including nutrient acquisition and metal detoxification [6]. Evidence for a direct role of organic acids in plant nutrition is available only for P, Al, iron (Fe) and Mn. This review will concentrate on P and Al, as Fe is normally not limiting in acidic soils and Mn toxicity is insignificant compared to Al toxicity. We discuss how organic acids exuded from roots affect the P nutrition of plants and help to detoxify Al^{3+}, and conclude by outlining molecular approaches for developing plants with an improved ability to access P from soils and fertilisers, and for greater tolerance of Al in acid soils.

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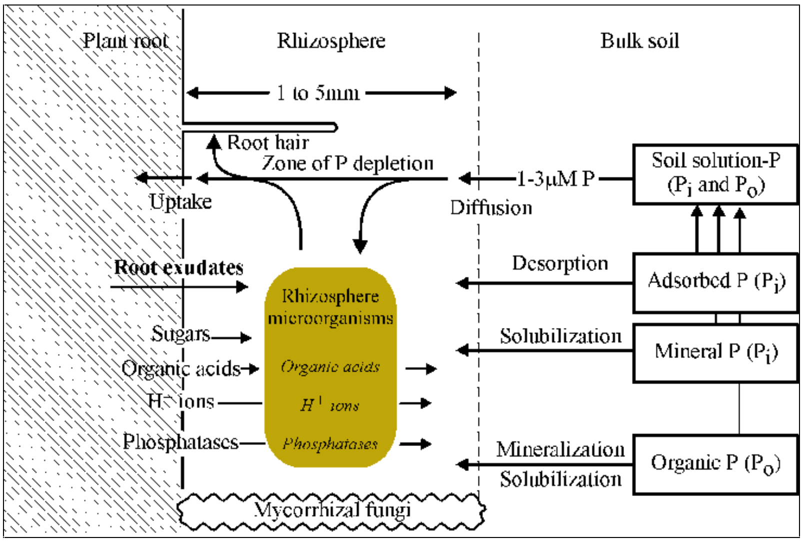

FIG. 1. Outline of the major processes affecting P availability in the rhizosphere and P supply to plant roots. Roots take up inorganic P (P_i) from the soil solution, which is replenished from (P_i) and organic P (P_o) in the solid phase. Root exudates, particularly organic acids, increase the rates of solubilisation, desorption and mineralisation, either directly or via effects on microorganisms. Mycorrhizas increase the effective absorbing area of the root and extend the volume of soil explored. (Reproduced from [8] with kind permission of Springer-Verlag Tokyo.)

2. PHOSPHORUS

2.1. Phosphorus in soils and uptake by plants

Phosphorus plays a major role in agricultural production because of its influence on plant growth and development. However, the supply of plant-available P is inadequate in most acid soils, even though the total amount of P may greatly exceed crop or pasture requirements [7]. Only a small fraction of the total P in soils is in solution in the inorganic (P_i) form (Fig. 1). This is important, as only P_i in the soil solution is directly available for uptake by roots. Because of the low P concentration in the soil solution, mass flow is relatively unimportant in supplying P to roots, and, therefore, diffusion is the major process influencing P uptake by plants. As plants deplete P_i in the soil solution, it is replenished by desorption from charged surfaces, solubilisation of P-containing minerals, and the hydrolysis of organic P compounds (Fig. 1). Despite this, rates of diffusion of P_i in soils are low (~0.13 mm day^{-1}) and generally insufficient to match rates of uptake by roots [9]. Consequently, it is necessary to apply fertiliser P to most agricultural soils to maintain a source of soluble P_i close to the roots to meet crop requirements. However, crops take up only about 10 to 20% of the fertiliser P in the season of application, even after many years of applying it [10, 11]. Most of the fertiliser P is either immobilised in soil organic matter, or sorbed on soil colloids or, particularly in acid soils, fixed by precipitation as Al or Fe phosphates. Soil P accumulated in fixed forms from past P applications represents a major investment by farmers, so improving the ability of plants to access it is highly desirable. In this context, plants capable of secreting large amounts of organic acids from their roots play an important role, as solubilisation of fixed P due to organic acids occurs in the rhizosphere, so that the P released is directly available to plants.

3. ROLE OF ORGANIC ACIDS IN P UPTAKE BY PLANTS

In the early 1980s, Gardner et al. [12–14] provided the first evidence linking organic acid exudation from roots to solubilisation of poorly available soil P and enhanced uptake of P. Specialized proteoid roots of white lupin (*Lupinus albus*) were shown to exude citric acid, and it was proposed that citrate improved the P nutrition of the plant by forming a ferric-hydroxy-phosphate polymer in the rhizosphere that diffused to the root, and there released the P after reduction [14]. Since then, there has been worldwide interest in the role of organic acids in enhancing nutrient acquisition by plants [15–19].

TABLE I. ORGANIC ACIDS EXUDED FROM ROOTS OF SELECTED SPECIES [8]

Species	Growth conditions	Organic acid released from roots (whole root systems; mmol h^{-1} g^{-1} dry wt.[a])				Ref.
		Citric	Malic	Malonic	Other	
White lupin	P-deficient solution	11.0	8.0			[20]
Rice	Soil, low P	2.3			Traces of oxalic, malic, lactic, fumaric.	[21]
Maize	Nutrient-deficient	1.3	6.0			[22]
Narrow-leaved lupin	solution with nitrate as N source	1.2				[23]
Pigeon pea	Full nutrient solution	0.002	Trace	0.58	Oxalic (0.19) piscidic (0.09) tartaric (0.001)	[24]
Chickpea	Fe-deficient solution	0.001	Trace	0.006	Tartaric (0.002) fumaric (0.001)	[25]

[a]Assumes dry weight is 7% of fresh weight where conversion required.

3.1. Mobilisation of P in the rhizosphere

Many studies have shown that plants exude organic acids from their roots. Citric, malic, oxalic and malonic acids are commonly found, and succinic, tartaric, piscidic, aconitic and fumaric acids have been reported also (Table I). The effectiveness of an organic acid in mobilising fixed soil P depends on its ability to complex metal ions such as Al and Fe, and displace P from charged surfaces. Organic acids desorb P in soils in the order tricarboxylic > dicarboxylic > monocarboxylic acids, and the amount of P released is proportional to the propensity to complex Al and Fe [15, 26]. Citric, a tricarboxylic acid, binds more strongly than do the di- and mono-carboxylic acids to metals such as Al and Fe that are important in the P chemistry of acid soils [15, 27]. Citric acid is effective also at releasing P in soils containing calcium (Ca) phosphates or rock phosphate fertiliser [22]; it is exuded in considerable quantities by some species, such as white lupin (Table I), especially from recently developed portions of proteoid roots [28, 29]. Significant quantities of citric acid have been detected in the rhizosphere soil of proteoid roots [30–33].

Organic acids exuded from roots can modify the chemistry of the rhizosphere, and thus alter the availability of P compounds. This occurs indirectly through promoting the growth of soil micro-organisms that mineralise P [34], or directly by:

- Changing conditions in the soil solution (e.g. pH), thus increasing the dissolution of sparingly soluble P minerals,
- Altering the surface characteristics of soil particles,
- Competing with phosphate ions for adsorption sites,
- Complexing cations that are bound to P [15].

The importance of each of these factors depends on the soil type and the forms of P present. For example, an increase in organic acid exudation can increase soil-solution P by solubilising Ca phosphates (such as from rock phosphate fertiliser) due to a decrease in pH in the rhizosphere, or by desorption reactions in acidic soils where P solubility is controlled by ion-exchange equilibria involving charged clay minerals and organic matter [35].

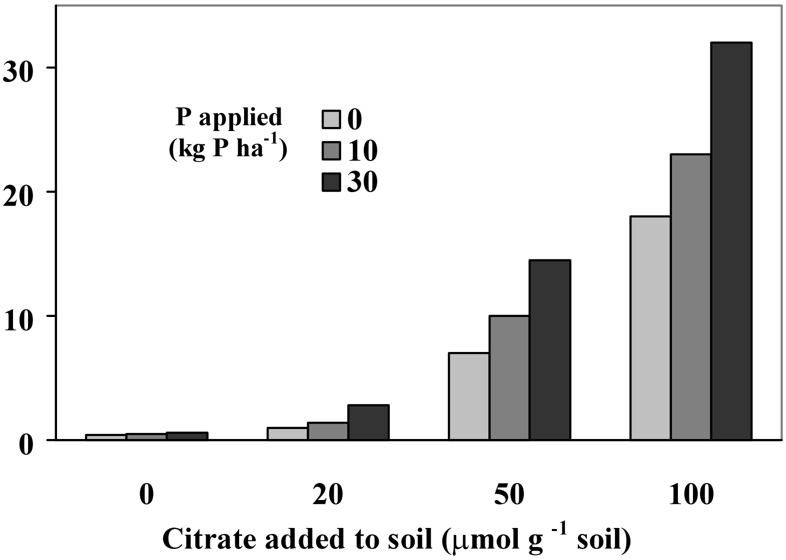

FIG. 2. Effect of eluting an Oxisol with various concentrations of citrate on the amount of P extracted. A level of 50 μmol citrate g^{-1} soil is similar to the concentration of citrate found in the rhizosphere of white lupin. Note that citrate increased the extraction of both native and fertiliser P (G. Keerthisinghe, unpublished).

3.2. Exudation of organic acids

There is considerable evidence for the importance of organic acid exudation from roots in the acquisition of soil and fertiliser P by plants. The addition of organic acids, particularly citrate, to soils can solubilise significant quantities of fixed P [15, 36] (Fig. 2), or reduce the sorption of newly applied fertiliser P [22, 26]. A number of species respond to P deficiency by increased rates of organic acid exudation from their roots, which may be beneficial under P-limiting conditions. For example, root exudates containing citrate collected from P-stressed white lupin solubilised P bound to Fe [14]. Rhizosphere soil of proteoid roots of white lupin had elevated levels of citrate, and soluble P, Al, Mn and Fe [13, 31]. Similarly, exudates from pigeon pea (*Cajanus cajan*) roots containing malonic and piscidic acids solubilised P bound to Fe or Al in an acid soil, and the Fe-P solubilising activity of the exudates increased with increasing P stress [37]. The P mobilised by citrate exuded from proteoid roots of white lupin may persist in the soil for more than 10 weeks, although the extent to which this P is available to plants is uncertain [38]. However, wheat (*Triticum aestivum*) following white lupin had better growth and P nutrition than after wheat [39] (Table II), suggesting some carry-over benefit.

There is evidence also that organic acids exuded from roots enhance the availability of P from organic P substrates such as phytate (inositol hexaphosphate). Organic acids can free phytate that is complexed with metal ions in acid soils, making it available for breakdown by extracellular phytase enzymes [6]. However, further studies are required to establish the role of organic acids in relation to improving the capacity of agricultural plants to obtain P from phytate.

3.3. Organic acid exudation and plant access to different pools of P in the soil

Although it is clear that species differ in the amounts of P they obtain from a soil [40], it is difficult to determine if they access different P pools, or the same pools but at different rates. Studies comparing the capacity of pasture [41] and crop [42] species to obtain P, using the ^{32}P-dilution (L-value) technique, showed that the L-values were similar for the species in both studies, indicating access to the same pools of P but with different rates of uptake. However, the species used in these studies are not known to exude organic acids.

In contrast, studies including species known to exude organic acids showed inter-specific variation in capacity to access P in different pools in the soil. For example, maize (*Zea mays*), sorghum (*Sorghum bicolor*) and chickpea (*Cicer arietinum*) obtained more P from Ca phosphate than from phosphates of Fe or Al, whereas pigeon pea took up P equally well from Ca- and Fe-bound P [43, 44]. Braum and Helmke [45] and Hocking et al. [46] used the ^{32}P-dilution technique to show that white lupin accessed soil P that was not available to soybean (*Glycine max*). Hocking et al. [46] grew seven species, including white lupin and pigeon pea, in an acidic highly P-fixing Oxisol labelled with ^{32}P. After 5 weeks of growth, the L-values indicated that the pool of soil P available to white lupin was substantially larger than that available to the other species (Fig. 3), probably due to high rates of citrate exudation from proteoid roots of white lupin. The L-value for pigeon pea, although lower than that of white lupin, was higher than values for narrow-leaved lupin (*Lupinus angustifolius*), soybean, oilseed rape (*Brassica napus*), wheat and sunflower (*Helianthus annuus*). The lower L-value for pigeon pea may be due to malonic and piscidic acids being less effective than citrate in freeing fixed P, or to lower rates of organic acid exudation than from white lupin [24]. Oilseed rape was ineffective at obtaining P from poorly available sources in this acidic Oxisol (Fe- and Al-bound P) (Fig. 3), although it can solubilise some P from Ca-bound P in rock phosphates [47, 48]. The inability of P-deficient rapeseed to access P from the Oxisol may have been due to the low rates of organic acid exudation, particularly of citrate, from its roots (3% of the rate from proteoid roots of white lupin [8]), and the rapid sorption of the organic acids exuded from roots by the Oxisol [6].

TABLE II. EFFECT OF PREVIOUS CROP ON GROWTH AND P UPTAKE BY WHEAT [39]

Previous crop	Dry matter (g plant^{-1})	P concentration (mg g^{-1})	P uptake (mg plant^{-1})
Wheat	0.36	2.06	0.74
White lupin	0.69	1.25	0.86

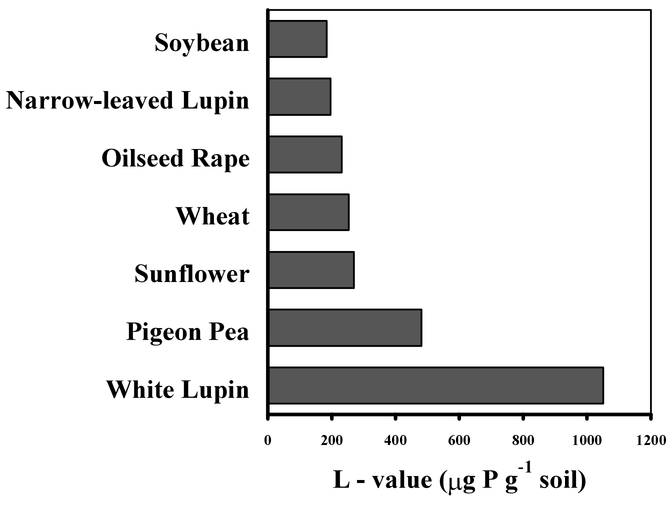

FIG. 3. Estimates of soil P available to crop species grown in an Oxisol with 1.8 mg kg^{-1}Bray-1 extractable P and 3.1 g kg^{-1} total P. The soil was thoroughly mixed with $^{32}P_i$ to label the isotopically-exchangeable P pool. L-values are a measure of the availability: the larger the value, the more P is available to the plant [46].

4. INCREASING THE ABILITY OF PLANTS TO ACQUIRE P

Although there is evidence that species that exude organic acids differ are superior in their ability to access different pools of soil P, there is very limited information on intra-specific variation in organic acid exudation from roots. Experimentally, it is difficult to show consistent differences between genotypes because exudation rates are altered by plant P status, root age and environmental factors. Recent work with pigeon pea cultivars did not directly measure organic acid exudation, but instead measured the ability of root exudates to solubilise soil P bound to Fe or Al [37]. Phosphorus uptake by pigeon pea from Fe-P in vermiculite culture was measured also [49]. Differences between cultivars were reasonably consistent using the two approaches. Such approaches are promising and offer hope for the development of a screening procedure to select for genotypes with enhanced organic acid exudation.

The only reported attempt to increase organic acid exudation by genetic engineering involved the enzyme citrate synthase. Tobacco transformed with a bacterial citrate synthase gene had both increased internal concentration and exudation of citrate in and from its roots [50]. Although, the significance of these changes for P nutrition has yet to be evaluated, it demonstrates the potential of a molecular approach. The next step is to characterize genes controlling the efflux of organic acids from roots so that the interaction between the biosynthesis and efflux of organic acids can be optimised.

5. ALUMINIUM TOLERANCE

Aluminium-tolerance mechanisms can be grouped into those that keep Al^{3+} out of root cells, and those that detoxify Al^{3+} internally. Recent research has focussed on the exudation of organic acids that chelate Al^{3+} in the rhizosphere and render it non-toxic. However, the ability of organic acids to chelate Al varies considerably. For example, citric, oxalic and tartaric acids were the most effective in protecting cotton (*Gossypium hirsutum*) roots from Al^{3+} toxicity, whereas malic, malonic, and salicylic acids were of moderate effectiveness, and succinic, lactic, formic, acetic, and phthalic acids provided little protection [27]. The effectiveness of organic acids in protecting roots against Al^{3+} toxicity is related to the relative positions of OH/COOH groups on the main carbon chain. Organic acids able to form stable 5- or 6-bond ring structures with Al^{3+} provide the best protection. In this review, we consider Al tolerance mechanisms based on the organic acid exuded.

5.1. Malate

Initial evidence of a role for organic acids exuded by roots in Al tolerance came from Christiansen-Weniger et al. [51] who found that an Al-tolerant wheat cultivar exuded more malate than did a sensitive cultivar. Subsequently, it was shown that for two near-isogenic wheat lines, Al^{3+} stimulated a 5- to 10-fold greater efflux of malate from roots of the Al-tolerant genotype than from the sensitive genotype [52] (Fig. 4). The malate was exuded mainly from the terminal 3 mm of the root, which is the part most susceptible to Al toxicity [53, 54]. This has since been confirmed for other wheat cultivars differing in Al tolerance [55, 56]. A strong correlation was found between malate efflux and Al tolerance among thirty wheat cultivars from diverse sources that covered a range of Al tolerances, suggesting that genes encoding for malate efflux account for a large proportion of the Al tolerance found in hexaploid wheat [57].

There is evidence that Al^{3+} activates a pre-existing mechanism for the transport of malate through a malate-permeable anion channel in Al-tolerant wheat, as there was no appreciable lag phase in malate secretion after adding Al^{3+} to the external medium [53] (Fig. 4). While the activities of key enzymes showed that both Al-tolerant and Al-sensitive genotypes had equal capacity for malate synthesis, the tolerance to Al^{3+} seemed to be related to the transport of malate out of root cells through Al-activated ion channels [53].

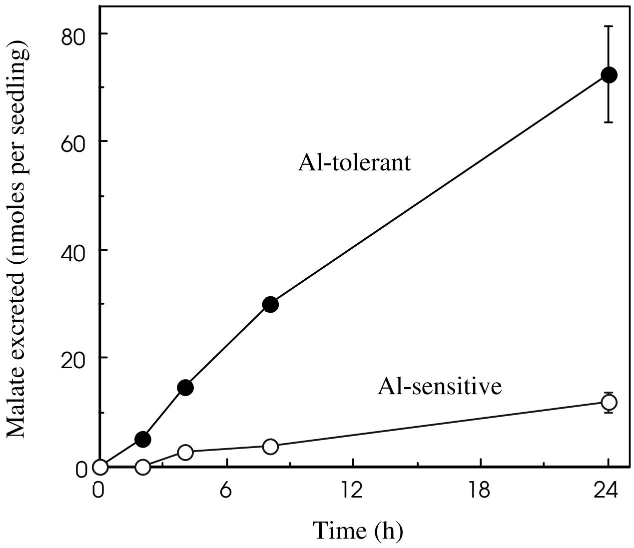

FIG. 4. The effect of exposure to 50 mmol m^{-3} Al^{3+} on the exudation of malate from roots of Al-tolerant and Al-sensitive wheat seedlings. In the absence of Al^{3+}, both genotypes secreted similar low amounts of malate. Vertical bars denote ± range, n=2. (Reproduced from [52] with kind permission of Plant Physiology.)

5.2. Citrate

Citrate is probably the most effective chelator of Al, and a role for its exudation from roots in Al tolerance was initially proposed after it was found that an Al-tolerant snapbean (*Phaseolus vulgaris*) cultivar secreted 10-fold more citrate than one that was Al-sensitive [58]. Subsequently, it was shown that an Al-tolerant maize cultivar also secreted 10-fold more citrate than a sensitive one [59]. Although the efflux of citrate occurred primarily from the root apex, there was a lag phase before maximum efflux occurred, unlike the immediate response for malate efflux from wheat. This suggests that Al induces the *de-novo* synthesis of proteins involved in citrate biosynthesis and/or its transport out of maize roots. Citrate efflux from root tips of Al-tolerant maize was subsequently confirmed using another pair of cultivars differing in Al tolerance, and it was shown that citrate chelated Al^{3+} and reduced its accumulation in the root apex of the tolerant cultivar [60].

Ma et al. [61, 62] showed that Al^{3+} resulted in 2.5- to 3-fold more citrate exudation from roots of the Al-tolerant shrub *Cassia tora* than from the Al-sensitive *C. occidentalis,* and provided further evidence for the induction of citrate exudation by Al^{3+}. There is evidence also that Al-tolerance mechanisms based on the exudation of organic acids occur in tree species. Aluminium increased the exudation of citrate from roots of three leguminous trees, and this was not related to P-deficiency stress [63]. The quantities of citrate exuded were correlated with the degree of Al tolerance amongst the three species examined. Tobacco transformed with a bacterial citrate synthase gene showed enhanced Al tolerance that was associated with a 10-fold greater internal citrate concentration in the transgenics than in wild-type plants [50]. Similar results were obtained when the citrate synthase gene was over-expressed in papaya (*Carica papaya*), suggesting that this gene may be used as a general method to enhance Al tolerance by genetic engineering [50].

5.3. Oxalate

The exudation of oxalate from roots has been implicated in the Al tolerance of buckwheat (*Fagopyrum esculentum*). Exposure of its roots to Al^{3+} elicited exudation of oxalate, with kinetics similar to those of Al-stimulated efflux of malate from wheat roots [64]. Unlike wheat, buckwheat accumulated high concentrations of Al in leaves, much of it complexed with oxalate, the mechanism of which is not known. The efflux of oxalate and the internal chelation of Al by oxalate are likely to represent two related mechanisms that confer Al tolerance on buckwheat.

6. CONCLUDING REMARKS

Initially, researchers looked for variation in P-uptake efficiency within agricultural species that might be exploited by breeding and selection. Work to understand mechanisms proceeded at the physiological level following the discovery of high rates of citric acid exudation by roots of white lupin [12]. This understanding at the physiological level laid the foundation for the current progress at the molecular level. There is convincing evidence that some species secrete organic acids either to increase P uptake or to protect their root tips from Al toxicity. The strongest evidence supports a role for organic acids such as citrate, malonate and oxalate in enhancing P uptake, and malate, citrate and oxalate in Al tolerance. However, more work is needed to assess the efficacy of organic acid exudation in improving plant access to fixed P in different soils and for different forms of P fertiliser. At the agronomic level, the role of plants that exude organic acids needs to be evaluated in the P economy of crop and pasture sequences. Further research is needed to identify the mechanisms involved in activating or inducing the efflux of specific organic acids out of root cells by P deficiency or exposure to Al^{3+}, and to clone genes involved in these processes. The first report of genetic engineering to increase citrate synthase activity and citrate efflux from roots [50] opens up the possibility of enhancing the access of crop and pasture species to poorly available soil P and/or increasing their Al tolerance by genetic modification. The isolation of genes the products of which are involved in transport of key organic acids across the plasma membrane is likely to further enhance both conventional and genetic engineering approaches aimed at improving the P uptake and Al tolerance of agricultural plants on acid soils.

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PHOSPHATE FERTILISER MANAGEMENT AND MODELLING

PHOSPHATE FERTILISERS AND MANAGEMENT FOR SUSTAINABLE CROP PRODUCTION IN TROPICAL ACID SOILS

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Abstract

Extensive research has been conducted over the past 25 years on the management of plant nutrients, especially N and P, for crop production on acidic infertile tropical soils. Under certain conditions, the use of indigenous phosphate rock (PR) and modified PR products, such as partially acidulated PR or compacted mixtures of PR with superphosphates, are attractive alternatives, both agronomically and economically, to the use of conventional water-soluble P fertilisers for increasing crop productivity on Oxisols and Ultisols. A combination of the effects of proper P and N management including biological N_2 fixation, judicious use of lime, and the use of acid-soil tolerant and/or P-efficient cultivars in cropping systems that enhance nutrient cycling and use efficiency, can provide an effective technology to sustainably increase crop productivity and production in tropical agro-ecosystems dominated by these acid soils.

1. INTRODUCTION

The world's population is expected to increase from 6 to 7.3 billion between 1999 and 2025, with most growth occurring in Latin America, Asia, and Africa. In order to feed the expected population of the developing world, food production will need to increase by over 50% during the next 25 years [1].

Perhaps the greatest potential for increased agricultural production lies in agro-ecosystems dominated by acid, infertile soils. These occur largely in the tropical rainforest and savannah regions of Latin America and Africa, and, to a lesser degree, in less populated areas of south-east Asia. Because of the negative environmental impact of slash-and-burn agriculture and deforestation, agricultural development is increasingly focused on the regions of tropical acid-soil savannahs.

Acid-soil savannahs occupy approximately 240 Mha of land in the Llanos of Colombia and Venezuela, and the Cerrado region of Brazil. The predominant soils are classified as Oxisols and Ultisols and represent approximately 34% and 21%, respectively, of the total land area of tropical America [2]. These soils generally have a favourable topography for agriculture, and adequate temperatures and moisture for plant growth [2]. However, the low native soil fertility as well as acidity and Al toxicity have limited widespread agricultural development in these areas. Acid savannah soils occupy much smaller areas in Africa and Asia, but they are nevertheless important resources for increased agricultural production. Moreover, in south-east Asia, significant areas have been deforested in large transmigration schemes exposing highly acidic soils to agricultural development. These soils, also predominantly Oxisols and Ultisols, share the same constraints of low inherent fertility to productive agriculture as do those of the tropical savannahs.

Increasing agricultural production on highly acidic, infertile Oxisols and Ultisols requires nutrient inputs, either organic or mineral, to satisfy the requirements of crops, as well as to replace nutrients removed in harvested products. Phosphorus (P) is the major limiting nutrient; these soils are low in both total and available P and frequently have a high P-fixation capacity. Unlike nitrogen (N), which can be supplied indirectly through biological fixation by rhizobia in symbiosis with legumes, P must be supplied from inorganic sources or through biomass transfer from more enriched soils. Phosphorus fertiliser is a costly input with very low use efficiency by crops.

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Sanchez and Salinas [2] discussed six strategies to manage P-nutrient inputs in acid savannah soils:

– Determine the most appropriate combination of rates and placement methods to enhance initial and residual effects,
– Improve soil-fertility evaluation procedures for making P recommendations,
– Use more cost-effective P sources such as indigenous phosphate rocks (PRs),
– Use moderate amounts of lime to reduce soil P-fixation capacity and increase P availability,
– Select species and varieties of crops that grow well at low available-P levels,
– Enhance mycorrhizal associations with plants to increase P uptake.

Much research on P management for Oxisols and Ultisols during the past 25 years has focussed on these areas.

In order to improve the accessibility of P fertilisers to resource-poor farmers, IFDC has been conducting an extensive research programme since 1975 on the development and use of P fertilisers in Latin America, Africa, and Asia. This paper presents a brief review of that programme on the development of alternative non-conventional P fertilisers and the management of P fertilisers in tropical acid soils, with particular emphasis on the acid savannah soils of Latin America.

2. NON-CONVENTIONAL PHOSPHATE FERTILISERS

High P-fixing Oxisols and Ultisols require additions of at least 200 mg P/kg to provide 0.2 ppm P in soil solution, a level considered adequate for optimal growth of crops such as maize [3]. Approximately 72% of the land surface occupied by Oxisols and Ultisols have soils with high P-fixation capacity [2]. Although high rates of conventional water-soluble P fertilisers, e.g. triple superphosphosphate (TSP) and single superphosphate (SSP), on such soils can be agronomically effective, their use may be economically prohibitive, especially for poor farmers. For example, on virgin soils in the Brazilian Cerrados, initial applications of 100 to 200 kg P/ha of water-soluble P fertilisers were needed to produce high yields of maize, soybean, wheat, and upland rice [4].

The IFDC's P-research programme has focussed particularly on the use of indigenous PRs as a low-cost alternative to soluble P fertilisers for crop production on highly acidic soils. The programme included chemical and mineralogical characterisation of PR deposits, processing technologies for direct use or chemical and physical modification, soil chemistry and greenhouse studies to elucidate factors affecting PR availability to plants, agronomic evaluation under field conditions, and economic assessment of cost:benefit ratios.

2.1. Phosphate rock characteristics and soil factors affecting P availability to plants

Phosphate rocks consist mainly of the mineral apatite, and may be either sedimentary or igneous in nature. The agronomic effectiveness of PR depends greatly on its chemical reactivity, which is determined by its chemical and mineralogical properties, principally the degree of isomorphous substitution of carbonate for phosphate in the apatite crystal lattice [5]. It has been found that the solubility values of PR in neutral ammonium citrate solution (AOAC method), 2% citric acid, and in 2% formic acid, correlate with carbonate substitution and agronomic effectiveness. Consequently, these three values are now widely used as a basis for the determination of PR reactivity. Phosphate rocks are classified accordingly, as being of low, medium or high reactivity.

The availability of P from PR sources depends not only on characteristics of the PR, but also on soil properties and plant attributes. Phosphate rock dissolution involves the consumption of protons (H^+ ions), and the release of Ca and phosphate ions to soil solution. Consequently, soils with a large source of free protons (acid soils), and large sinks for Ca and phosphate ions (that is, low exchangeable Ca and high P-retention capacity) are well suited for PR application and dissolution [6]. Since Ca and, especially, P are relatively immobile in soil, PR application methods that favour a high degree of PR/soil contact also enhance PR rates and P availability.

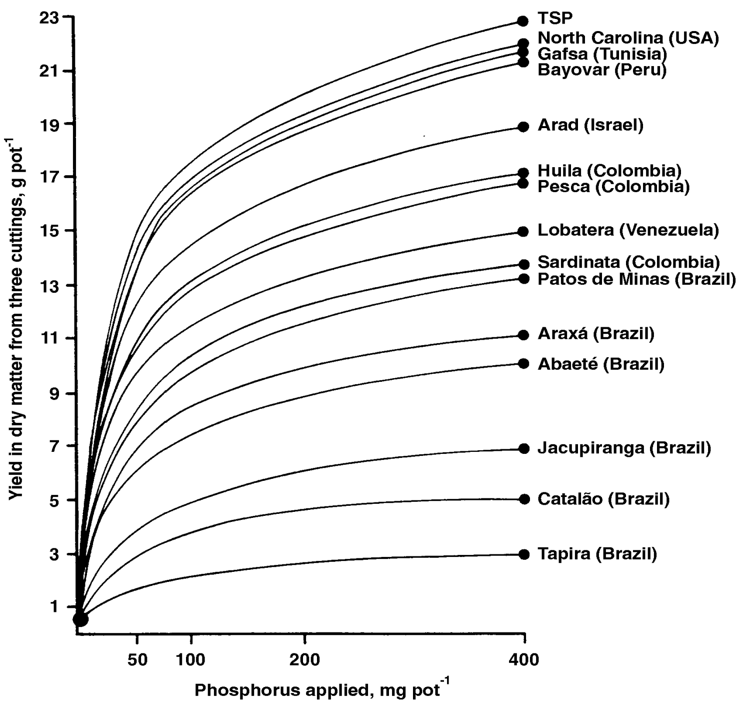

FIG. 1. Response of guinea grass to application of PR sources on an Oxisol [6].

2.2. Agronomic effectiveness of PR sources for crops

Phosphate-rock deposits exist in several countries of Latin America [7]. Their agronomic effectiveness varies widely, from some that are as effective as TSP to those that produce no effect on crops over the control (Fig. 1) [6]. The effectiveness of the various PR materials is related to their reactivity. Medium-reactive PRs (e.g., Huila in Colombia, Riecito in Venezuela) or highly reactive PRs (e.g., Sechura in Peru, Bahia Inglesa in Chile) are economically attractive P sources for crop production, especially when the residual value of the PR is considered (Fig. 2) [6]. In a study conducted on an Oxisol on the Colombian Llanos, Huila PR was as effective as TSP in increasing grain yields of two rainfed rice varieties (Fig. 3) [6]. This and similar findings have created a growing demand for Huila PR, accounting for approximately 25,000 t (about 15% of Colombia's annual consumption of P fertilisers) sold and applied to Colombian farmers' fields in 1994. Using this indigenous PR source saves the country approximately US $1 M in foreign exchange each year [8]. In Brazil, indigenous PRs have not been used for direct application because of their very low reactivity. However, the country is importing a substantial quantity (350,000–400,000 t in 1998) of highly reactive PRs, mainly Arad from Israel and Gafsa from Tunisia, for direct application to acid savannah soils.

There are numerous deposits of PR in sub-Saharan Africa, e.g., Hatotoe in Togo, Kodjari in Burkina Faso, Parc W and Tahoua in Niger, Tilemsi Valley in Mali, Matam in Senegal, Minjingu and Panda Hills in Tanzania, Sukulu Hills in Uganda, and Dorowa in Zimbabwe. The IFDC has conducted extensive characterisation and evaluation studies of these PRs and has found that, in general, only Tahoua, Tilemsi Valley and Minjingu are suitable for direct application under appropriate soil and crop conditions. For example, Tahoua PR was found to be 90 to 95% as effective as TSP, whereas the less reactive Parc W was only 49 to 63% as effective in terms of increasing millet grain yields in one-time applications in a 3-year trial on an acidic sandy Alfisol in Niger [9]. The same study showed that one initial application of a large dose was more effective than three annual applications, presumably because of the very low P-fixation capacity of this Alfisol. In Mali, Tilemsi Valley PR was 78 to 100% as effective of TSP during a 4-year study of a maize/cotton rotation [10].

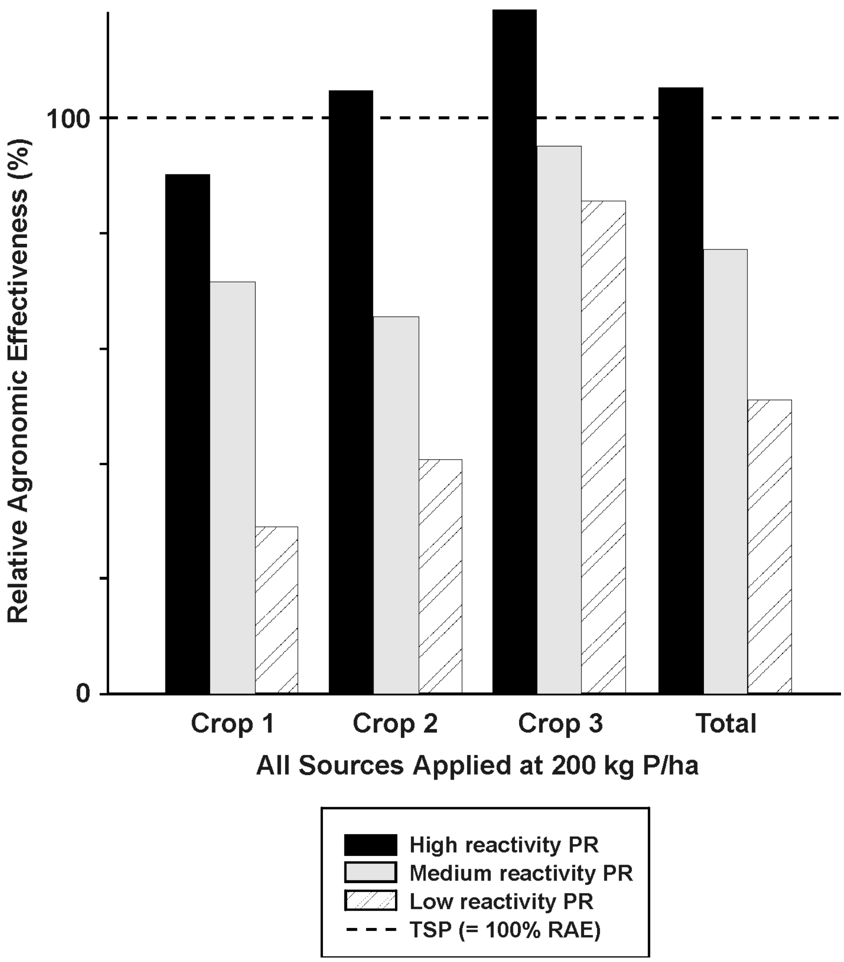

FIG. 2. Relative agronomic effectiveness of PR sources on growth of beans on an Andosol [6].

Although Oxisols and Ultisols amenable for directly applied PR occur widely in south-east Asia, no significant deposits, apart from Christmas Island PR (owned by Australia), have been found in the region (Indonesia, Malaysia, Thailand). Most PR sources in mainland Asia and on the sub-continent (India, China, Viet Nam) are not suitable for direct application because of low reactivity. As shown in Fig. 4 [11], Mussoorie PR (India) was less effective than TSP in increasing grain yields of rice and wheat. Nevertheless, PR sources, mostly of medium reactivity, find widespread use in the plantation sector, particularly in Malaysia. Several studies have also evaluated imported PR sources on annual food crops. These were of medium or high reactivity, imported from Tunisia (Gafsa), Jordan (El-Hassa), USA (North Carolina), and Morocco.

From 1987 to 1990, IFDC compared the agronomic effectiveness of PRs of medium (Jordan) and high (North Carolina) reactivity, against TSP in rotations of maize or upland rice with soybean or cowpea at five sites on Sumatra, Indonesia [14]. The effect of grinding on PR effectiveness was also examined. Responses of upland rice on a slightly acidic soil (pH 6.3) and of maize on a moderately acidic soil (pH 5.2) are shown in Fig. 5 [12]. Crop responses to the various PR sources were similar to the effect of TSP. Moreover, differences in initial soil pH, exchangeable Ca, and P-fixation capacity among sites, did not alter the effectiveness of the PR sources. All P sources produced substantial residual effects, increasing grain yields of soybean or cowpea planted after the cereals without additional applied P, by two to eight fold. In most cases, there was no significant difference in agronomic effectiveness between a single 120 kg P/ha initial application and three annual applications of 40 kg P/ha.

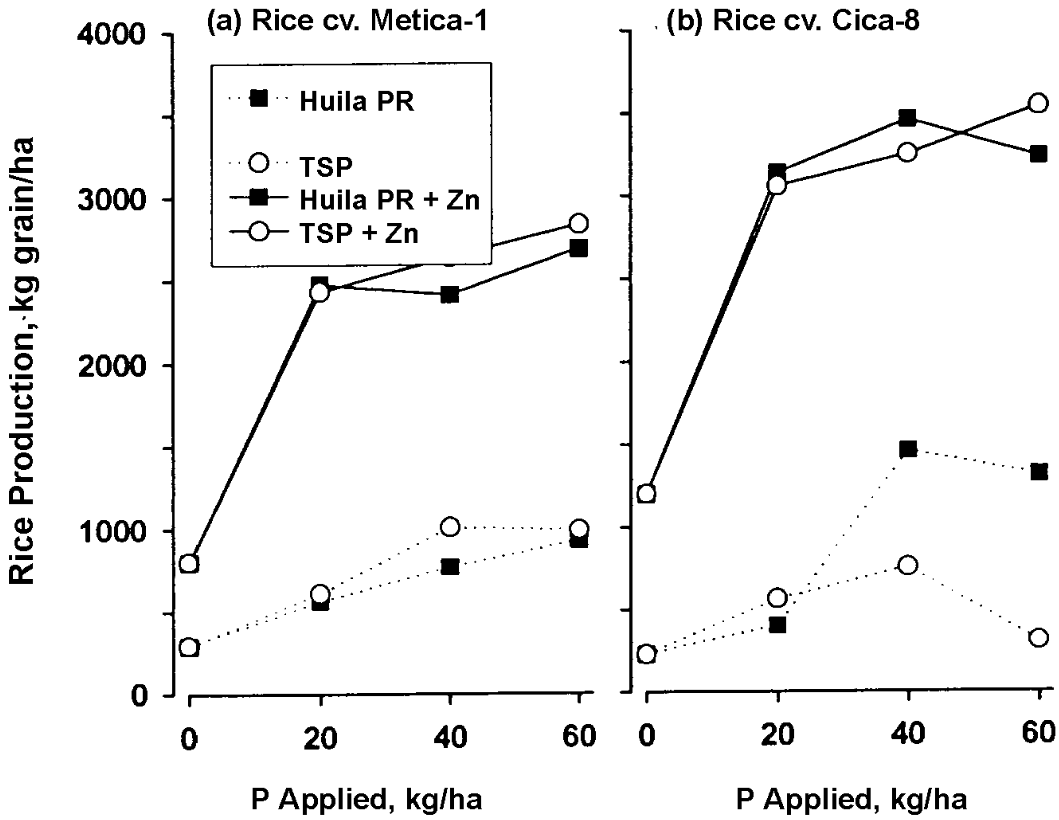

FIG. 3. Response of rain-fed rice to Huila PR (Colombia) and TSP on an Oxisol [6].

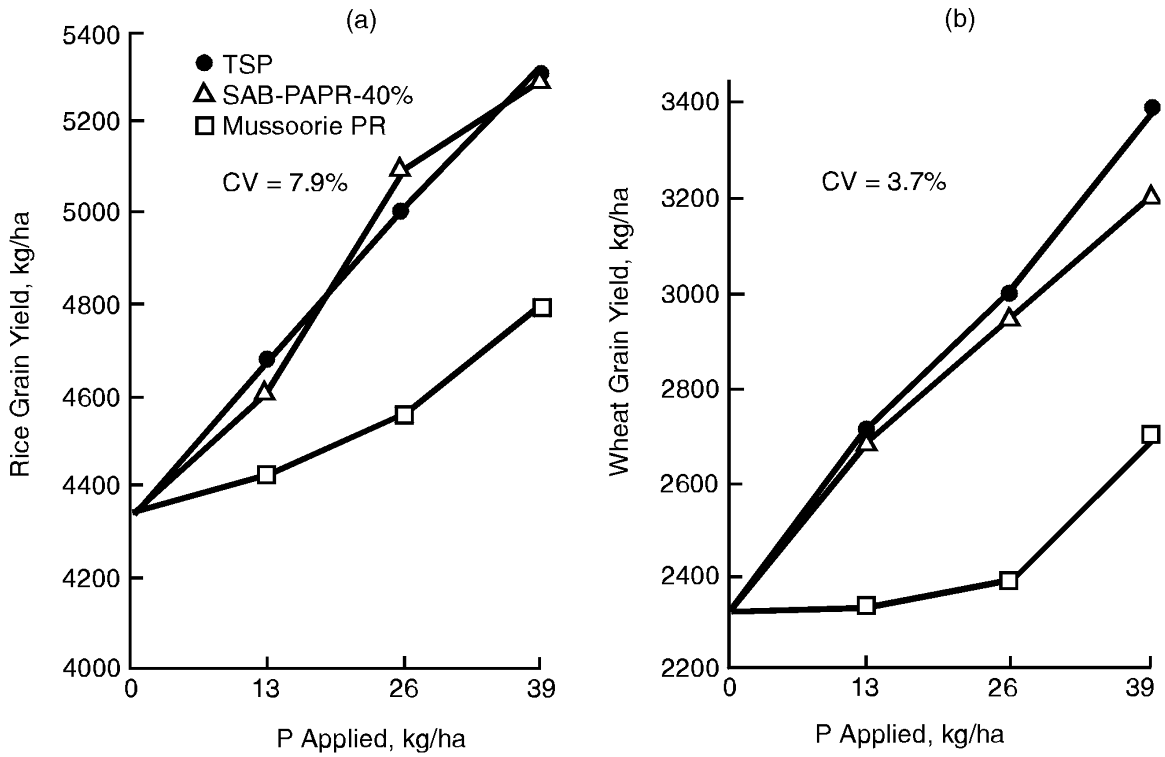

FIG. 4. Effect of partial acidulation of Mussoorie PR (India) on yields of (a) rice at Kanpur, Uttar Pradesh, and (b) wheat at Ranchi, Bihar, India [11].

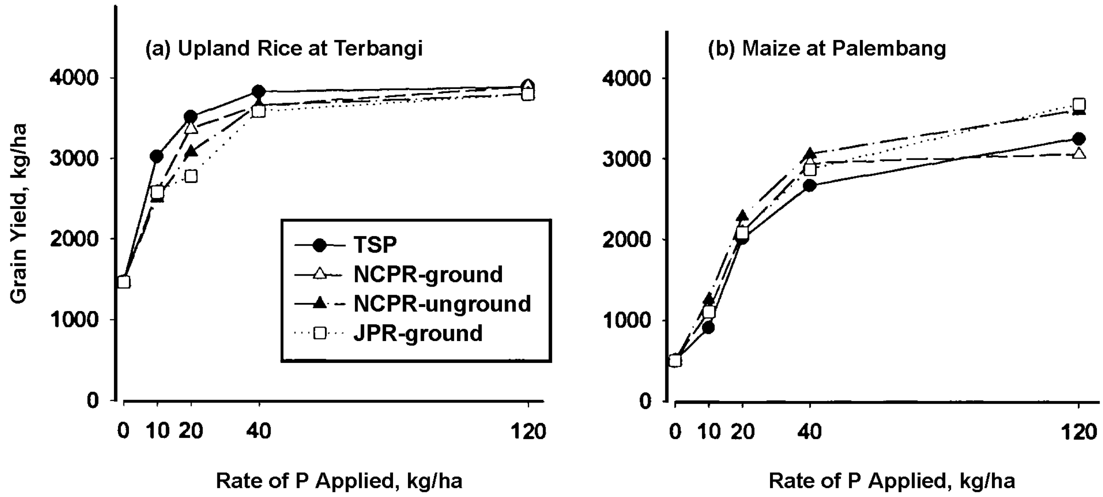

FIG. 5. Effects of P sources on grain yield of (a) upland rice, and (b) maize at two sites (Ultisols) in Indonesia [12]. Ground refers to 0.15 mm and unground to 0.425 mm.

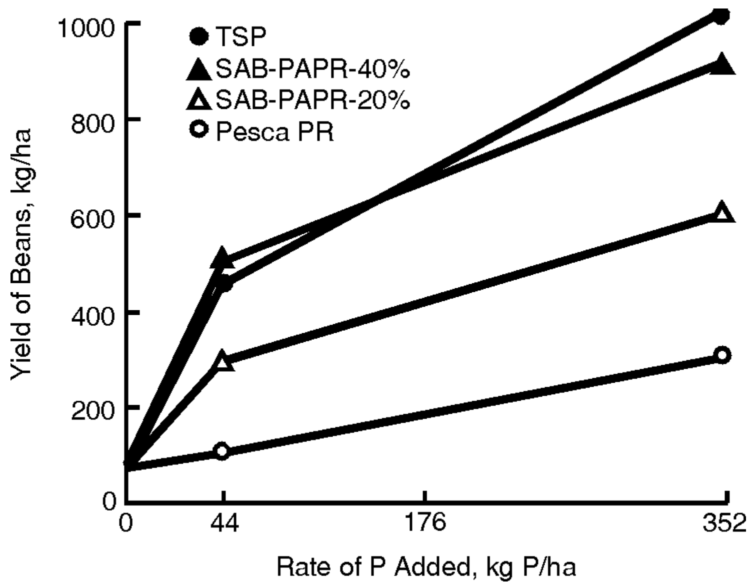

FIG. 6. Effect of partial acidulation of Pesca PR (Colombia) with H_2SO_4 (SAB-PAPR) on bean yield on an Andept [13].

2.3. Partial acidulation of PR and compaction with TSP

For PRs of low reactivity that are unsuitable for direct application, partial acidulation can be an effective and economic means of improving agronomic effectiveness. Partial acidulation refers to the use of less than the stoichiometric amount of acid, H_2SO_4 or H_3PO_4, required to completely convert the PR to soluble SSP or TSP, respectively, resulting in a product that essentially contains a mixture of unaltered PR and soluble phosphate. For example, partially acidulated PR (PAPR) produced at 40% acidulation with H_2SO_4 from the poorly reactivity Pesca PR (Colombia) was as effective as TSP in increasing bean yields on a Colombian Andept (Fig. 6) [13]. Products that are chemically equivalent to PAPR can be produced also by the process of dry compaction of PR with water-soluble P fertilisers such as SSP, TSP and monoammonium phosphate (MAP).

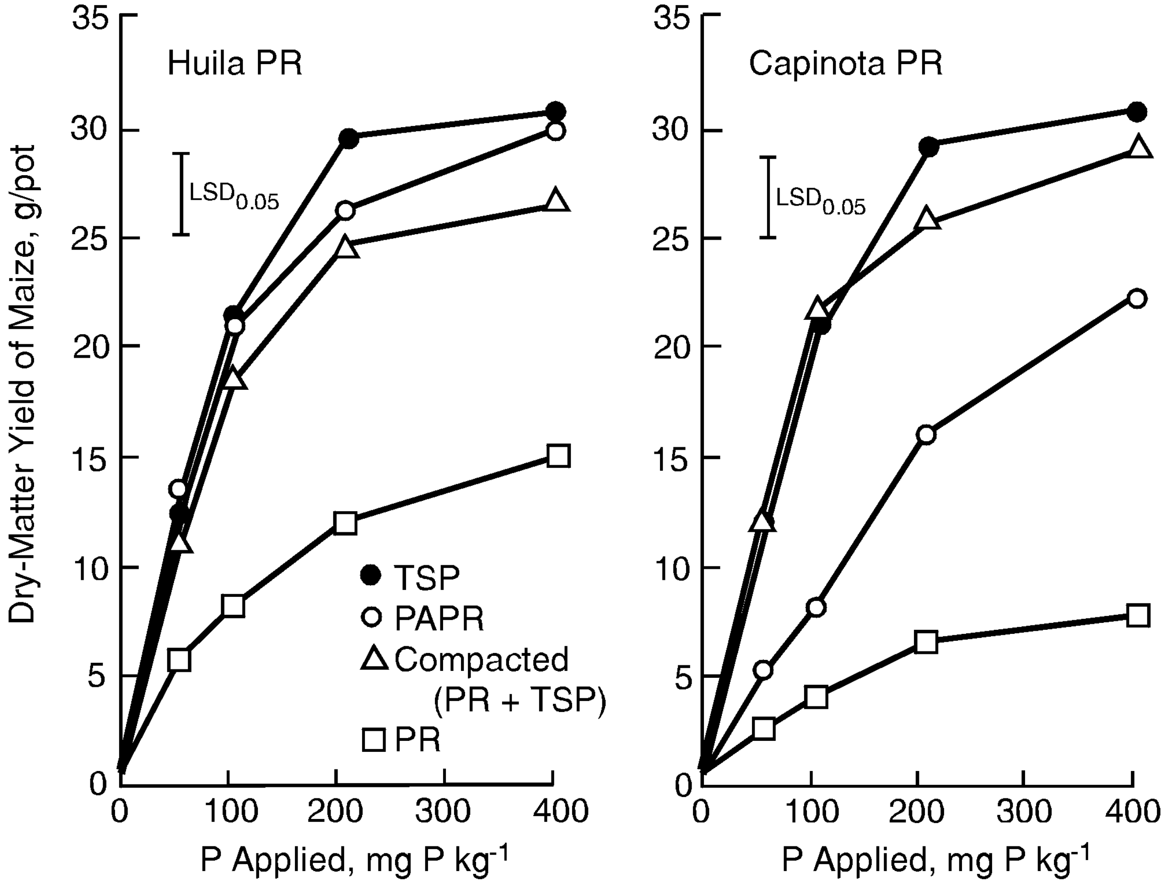

FIG. 7. Maize dry-matter yield response to PR, PAPR-50% H_2SO_4, compacted PR+TSP (50:50 P ratio), and TSP applied to an Ultisol [15].

The enhanced effectiveness of the residual PR in the PAPR, or the PR component of the compacted PAPR equivalent, is attributable to the "starter effect" of the water-soluble P component that promotes early root development, enabling the plant to use the unacidulated PR component more effectively than after treatment with PR alone [13]. Using the isotope-dilution technique with ^{32}P, it was shown that uptake of P, from a PR of medium reactivity, was increased 165% for maize and 72% for cowpea over TSP alone when the PR was mixed at a 1:1 P ratio with TSP [14].

Compacted mixtures (PR+TSP or SSP) or chemically prepared PAPRs with equal soluble-P:PR-P ratios generally have the same agronomic effectiveness if the PR does not contain significant amounts of iron (Fe) and of aluminium (Al) oxide (e.g., Huila PR; Fig. 7) [15]. However, compacted PR+TSP mixtures are more effective agronomically than PAPR for PRs of high Fe and Al oxide contents. For example, PAPR produced with Capinota PR from Bolivia (8.8% Fe and Al oxide) was much less effective than the compacted equivalent (Fig. 7). This is attributed to the reaction of H_2SO_4 with Fe and Al oxides in PR during the acidulation process, resulting in a reduction of water-soluble P [16]. On the other hand, increasing soil P-fixation capacity due to increasing Fe and Al oxide content *of the soil* increases the relative agronomic effectiveness of PAPR with respect to SSP and TSP (Fig. 8) [17] due to the interactions of PR and monocalcium phosphate (MCP) components in PAPR granules with soil Fe-Al oxide minerals [13].

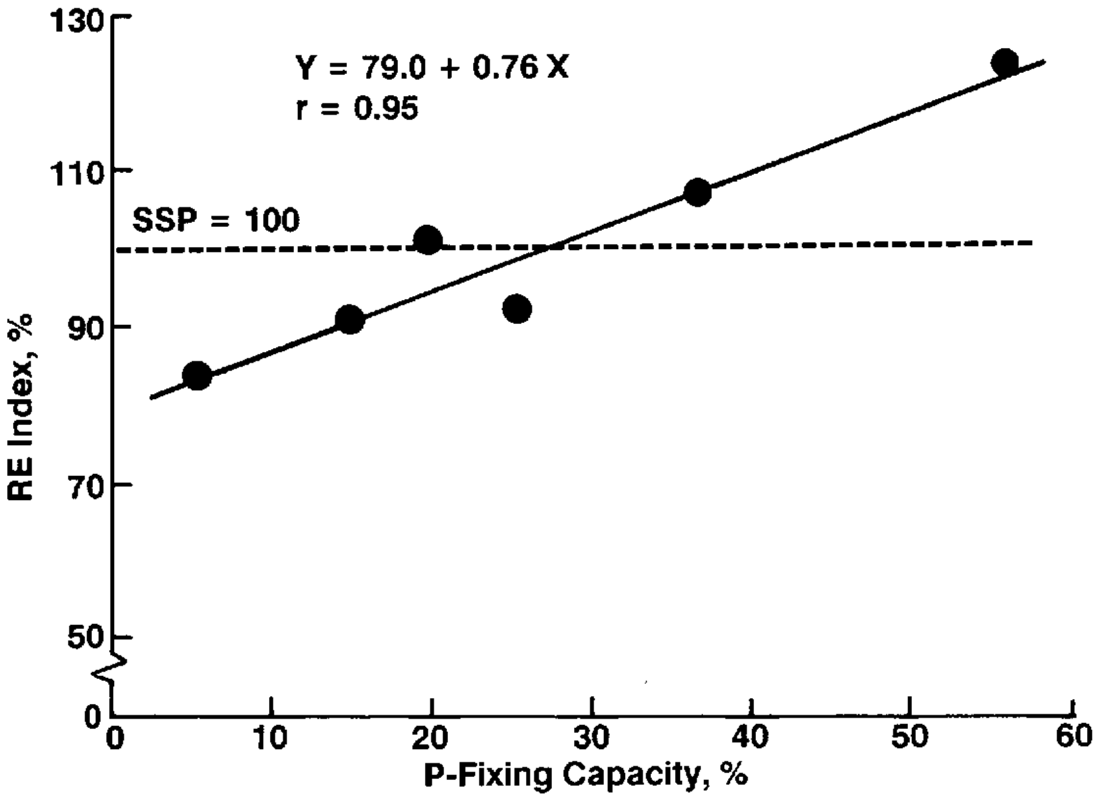

FIG. 8. Relative agronomic effectiveness (RAE) of partially acidulated Huila PR (Colombia) (50% acidulation with H_2SO_4 with respect to SSP) in increasing dry-matter yield of maize [17].

Another effective way of improving the effectiveness of PR is to broadcast and incorporate it into the soil and band a starter amount of TSP. This promotes early plant growth similar to the "starter effect" mentioned above for PAPR and compacted PR+TSP mixtures. For example, a broadcast application of 86 kg P/ha of PR plus 8.6 kg P/ha of TSP banded at planting was found to be effective for maize grown on Oxisols in Colombia for three consecutive years [6].

The agronomic effectiveness of many poorly reactive PRs in sub-Saharan Africa can also be significantly increased by partial acidulation or compaction with SSP/TSP [11]. In a greenhouse experiment using an Ultisol, Togo-PR was a completely ineffective as a source of P for maize and cowpea, whereas, when acidulated at 50% H_2SO_4 or compacted with TSP at a 50:50 P-basis ratio, the modified Togo PR was 73 to 85% as effective as SSP for maize and 88 to 97% as effective for cowpea (Fig. 9) [18]. On an Ultisol in the field in Sierra Leone, the same Togo-PAPR was as effective as SSP in increasing maize grain yield (Fig. 10) [13]. Similarly, partial acidulation of the poorly reactive igneous PRs from Dorowa (Zimbabwe) [19] and Sukulu Hills (Uganda) [20] was found to significantly increase their agronomic effectiveness. In India, 40% partial acidulation of the Mussoorie PR with H_2SO_4 rendered it equally as effective as TSP (Fig. 4) [11]. Similar results were obtained with other Asian PR sources, for example, Jamakotra PR (India) and Jiangxiang PR (China), either by partial acidulation or compaction with TSP or MAP at equal soluble-P:PR-P ratios.

The IFDC research programme on evaluation and modification of PR sources has led to adoption of these technologies in several countries. For example, with the assistance of IFDC, a fertiliser plant was built in 1998 and commercialised in Venezuela to produce 150,000 t/yr of PAPR-40% H_2SO_4 using the indigenous Riecito PR. This PAPR will supply the domestic P demand of annual crops on acid soils and will be available for exportation to the region.

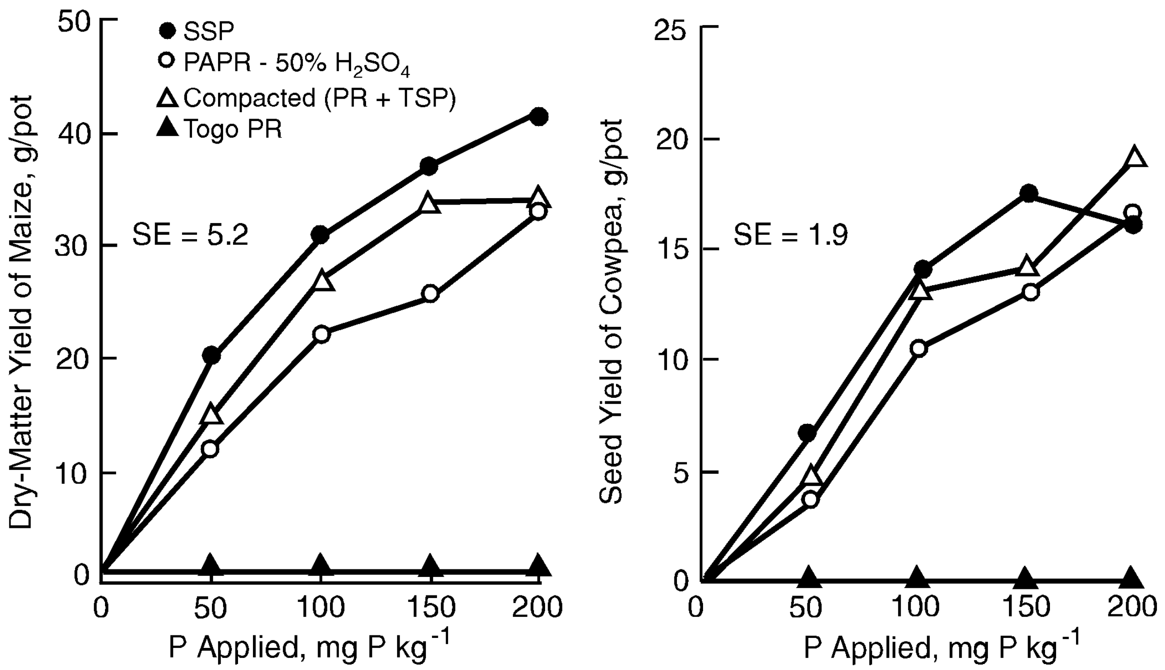

FIG. 9. Dry-matter yield of maize and cowpea grain yield response to various P sources on an Ultisol [18].

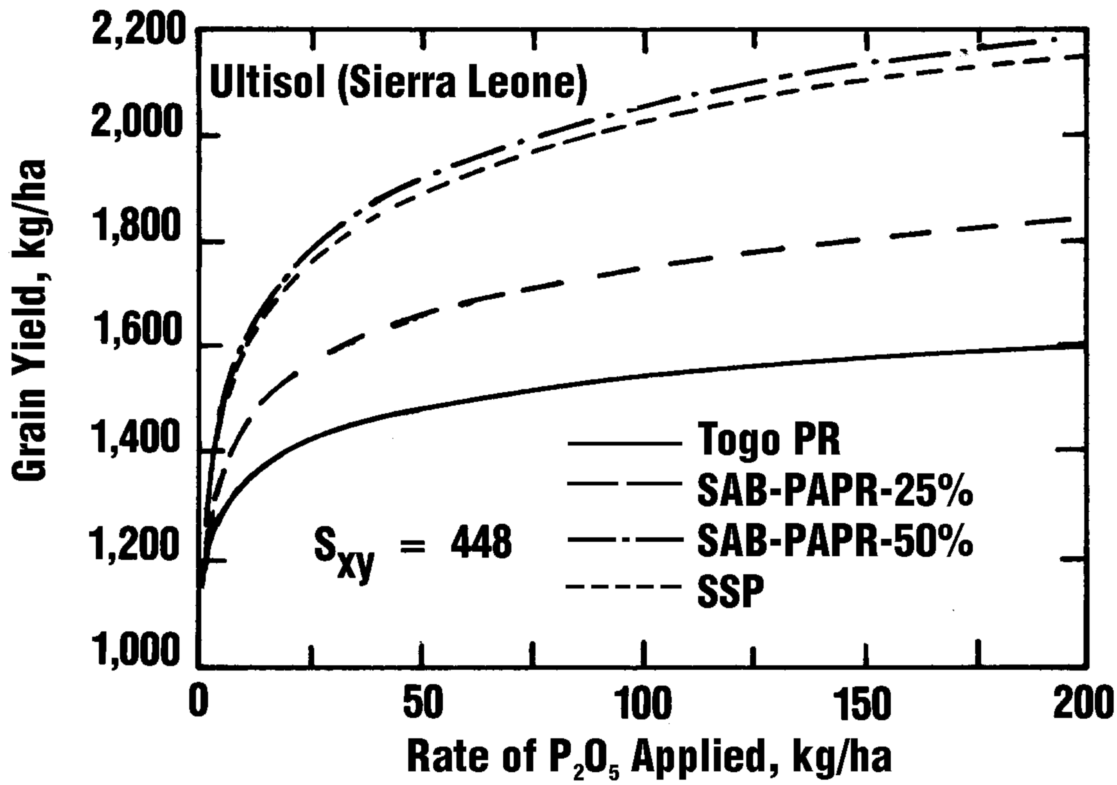

FIG. 10. Maize grain-yield response to Togo PR, Togo-PAPR, and SSP on an Ultisol in Sierra Leone [13].

TABLE I. SOYBEAN YIELDS AND AMOUNTS OF NITROGEN BIOLOGICALLY FIXED [24]

P source	Seed yield (g/pot)	Amount of N fixed (mg N/pot)	
		Seed	Whole plant[a]
Check	1	11	12
Sechura PR	12	609	892
TSP	14	784	1,170

[a]Including root, stem, leaf, pod, and seed.

2.4. Use of P-efficient crop species and varieties

Since PR and modified PR sources provide lower concentrations of P in soil solution than do their water-soluble counterparts, their optimal use may be obtained in combination with crop species and varieties that are relatively tolerant of low levels of soil-available P or that utilize soil P more efficiently. For example, cowpea requires only two-thirds of the soil-solution P concentration that maize needs to reach maximum growth potential [21]. Some crops, such as rapeseed and buckwheat, are known to extract P from water-insoluble P minerals in soils more efficiently than, for example, wheat or maize [22]. Root-induced changes in the rhizosphere, including the release of organic acids, hydrogen ions and acid phosphatases, enable such P-efficient plants to acquire P from less-available pools [23]. There is a continuing need to combine the approaches of screening of crop species/varieties and selecting P-sources varying in water solubility to maximise the utilisation efficiency of P in acid soils.

2.5. Effect of PR on biological N_2 fixation

Since mineral-N fertiliser is costly for resource-poor farmers, the cultivation of legumes – as pulses, pastures, green manures, and cover crops – is an attractive alternative for crop production. However, biological N_2 fixation (BNF) requires adequate nutrient P for nodule formation and function, and for host-plant growth. A combination of indigenous PRs with legumes could be a cost-effective means of providing both P and N for sustainable crop production in cereal/legume systems. For example, using the ^{15}N-dilution technique, it was found that Sechura PR was 76% to 78% as effective as TSP in enhancing BNF and soybean grain and biomass production on an Ultisol (Table I) [24].

2.6. Micronutrients in PR

When directly applied, PRs can be a source of micronutrients that are likely to be removed and lost in the process of soluble P-fertiliser production. Work by IFDC scientists on an Oxisol in Colombia suggested that indigenous Huila PR, which contains Zn at 136 mg/kg, produced a higher grain yield of rice than did TSP as a result of its Zn content (Fig. 3; L.L. Hammond, personal communication). In New Zealand, Sechura PR, which contains molybdenum (Mo) at 43 mg/kg, increased dry-matter yields of pasture herbage more than did TSP at sites where the PR significantly increased Mo levels in clover (Fig. 11) [25]. More information is needed on the micronutrient contents of PRs that have potential for crop production on acid soils.

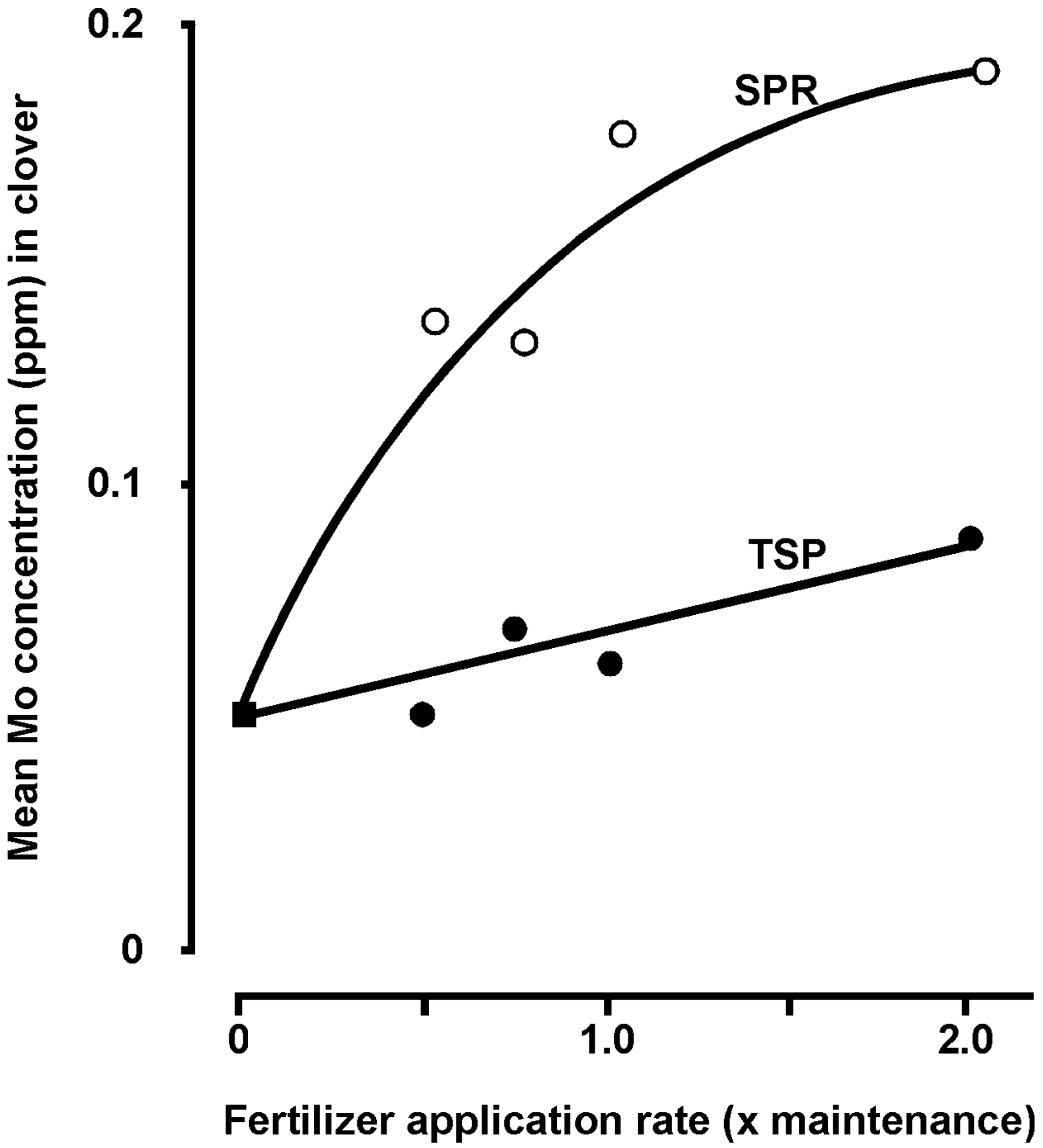

FIG. 11. Effect of Sechura PR (SPR) from Peru and TSP on Molybdenum (Mo) concentration in clover [25].

2.7. Soil acidity related to the use of PR

Among the major chemical and nutritional constraints to crop growth on acid soils are toxic levels of Al and Mn and deficiencies of Ca and Mg. Although lime is effective for alleviating these constraints, it is often unavailable or is costly to transport. Screening crop species and varieties to identify those that are tolerant of soil acidity would reduce costly lime requirements.

Phosphate rocks have liming properties and are a source of Ca for crops. This is because hydrogen ions are consumed in the dissolution (acidulation) process in soil. Moreover, PRs contain 20 to 40% structural Ca in addition to $CaCO_3$ as impurities. Research at IFDC has shown that application of medium to highly reactive PRs can result in significant liming effects on acid soils. Although the increase in pH is generally less than 0.5, the decrease in exchangeable Al can be significant if the soil pH is less than 5.5. For example, exchangeable Al was reduced from 2.0 meq/100 g to 0.40 meq/100 g when a Colombian Oxisol was treated with Sechura PR in a soil incubation study (Fig. 12a) [7]. The soil pH was correspondingly increased from 4.6 to 5.0 and exchangeable Ca was increased from 0.2 to 1.5 meq/100 g (Fig. 12b) [7]. Aluminium saturation was reduced from approximately 80% to 20%. Thus, plant-growth responses may have been due both to increased P availability and to alleviation of Al toxicity (Fig. 13) [7].

Phosphate rocks such as Huila and Capinota, which contain free carbonates, can supply nutrient Ca in addition to reducing Al saturation. The potential agronomic value of Ca in some PRs from Latin America was reported by Hellums et al. [26]. For example, Bahia Inglesa PR was found to be 90% as effective as $CaCO_3$ as a source of Ca in increasing dry-matter yield of maize when P was not plant-growth limiting (Fig. 14) [26]. More research is needed to evaluate the potential liming value of non-conventional P sources such as PR and PAPR, for crops on Oxisols and Ultisols.

The application of lime can have a detrimental effect on PR effectiveness because increases in pH and exchangeable Ca, through the common-ion effect, reduce the driving force for PR dissolution. For example, in a greenhouse study, the effectiveness of Sechura PR with Al-tolerant soybean cv. Perry decreased from 84% to 66% of TSP after an Ultisol (pH 4.8, Al-saturation 48%) was limed [27]. In a field experiment conducted in an Oxisol (pH 4.2, Al-saturation 70%) in Colombia, the effectiveness of Huila PR decreased from 70% to 57% of TSP with a local Al-tolerant soybean, cv. ICA Soyica Araria, after 1.5 t lime/ha.

On highly acidic soils, some lime application may be necessary to overcome Al toxicity in sensitive crops. On another Oxisol in Colombia (pH 4.8, Al-saturation 75%), acid-tolerant maize cv. CIMMYT SA3 was used to test the agronomic effectiveness of Huila and Capinota PRs and mixtures of PR and TSP; whereas the PRs were less effective than TSP, the PAPR or compacted PR/TSP products were as effective as TSP for the first crop after the soil was treated with only 300 kg/ha of dolomitic lime (Fig. 15). The good performance of Capinota PAPR in this study, in comparison with the poor result shown in Fig. 7 [15], suggests that the acid-tolerant maize was able to utilize effectively water-insoluble P components in Capinota PAPR. In experiments on Sumatra, Indonesia, maize responses to TSP and to medium and highly reactive sources of PR were severely limited without lime. Judicious applications based on exchangeable Al contents produced increases in maize grain yields that were similar in TSP and PR treatments.

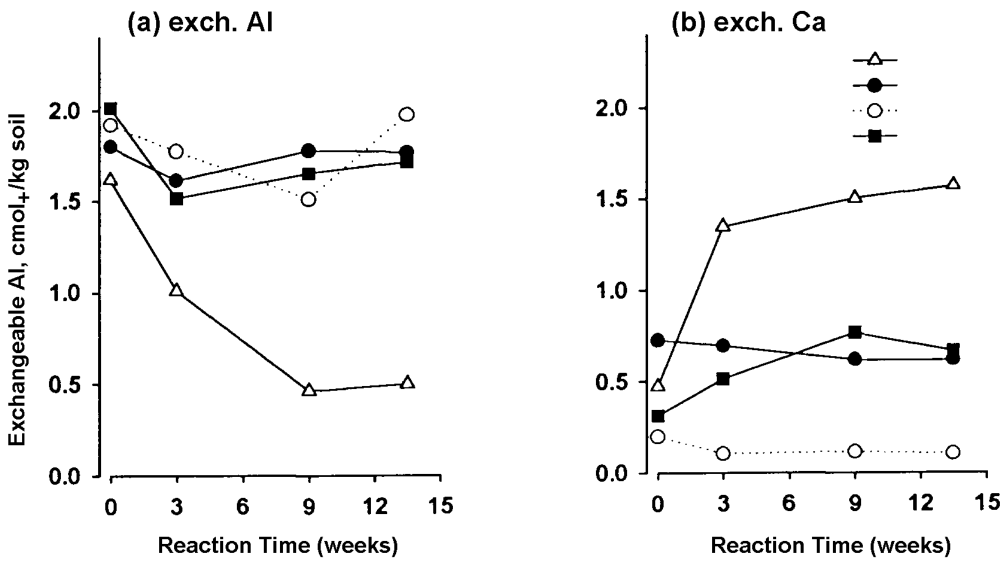

FIG. 12. Effect of P sources applied to a Colombian Oxisol on (a) soil exchangeable Al content, and (b) exchangeable Ca content [7].

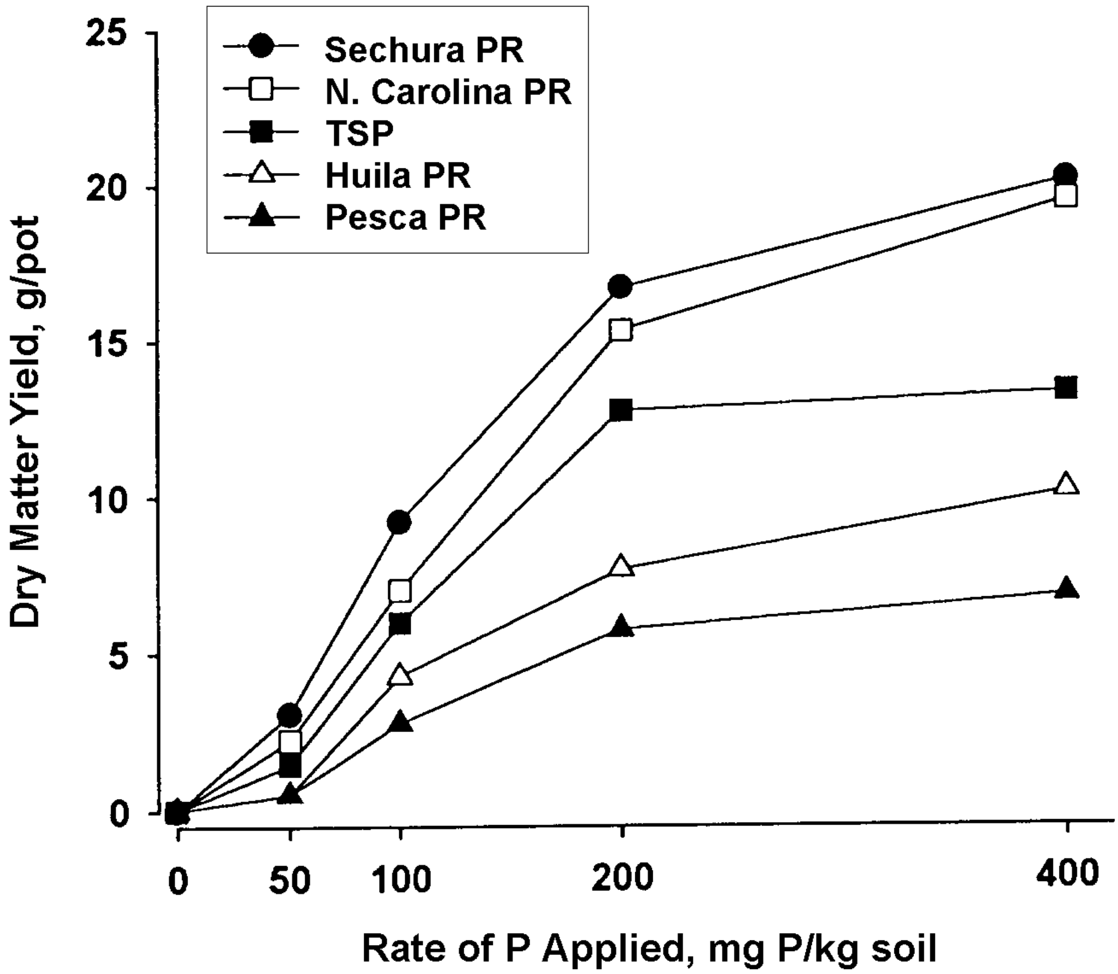

FIG. 13. Effect of P sources on Panicum maximum *dry-matter yield (sum of three cuts) on a Colombian Oxisol [7].*

The results suggest that liming is necessary for food crops grown in highly acidic soils even with PR that may have an inherent lime value. However, lime rates should be carefully chosen to avoid adverse effects on PR dissolution. Further research is required on strategies that combine the use of acid-tolerant cultivars with liming practices and management of alternative P fertilisers. Use of PR, or mixtures of PR and water-soluble P, in combination with acid-soil-tolerant cultivars that require no or minimum liming may be an alternative strategy for managing acid soils for sustainable crop production.

3. NUTRIENT CYCLING IN CROPPING SYSTEMS

Enhanced nutrient cycling is an essential facet of increased efficiency of use of nutrient inputs. The cropping system strongly influences the extent of nutrient cycling. From 1992 to 1998, IFDC collaborated with CIAT in a long-term crop-rotation and ley-pasture systems experiment on the Colombian savannahs [8, 28]. The experiment compared alternative systems based on upland rice or maize with respect to their effects on various soil properties and processes including nutrient cycling. In addition to monocultures, rice and maize were rotated with grain legumes (cowpea or soybean), green manures or improved grass-legume pasture leys. Native savannah plots were maintained for baseline comparisons. In addition, other experiments addressed the issue of residual effectiveness of P-fertiliser applications to cereal/grain-legume rotations on high P-adsorbing Oxisols.

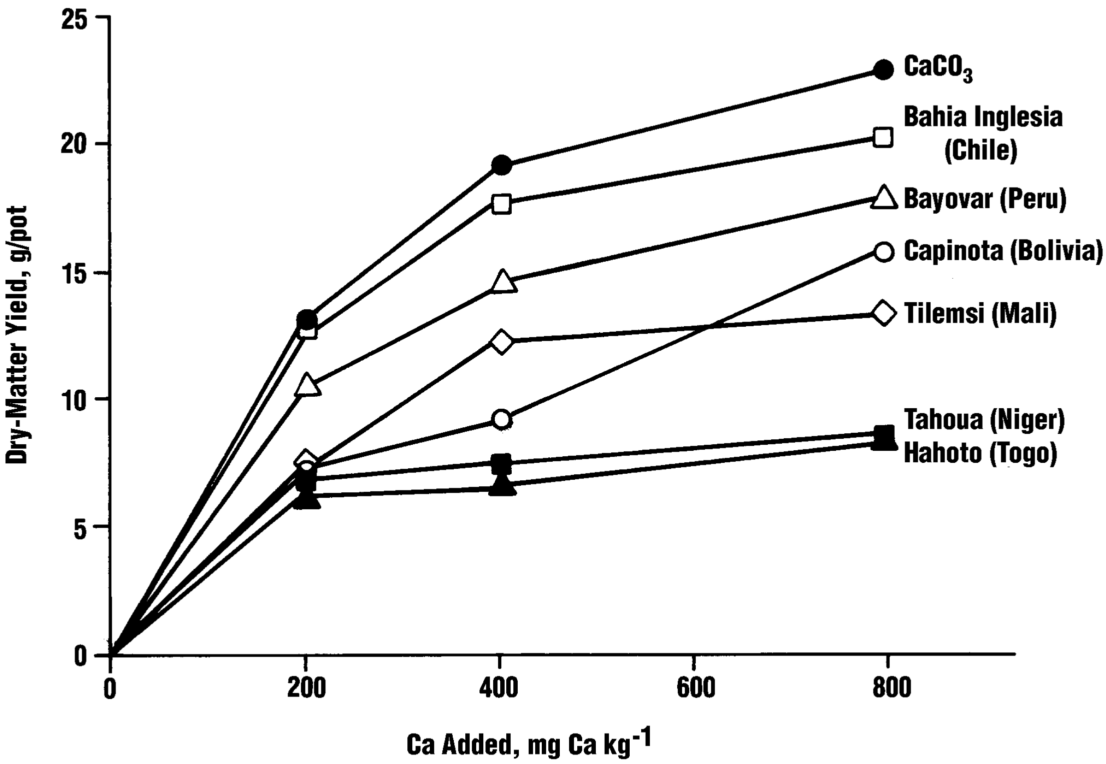

FIG. 14. Maize dry-matter yield response to various PR sources and $CaCO_3$ in an Ultisol [26].

3.1. Phosphorus cycling

Cycling of P in agro-ecosystems involves the soil organic pools and micro-organisms. Measurements of microbial and other P fractions to examine the disposition of soil P under native and improved legume-based pasture systems showed that the presence of legumes increased the general level of biological activity in the system and the content of P in the organic pools [29]. Investigations of P dynamics in crop rotations revealed transient fluxes into organic P fractions suggesting that the pools they represent are all labile. In fact, the dynamics of soil P under cropping systems suggested that P flowed preferentially into labile inorganic P pools and then more slowly into organic P pools; flows into non-labile inorganic and organic pools tended to be very slow [30]. Since P enters organic pools by plant assimilation and subsequent decay of derived residues and roots, systems such as pastures that acquire P more efficiently and produce more residues have more influence on soil organic P pools than those that do not. This contributes to increased cycling of P and the possibility of sustained pasture productivity with low P inputs despite the high P-fixing nature of the soil, possibly because P maintained in organic pools is better protected from loss through fixation than P flowing through inorganic pools in the soil.

3.2. Residual P

Measurements of residual P in highly weathered tropical soils are rare, but essential for improving the efficiency of fertiliser-P use, estimates of which frequently do not take account of build-up in soil-available P with repeated applications. The IFDC collaborative research at CIAT included long-term studies of the residual effectiveness of P-fertiliser applications in high P-fixing acidic savannah soils [8, 28]. Experiments with maize/soybean and upland-rice/cowpea rotations at two sites over a period of 5 to 6 years measured crop responses to several rates of one-time and annual applications of TSP. Fractionation methods were used to estimate flows of P among labile and non-labile inorganic and organic P pools. These data were used to parameterise a simple P-residual value model for Colombian savannah Oxisols [31]. This work showed that (a) crop requirements for P on newly opened savannah of Colombia were relatively modest, at 40 to 80 kg P/ha, despite the apparently high P-fixing capacity of the soil, and (b) soluble P fertiliser applications had a substantial residual effectiveness, losing about 30% of their value annually to succeeding crops.

3.3. Modelling P dynamics

Among the objectives of the IFDC/CIAT long-term experiments on the eastern plains of Colombia was the development of models of nutrient dynamics and cycling to enable the transfer of results to other tropical acid soils in Latin America, Asia and Africa. In collaboration with Michigan State University, the data-sets were used to parameterise and calibrate a P sub-model developed for the CERES-maize simulation model [32, 33]. Validation of the model for a wider range of soils and climatic regimes will enable agronomists to assess the potential of various P sources in various cropping systems and design methodologies that enhance the efficiency of P inputs.

4. CONCLUSIONS

Although much knowledge has been gained from extensive research on the management of phosphate fertilisers in tropical acid soils, the fact that crops recover less than 20% of applied P indicates considerable potential for improvement in P-use efficiency. Continued research effort is needed, therefore, to improve technologies to further increase crop production on acid savannah Ultisols and Oxisols in order to meet expected increased global demands for food. The major constraints for increasing crop production in these acid soils are deficiency of plant nutrients, especially N and P, Al toxicity, and high P-fixation capacity. Research involving the technologies that combine the effects of N and P management, liming practice, N_2 fixation by legume crops, and breeding for acid tolerance and/or P efficiency in sustainable cropping systems offers an effective means of achieving the goal of successful agricultural development on these tropical acid soils.

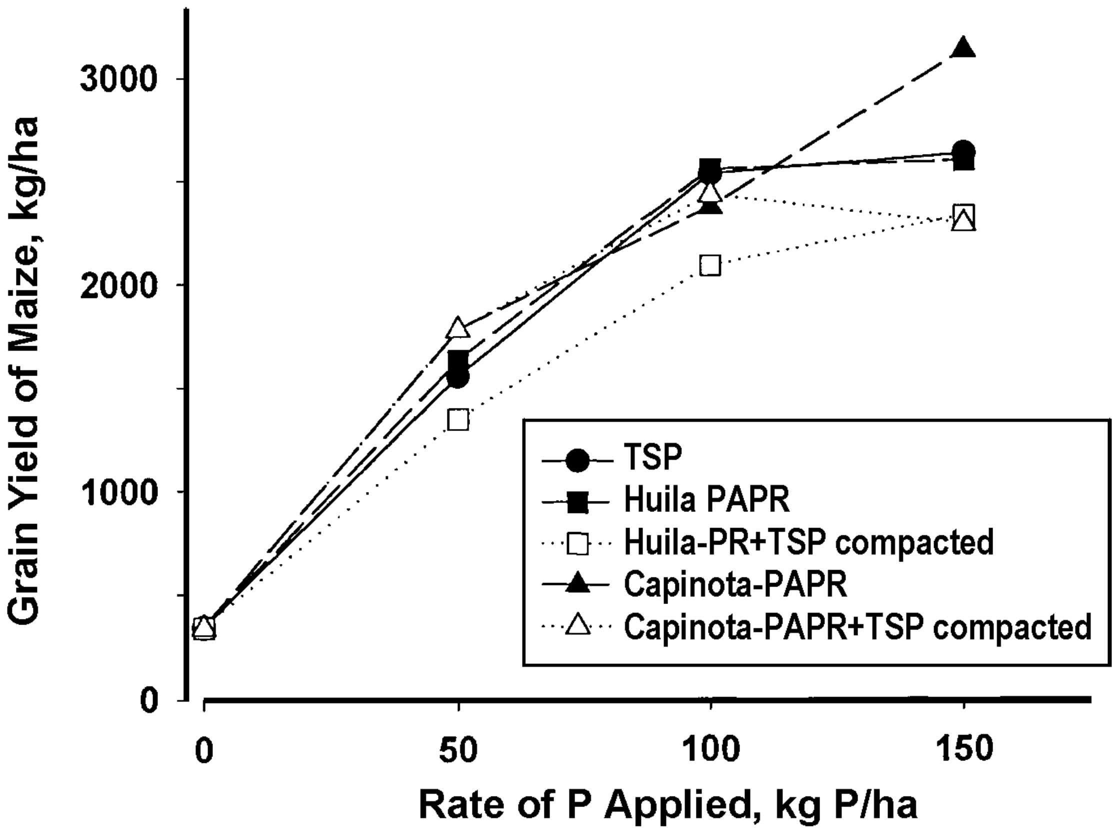

FIG. 15. Grain yield response of an acid-soil tolerant maize cultivar (CIMMYT variety SA3) to various P sources on a Colombian Oxisol (IFDC/CIMMYT unpublished report).

ACKNOWLEDGEMENTS

The research summarized in this paper represents the collaborative work of several individuals and institutions. In particular, we acknowledge the contributions of Drs. L. Alfredo Leon, L.L. Hammond, A. Bationo, D. Hellums, U. Mokwunye, R.G. Menon, R. Thomas, and A. Oberson, as well as CIAT, ICRISAT, CSR (Indonesia), and ICAR (India).

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EVALUATING AGRONOMIC EFFECTIVENESS OF PHOSPHATE ROCKS USING NUCLEAR AND RELATED TECHNIQUES: RESULTS FROM AN FAO/IAEA CO-ORDINATED RESEARCH PROJECT

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Abstract

An FAO/IAEA Co-ordinated Research Project, "The use of nuclear and related techniques for evaluating the agronomic effectiveness of phosphatic fertilisers, in particular rock phosphates," was in operation during the period 1993–98. The research network comprised twenty-three scientists, of whom seventeen were in developing countries, with six in industrialized nations. Conventional and ^{32}P-isotope techniques were utilized to assess the bio-availability of P in soils amended with phosphate rock (PR) and water-soluble fertilisers, and to evaluate the agronomic effectiveness of PR products. No single chemical extraction method was found to be suitable for all soils and fertilisers. The Pi strip method showed promising results, but more testing is needed with tropical acid soils. The ^{32}P-phosphate-exchange kinetics method allowed a complete characterization of P dynamics, and provided basic information for estimating the kinetic pools of soil P. The agronomic effectiveness (AE) of PRs depends on their solubility (reactivity), which is related to the degree of carbonate substitution for phosphate in the apatite structure. Rock phosphates of low reactivity were unsuitable for direct application to annual crops. Research in Venezuela, China, Cuba, Brazil, and Thailand demonstrated that AE can be increased by partial acidulation, or by mixing with organic materials or a water-soluble source. The AE can be enhanced also through inoculation with mycorrhizal fungi and rhizobacteria. The AE, which depends on species, is particularly high in crops such as canola and lupin that exude organic acids from the roots. Agronomic effectiveness of PR is higher on soils with low pH, low available P, low exchangeable Ca, high cation exchange capacity and high organic-matter content. The ^{32}P-techniques are powerful tools for studying the factors that affect AE. Information from field trials was used to create a database for validating a model for providing recommendations for PR application.

1. INTRODUCTION

Phosphorus (P) is vital for the growth of plants, and its deficiency in soils can severely restrict crop yields. It is absorbed from the soil solution mainly as monovalent and divalent orthophosphate anions. The predominant forms of P in soils depend on complex physico-chemical reactions determined by the pH and specific soil components.

Deficiency in P is widespread in tropical acid soils. Moreover, low plant-availability of P is common, due to the reactions mentioned above, for example with free calcium carbonate in calcareous soils. Under such circumstances, applications of phosphatic fertilisers are required for optimum crop growth and adequate production of food and fibre.

Commercial phosphatic fertilisers are available mainly as superphosphates produced by treating phosphate rocks (PRs) with sulphuric (single superphosphate) or phosphoric (triple superphosphate) acid. The main nutrient compound present is the water-soluble monocalcium phosphate, which is available to plants. In many developing countries, these fertilisers must be imported using valuable foreign currency, and supplies to farmers in rural areas frequently are limited. On the other hand, many developing countries with P-deficient acid tropical soils have deposits of PR. Thus, the constraint of the low P in these soils can be removed, at least partly, by direct application of PR as an inexpensive alternative for resource-poor farmers [1].

It is necessary to evaluate the agronomic effectiveness (AE) of PRs with respect to commercially available superphosphate. Isotope techniques, using ^{32}P, provide reliable, accurate data on aspects of phosphate-fertiliser management and, in general, of the behaviour of P in soil and soil-plant systems [2, 3, 4]. These were the basic considerations when a research project on phosphate was conceived in

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1991, prompted by then-recent developments in the enhancement of AE of PR, which needed to be evaluated in a network of field trials. The objectives and work plan were defined in a Consultants Meeting in Vienna, in May 1993. The title of the project was FAO/IAEA Co-ordinated Research Project (CRP) on "The Use of Nuclear and Related Techniques for Evaluating the Agronomic Effectiveness of P Fertilisers, in Particular Rock Phosphates."

This paper reviews the strategies and experimental approaches followed in the implementation of that project, as well as the main findings. This information is relevant to the new CRP on tropical acid soils, which will continue research in a broader perspective with the ultimate goal of sustainable agricultural production by improving the fertility of tropical acid soils.

2. FAO/IAEA CO-ORDINATED RESEARCH PROJECT ON "THE USE OF NUCLEAR AND RELATED TECHNIQUES FOR EVALUATING THE AGRONOMIC EFFECTIVENESS OF PHOSPHATE FERTILISERS, IN PARTICULAR ROCK PHOSPHATES" (1993–98)

2.1. Rationale

Soils in the tropics, i.e. in many developing countries, are often deficient in available P, and, therefore, require inputs of P fertilisers for optimum production of food and fibre.

In making P-fertiliser recommendations for developing countries, the availability of supplies and cost of procurement should be considered within the context of Integrated Plant Nutrients Management, which FAO/IAEA and others are actively supporting. This implies the development of an effective and economic phosphate-management programme, in which the use of PR deposits plays a key role.

Phosphate-rock deposits exist in many developing countries of Asia, Africa and Latin America. Direct application after pulverization is among the cheapest means of supplying P to crops in tropical acid soils.

Some PRs are better – i.e. more reactive – than others. Several factors influence how readily they supply P to crops. Also, quantifying the P-availability from PRs in soil, in a variety of crop management and environmental conditions, is imperative for making fertiliser recommendations for maximum agronomic and economic returns. ^{32}P techniques are useful for such studies.

Various ways of enhancing the reactivity of PRs existed, but there was need for testing and evaluation across a network. Of particular relevance was the use of PR-based products, the exploitation of crop-genotypic differences in P uptake and utilization, and the use of micro-organisms alone and in combination with organic materials.

2.2. Objectives

The objectives of the CRP were to:

- To assess the initial available soil-P status and monitor changes after amendment with PR products and water-soluble P fertilisers, in a variety of agro-ecosystems using conventional (chemical) and isotopic techniques,
- To quantitatively evaluate the uptake and utilization of P fertilisers, in particular PR-based products, by crops under a variety of soil and climatic conditions; thus, the project aimed at evaluating AE of natural PR deposits and, where necessary, at devising means of enhancing their effectiveness,
- To obtain agronomic and economic recommendations on the use of P fertilisers, in particular PR-based products.

2.3. Implementation

The research network comprised twelve Contract Holders, from Brazil, China, Chile, Cuba, Ghana, Indonesia, Kenya, Malaysia, Romania, Thailand, Venezuela and Viet Nam, and six Agreement Holders from USA (IFDC and TVA-NFERC), France (CIRAD and CEA/CEN-Cadarache), Australia (CSIRO) and Spain (CSIC). Five additional contractors from Belarus, Hungary, Lithuania, Poland, and Russia were included through the generous support of the French Government. The participants, titles of the projects and key words related thereto, are shown in Table I.

2.3.1. Work plan

The work plan was implemented in three phases, which were decided at the Research Co-ordination Meetings (RCM) of the network scientists:

– Phase 1 was between the first RCM (held in Vienna, November 1993) and the second (Montpellier, April 1995), during which period the main activities were soil sampling, site selection, and soil and local PR characterization; initial (laboratory and greenhouse) studies; staff training in ^{32}P techniques,
– Phase 2, was between the second and third (Vienna, March 1997) RCMs; greenhouse and field experiments were done, using ^{32}P techniques for evaluating the AE of PR-based products,
– Phase 3, was between the third and fourth (Vienna, November 1998) RCMs; greenhouse and field experiments were completed on the enhancement the AE of PRs; larger field trials evaluated management practices for PR and effects on crop yields; standard characterization of soils and PRs used in the CRP were completed.

2.3.2. Methods

Conventional and ^{32}P techniques were used as follows:

– Several chemical extraction methods for soil-P testing were variously employed by the participants; resin and Pi-strip methods were tested also,
– The ^{32}P-phosphate-exchange kinetic method (P-32 PEK) was utilized for the characterization of soil-P dynamics and as a reference for cross-comparisons with conventional methods [3, 5],
– ^{32}P-dilution methods were used in the greenhouse and field studies [6–10],
– As an additional activity with the financial support of IMPHOS, the standard characterization of soils and PRs utilized in the network was made in selected laboratories engaged in routine analysis of these materials, to improve the comparability of the results.

2.3.3. Main features

The main features of the project, many of which were drafted at a Consultants Meeting in May 1993 before the start of the project, can be summarized as follows:

– Focus on representative (bench mark) tropical acid soils of low fertility,
– Focus on integrated plant-nutrition management,
– Sustainability and use of locally available natural resources,
– Testing technologies for enhancement of the AE of natural PR sources,
– Close collaboration with IFDC, CIRAD, IMPHOS, TVA, and Latin American PR network,
– Support (research, training and services) from the IAEA Laboratory (Seibersdorf), CEA/CEN Laboratory (Cadarache), IFDC, CIRAD, and IMPHOS,
– Extra-budgetary resources were provided by the French Government and IMPHOS,
– Validation of a soil P sub-model for inclusion in the IBSNAT crop models and for providing better P fertiliser recommendations of major food crops in developing countries.
– Standard characterization of soils and PRs utilized in the network.

TABLE I. LIST OF PARTICIPANTS IN THE PHOSPHATE CRP, AND TOPICS OF STUDY

Participant/Institute/Country	Title of project	Key words
Ms.Zaharah ABDUL RAHMAN Dept. Soil Science, Universiti Putra Malaysia, Serdang, Selangor, MALAYSIA	Evaluation of current and residual effects of natural PRs on annual crops on highly weathered soils of Malaysia.	Ultisols, Oxisols, maize, oil palm, natural & imported PRs, direct & residual effects, organic amendment, field & greeenhouse studies, ^{32}P, PR solubility, available P.
Mr. Eduardo CASANOVA Insituto de Edafología, Fac, de Agronomía, UniversidadCentral de Venezuela, Maracay, VENEZUELA	Studies on the agronomic effectiveness of Venezuelan PRs using isotopic techniques.	Ultisols, Oxisols, maize, sorghum, local natural PRs and PAPRs, avail. P, greenhouse field evaluation, P solubilising m.o., ^{32}P, available P.
Mr. José HERRERA ALTUVE Lab de Técnicas Nucleares y Biofertilizantes. Instituto Superior Agrícola de Ciego de Avila, CUBA	Studies on alternative P fertiliser sources for cropping systems grown in red ferralitic soils using nuclear techniques.	Alfisols, sugar cane, common bean, soybean, local and imported PRs, field evaluation, ^{32}P, available P.
Ms. Nancy KARANJA Department of Soil Science University of Nairobi, Nairobi, KENYA	Effect of mycorrhizal and rhizobia inoc'n on N fixation, P uptake and growth of *L. leucocephala* and *G. sepium* with PR and TSP.	Andosol, Acrisol,, N fixing trees, mycorrhiza and rhizobacteria inoc'n, Minjingu PR, ^{32}P, pot evaluation.
Ms. Jittiwan MAHISARAKUL Nuclear Research in Agric. Laboratory, DOA, Div. Agric Chem., Bangkok, THAILAND	Assessment of the relative agronomic effectiveness of PRs in a maize/soy rotation using isotopic techniques.	Ultisols, Inceptisols, local and imported PRs, mixture PR+TSP, greenhouse, field evaluation.
Mr. Takashi MURAOKA Soil Fertility Section, Centre for Nuclear Energy in Agric., USP, Piracicaba, BRAZIL	Agronomic evaluation of Brazilian PRs in tropical soils using nuclear and related techniques	Ultisols, Oxisols, rice, soybean, cowpea, eucalyptus, local natural and modified PRs, mixtures PR+TSP, greenhouse evaluation.
Ms. Inés PINO Dpto.Aplicaciones Nucleares Comisión Chilena de Energía Nuclear, Santiago, CHILE	Development of strategies for increasing the effectiveness of PRs in volcanic soils by means of isotopic techniques.	Andosols, Ultisols, wheat, rape, lupin, local and imported PRs, mixtures PR+TSP, greenhouse evaluation.
Ms. Elsje SISWORO Center for Appln. Isotopes and Radiation, Jakarta, INDONESIA	Studies on the direct and residual effect of PR materials in upland and lowland soils using nuclear and related techniques	Entisols, Ultisols, upland rice, soybean, mungbean, maize, local and imported PRs, mixtures PR+TSP, greenhouse and field evaluation.
Mr. Li Ming XIONG Dept of Soil Plant Nutrition Chemistry. Inst. Soil Sci., Nanjing, People's Republic of CHINA	Phosphorus dynamics and its availability of alternative fertilisers applied to sustainable agro-ecosystems in southern China.	Alfisols, Ultisols, Oxisols, greenhouse evaluation, plant species, ^{32}P, available P, mixture PR+TSP.
Mr. Rudolf ALEXAKHIN Russian Institute of Agricultural Radiology and Radioecology (RIARAE) Obnisnk, Kaluga Region, RUSSIAN FEDERATION	Studies on the effectiveness of rock phosphates as agricultural countermeasures in soils contaminated by radionuclides	Greenhouse evaluation, barley, local PRs, ^{137}Cs, ^{90}Sr, countermeasure, direct and residual effect, P forms fractionation.
Mr. Iossif BOGDEVITCH Belorussian Research Inst. for Soil Sci. and Agrochemistry, (BRISSA), Minsk, Rep. of BELARUS	Comparative evaluation of the effect of phosphate fertilizers:PR and monoammonium phosphate on plant P nutrition in mineral and peat soils	Histosols, Spodosols, lupin, rye grass, ^{137}Cs,^{90}Sr, countermeasure , pot evaluation, local PR, available P.

TABLE I (cont.). LIST OF PARTICIPANTS IN THE PHOSPHATE CRP, AND TOPICS OF STUDY

Participant/Institute/Country	Title of project	Key words
Mr. Zenoviu BORLAN Research Institute of Soil Science and Agrochemistry, Bucharest, ROMANIA	Soil conditions promoting and restraining agronomic effectiveness of water-insoluble phosphate sources, in particular PRs	Alfisols, Mollisols, rye grass, sunflower, maize, imported PRs, foliar application, PR solubility.
Mr. Marius FOTYMA Dept. Soil Fert. & Fertil'n, Inst. Soil Sci. & Plant Cultivation, Pulawy, POLAND	Evaluation of fertilisers, particularly PR, derived from soil phosphorus by biological and chemical methods.	Available P, chemical methods, imported PR, laboratory work.
Mr. Tamas NEMETH Dept. Plant Nutrition & Agric. Chem., Res. Inst. for Soil Sci. & Agric. Chem., Budapest, HUNGARY	Long-term evaluation of phosphate fertilizers in acid soils of Hungary.	Long term field trials, Ultisols, winter wheat, maize, spring and winter barley, pea, crop rotations, imported PR, SSP, available P, P balance, initial and residual effects.
Mr. Gvidas SIDLAUSKAS Dept. Agric. Chem., Lithuanian Inst. of Agriculture, LITHUANIA	Studies on the effect of liming on the agronomic effectiveness of Maardu PR.	Field evaluation, local PR, liming effect, fodder beet/barley rotation.
Mr. José Miguel BAREA Departamento de Microbiología, Estación Experimental del Zaidín, Granada, SPAIN	Isotope-aided experiments to evaluate interactions between arbuscular mycorrhiza and phosphate solubilising bacteria to improve PR utilization by crop plants	Inceptisols, greenhouse and field evaluation, legumes, intercrop, agrowastes, arbuscular mycorrhiza fungi (AMF), P solubilising bacteria (PGPR).
Mr. Sen H. CHIEN R & D Division. IFDC, Muscle Shoals, AL, USA	Evaluation of available phosphorus from alternative phosphate fertilisers applied to acid soils.	Ultisols, Available P, Pi strips, PAPR, mixtures PR-TSP, cowpea, maize, greenhouse, Cd uptake.
Mr. Jean Claude FARDEAU Dept. Plant Physiology & Ecosystems, CEN Cadarache, CEA, FRANCE	The use of P-32 isotopic exchange technique in the evaluation of the agronomic effectiveness of rock phosphates.	P-32 PEK, available P, Pi strips, P dynamics, P fixation, E value, laboratory and greenhouse evaluation, prediction AE of PR, modelling soil P pools.
Mr. Michael McLAUGHLIN / Mr. Daryl STEVENS Division of Soils, CSIRO, Glen Osmond, South AUSTRALIA.	Isotopic and conventional procedures to determine availability of P, Cd and F in soils and crops fertilised with soluble P fertilizers and reactive phosphate rocks.	Acid soils, pastures, PRs, available P, E value, laboratory evaluation, Cd and F uptake, modelling, field network.
Mr. Frank SIKORA Soil Testing Lab., Univ. of Kentucky Lexington, KY, USA.	Kinetics of PR dissolution as related to land reclamation and other environmental concerns.	Soil remediation, PR liming effect, revegetation, soil amendment, acid mine drainage treatment.
Mr. TRUONG BINH / Mr. Denis MONTANGE Centre de Cooperation Internationale en Recherche Agronomique pour le Developpement (CIRAD/CA) Montpellier, FRANCE	Soils and PRs mineralogical, chemical and physico-chemical characterization.	Soils, available P, laboratory and greenhouse evaluation, PRs characterization, mineralogy, chemical composition, particle size.

TABLE II. SUMMARY OF SOIL-TEST P RESULTS FROM THE PHOSPHATE CRP

Country	Soil type	PR studied	Standard extract	P availability indices studied	Good (o), over (+), or under (-) estimate avail. PR-P vs.TSP	Yield or P uptake vs. soil-P test
Venezuela	Ultisols, Oxisols	Riecito Monte Fresco	Bray 1	Bray 1 E_1	+	Yes
Cuba	Alfisols	Trinidad de Guedes La Pimienta; Riecito, NCPR	Oniani	Oniani Bray 1 E_1	+ -	
Brazil	Ultisols, Oxisols	Patos, Yoorin, and NCPR	Mehlich I	Resin Bray 1 Mehlich III E_1	.o o o	
Chile	Andolsols	Bahia Inglesa Bayovar; Imphos PRs	Olsen	Bray 1 Mehlich 1 Olsen Pi E_1	+ + o +	
Malaysia	Ultisols	NCPR, Tunisia, Jordan, Morocco, Christmas Island China	Bray 2	Bray2 Pi Exch. Ca 0.5 *M* NaOH L value E_1	+ o o o o o	Yes
China	Wide range from the sub-tropics	China	Olsen (U.S.)	E_1 Cp Bray 1 Mehlich III Olsen+NH_4F	(- or +,?) (- or +,?) + + o	Yes
Australia	Several of a National Reactive PR project	NCPR, Partially acid. NCPR	Bray 1	Bray 1 Resin Colwell E_1	o o o Moderate o	Yes
IAEA	Several			Pi vs. E_1	Good to not so good, bkg P	
USA	Ultisol	NCPR	Mehlich III	Bray 1 Mehlich III	+ +	

3. MAIN RESULTS

During the final RCM in November 1998, conclusions and recommendations were drawn up by four working groups, on the following main topics: i) P-availability studies, including environmental issues, ii) agronomic effectiveness of P fertilisers, iii) field evaluation of P fertilisers, and iv) phosphate studies in Eastern Europe. All were compiled in the Final Report of the project [11]. Issues that are relevant to tropical acid soils are reported here. The specific findings obtained by the participants in the project will be published by the IAEA. References are given to the methodologies utilised.

3.1. P-availability studies

The adequacy of several chemical-extraction methods for determining available soil P was examined using the ^{32}P method as the reference. The results of the participants working with tropical acid soils are summarized in Table II. The soils were Ultisols and Oxisols with exception of the Alfisols of Cuba.

With regard to the chemical extractants, it was found that in most cases Bray 1, Bray 2, Oniani, Mehlich I, Mehlich III over-estimated available P in PR-amended soils compared to water-soluble P fertilisers, whereas E_1 (isotopic), resin, Olsen, Pi, Exch.Ca, 0.5 *N* NaOH, NH_4 hepta-molibdate, and Colwell provided good estimates of P availability in PR-amended soils compared to water-soluble P fertilised soils. In the high P-fixing Oxisols of Brazil, Bray 1 and Mehlich III performed well in PR-amended soils. In the near neutral Alfisols of Cuba, Bray 1 under-estimated P availability in PR-amended soils compared to water-soluble P fertilised soils.

It was concluded that no single test is valid for universal use to estimate available P in soils amended with PR and water-soluble P fertilisers. However, the Pi test, which worked well in previous laboratory and greenhouse studies at IFDC [12, 13], compared well with E_1 (Malaysia). A modification of the method, 0.02 *M* KCl instead of 0.01 *M* $CaCl_2\,2H_2O$, was made for use in soils treated with PR and superphosphate [14]. Precautions are needed to avoid background P concentrations in the reagents, and to completely remove any soil particle from the strips.

The P-32 PEK method was valuable for assessing P dynamics in soil with or without the addition of P fertiliser. It provided a good description of soil-P status, i.e. intensity (C_p), quantity (E_1) and capacity (Q) factors. [3, 5]. The soil P-fixation capacity can be determined from these measurements [15]. The evaluation made after about 1 month of incubation can predict the AE of P fertilisers [4]. Furthermore the method can be used to identify various kinetic pools of soil P [16].

This isotopic method was applied to almost all soils used in the network [16, 17]. The E_1 value was used as a reference for cross comparisons of P-availability studies. Errors were found to be significant in determining E_1 values due to very low C_p values that can occur in low-available P or high-P-fixing soils (Australia, Chile, China, Venezuela).

It was concluded that the desirable criteria for a chemical extractant method for available P are:

– Rapid, reproducible, and sensitive to changes in Quantity and Intensity,
– It extracts a similar proportion of bioavailable P (Q/I) across a range of crops, soils, and management practices.

More work is needed with tropical acid soils.

Several recommendations were made for performing these P-availability studies [11].

3.2. Evaluation of the agronomic effectiveness of P fertilisers

This assessment was made in greenhouse and field conditions, using conventional and ^{32}P-dilution methods. The relative agronomic effectiveness (RAE) was measured in terms of response (dry matter, total-P uptake or P derived from the fertiliser) using a standard fertiliser of comparison, usually triple superphosphate [18]. Also the AE was evaluated through the use of substitution ratios, i.e. the number of kg P as PR that are equivalent to 1 kg P as superphosphate [2, 9]. Initial studies evaluated the AE of natural PRs and follow-up investigations attempted to enhance the AE of the PRs through several processes.

The results were analysed as a function of the main factors affecting the AE of the PRs applied directly to soil [19]:

(1) Inherent characteristics of the PR:
  - Most PRs used in the network were of sedimentary origin. The most important characteristic was the P solubility, which depends on the degree of carbonate substitution for phosphate in the apatite structure. This information can be obtained from mineralogical analysis and total chemical composition, or the solubility indices (measured by 2% citric acid or 2% formic acid);

(2) Soil characteristics:
  - The main soil groups included in the evaluation tests were Inceptisols, Alfisols, Mollisols, Spodosols, Ultisols and Oxisols, which exhibited a wide range of characteristics. Utilization of PR was most effective in soils of pH <5.0), low available soil P, high CEC and low exchangeable Ca and high organic matter content. These characteristics greatly affected the dissolution of PRs and, consequently, their effectiveness;

(3) Plant factors influenced P uptake and utilization from soil and fertiliser:
  - The RAE of natural PR and modified PR-based products depended on the rate of P applied and crop species. PRs were more effective with crops of long growth cycle, or with subsequent crops in a rotation, N_2-fixing crops, and with crops – canola, lupin, etc. – that exude organic acids from the roots. The strategy recommended was to identify species/cultivars/lines that can efficiently use the P from PRs, and include them in the crop rotation for improving the P status of the soil/plant system.

Low- to medium-reactive PRs are not suitable for direct application to crops, but their AE values can be greatly enhanced by partial acidulation, by granulating PR and superphosphates, by mixing the PR with a water-soluble P source or organic materials, as shown in Venezuela (Ultisol and Oxisol), China (Ultisol), Cuba (Alfisol), Brazil (Ultisol and Oxisol), and Thailand (Ultisol). This enhancement effect has been demonstrated in the USA by means of ^{32}P techniques [18].

The AE of PR can be enhanced also through biological approaches, such as i) the identification of plant genotypes with efficient P acquisition and their inclusion in crop rotations, as done in China and Chile, ii) the inoculation of trees with mycorrhizal fungi and P solubilising bacteria, as shown by the work done in Spain (shrubs) and Kenya (small N_2-fixing trees), iii) the use of mixtures of PRs with composting/fermentation products of agricultural wastes.

Several areas of further research were identified and recommended [11].

3.3. Field evaluation of P fertilisers, in particular phosphate rocks

Field experiments were located in a network of selected locations (bench mark soils) to study the interactive effects of soil, climate, and crop-management factors on the AE of PRs.

Though laborious and time-consuming, such trials should be established in on-farm trials in farmers' field, or on experiment sites with conditions close to those encountered by local farmers. They should be done at the cropping-system level to gather information on immediate and residual effects of PRs. Information thus obtained can be used to demonstrate impact over time and economic benefits.

Field trials were also carried out to validate the P sub-model for integrating soil, plant and climatic conditions and for extrapolating the results to other agro-ecological conditions. A set of data from these experiments was collected and a database is in preparation to further validate the P sub-model in selected locations.

The main features of the field trials were as follows:

– Different PR-based products such as natural PR, partially acidulated PR, PR+SSP, PR+TSP were evaluated. The effects of inoculating mycorrhiza and rhizobacteria on AE of PR were studied, also, one experiment included the use of organic amendments,
– Field experiments were carried out on a wide variety of soil types, but most were low in pH and in available P,
– Climatic conditions ranged from tropical to temperate, and all experiments were under rainfed conditions; application of P fertilisers including PR gave a good responses,
– A variety of plant species was utilized to measure the P-fertiliser efficiency, viz. maize (Venezuela, Hungary), sorghum (Venezuela), sugar cane (Cuba), lowland rice (Indonesia), upland rice (Brazil), soybean (Brazil), common bean (Cuba), cowpea (Brazil), winter wheat (Hungary), pastures (Australia), buckwheat (China), barley (Russia, Lithuania, Hungary), pea (Hungary), beet (Lithuania), eucalyptus (Brazil), pine (USA), fast-growing trees (Kenya), soybean/maize rotation (Thailand), wheat/maize/soybean rotation (Romania), alfalfa/corn intercrop (Spain), rice/soybean/mung-bean rotation (Indonesia),
– Several evaluation criteria were utilized; the most common were biological (dry matter) and agronomic (grain) yields, and P uptake; where ^{32}P techniques were employed, isotope-derived P-efficiency indices (Pdff, utilization coefficient, substitution ratio) were estimated; in some studies, specific criteria included indicators for revitalizing acidic, denuded land, uptake of Cd and F, and uptake of radionuclides such as ^{137}Cs and ^{90}Sr in Chernobyl-contaminated areas,
– Field experiments confirmed the utility of ^{32}P techniques in measuring plant uptake of P from various PR sources and assessing differences between treatments.

Recommendations were made for continuation and furtherance of on-going field studies, some of which will be undertaken within the framework of the new acid-soils project [11].

4. CONCLUSIONS

Investigations within this CRP demonstrated that ^{32}P is a powerful tool in phosphate studies, in particular for investigating soil-P dynamics and evaluating the agronomic effectiveness (AE) of natural and modified PR materials. These techniques were utilised in acid soils world wide, and have been refined for use in tropical acid soils.

Proper characterization of soils and PR materials is needed for better understanding of the factors influencing the AE of PR-based products, and to provide recommendations for direct application of PR.

Several technological and biological approaches were tested and found to be effective to enhance the AE of PRs in acid soils, but scope remains to investigate new approaches or combinations of existing methods at the cropping-system level in the sub-humid and humid tropics. For instance, field studies of P cycling and budgets/balances are required to further validate the P sub-model across a wide range of environments.

The FAO/IAEA programme, through research networks and other mechanisms, is promoting further applications of ^{32}P techniques in phosphate investigations for developing sustainable agricultural production systems in the tropics and sub-tropics.

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MODELLING, DATABASES AND THE P SUBMODEL

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Abstract

This paper provides a brief overview of computer-simulation decision-support systems, and describes the data necessary for their generation and validation, their role in modern agricultural research and their potential utility for researchers and growers. Data from field experiments in Venezuela and Thailand were used to test the P submodel within DSSAT (Decision Support Systems for Agrotechnology Transfer), and close agreements in the maize grain yields were obtained between measured and simulated numbers for various P treatments including phosphate rocks.

1. INTRODUCTION

With the wide spread use of personal computers and advances in information technology, simulation modelling is becoming increasingly important in helping to synthesise knowledge to solve practical problems. It plays a significant role in decision-making for industry, environmental regulators, government and consultants.

2. FUNDAMENTAL PRINCIPLES OF MODELLING

A model can be either a set of equations or a physical system – a simplified version or a description of reality. It can make a situation easier to define and manage by considering only the most important aspects and ignoring less-important detail. Although this is a strength of modelling, i.e. bringing simplicity from complexity, it is also a weakness in that contributions from less-important factors are ignored.

A model allows interpolation and extrapolation of a limited set of data so that repetitive, laborious and time-consuming experimentation can be reduced. It can also help to identify knowledge gaps and provide insights where experimental results are lacking or are incomplete. Although models are useful, they are considered complementary to experimentation and are not meant to take its place. A model cannot be developed or verified without a good set of data. Often much effort is spent in developing a model, whereas less effort is put into conducting appropriate experiments to parameterise and test it.

Models can be distinguished on the basis of whether they are developed primarily for research purposes or as guides for agricultural management. The former type tends to be more mechanistic, for helping to understand how processes underlying a system interact. The latter are more functional, in that the treatment of soil processes is simplified sufficiently for practical management decisions; the input information and computer-expertise requirements for their use are less demanding.

3. CROP-SIMULATION MODELS AND DECISION-SUPPORT SYSTEMS

Soil, climatic, plant, and management factors affect how a crop responds to irrigation, fertiliser, and other management practices. Determining appropriate crop-management strategies under these uncertainties has major economic and environmental implications. This is particularly so as demands on resources for food production become more critical. Computer-simulation models of the soil/crop/atmosphere system can make valuable contributions to our understanding of the processes determining crop responses and can predict crop performance in different areas. They can greatly facilitate the tasks of optimising crop and nutrient management and of deriving

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recommendations for crop management. And they can be used to investigate environmental and sustainability issues of agro-ecosystems, and aid in understanding the interplay among cropping-systems management, soil, and weather.

Many crop-simulation models have being developed, e.g. CERES [1], SUCROS [2], and CropSyst [3].

3.1. Decision-support systems

Computer-based decision-support systems (DSSs) interactively help decision makers utilise data and models to solve unstructured problems [4]. The main aim of such systems is to reduce the time and human resources required for analysing complex data. A DSS should support all phases of a decision-making process, characterised by:

– Searching for conditions calling for a decision by identifying possible problems or opportunities,
– Creating and analysing possible courses of action,
– Suggesting a course of action from those analysed.

Two popular DSSs are DSSAT (Decision Support Systems for Agrotechnology Transfer) and APSIM (Agricultural Production Systems SIMulator). They were designed for easy creation of experiments to simulate, on computers, outcomes of complex interactions among various agricultural practices, soil, and weather conditions, and to suggest appropriate solutions to site-specific problems.

3.1.1. Decision Support Systems for Agrotechnology Transfer

The DSSAT is a computer-software programme that provides users with easy access to soil, crop, and weather information as well as to crop models and application programmes to simulate, analyse, and display multi-year outcomes of alternative management strategies specified by the user. It is a product of the International Benchmark Sites Network for Agrotechnology Transfer (IBSNAT), in Honolulu. It is a network consisting of the contractor (University of Hawaii), sub-contractors and many global collaborators. Together, they have created a network of national, regional, and international agricultural research for the transfer of agrotechnology among global partners in developed and less-developed countries.

DSSAT allows users to ask "what if" questions, and simulate results by conducting, experiments on a desktop computer, which would otherwise take years to complete. Crop-model validation is accomplished by running it with the minimum data set, and comparing outputs. By simulating probable outcomes of crop-management strategies, DSSAT offers users information with which to rapidly appraise new crops, products, and practices for adoption.

The Seasonal, Sequence and Spatial (AEGIS/WIN) Analysis programmes within DSSAT links crop-growth simulation models with Geographic Information Systems (GISs) and, hence, expands the application of crop models to large areas across which soils, weather, and management vary. It allows the management of large amounts of spatial information related to crop production and environmental effects, and visualises crop-simulation results to improve understanding. DSSAT has been used to study fertiliser strategies, impact of global-climate change, farm-household-decision making within whole-farm systems, pest/crop interactions, and land-resource evaluations.

The crop models within DSSAT are included in CERES and CROPGRO. Currently, DSSAT is able to simulate maize, wheat, rice, sorghum, barley, millet, soybean, peanut, dry bean, chickpea, cassava, potato, sugarcane, tomato, sunflower and pasture.

3.1.2. Agricultural Production Systems Simulator

The APSIM programme was developed by the Agricultural Production Systems Research Unit, a joint effort of Queensland Departments of Primary Industries and Natural Resources, and CSIRO Tropical Agriculture, Australia. It incorporates the physiology of crop growth and development, effects of management on soil water, N, residues, erosion, cropping sequences, and intercropping, for simulating agricultural production systems. System processes in APSIM are in distinct modules, with soil as the central unit. Interaction between modules occurs via a communication engine [5]. APSIM has been developed to allow the user to configure a model by choosing a set of submodels from a suite of crop, soil and utility modules. Any logical combination of modules can be simply specified by the user "plugging-in" required modules and "pulling out" any modules no longer required. The crop modules available include maize, wheat, barley, sorghum, sugarcane, sunflower, cowpea, soybean, chickpea, mungbean, peanut and pasture.

3.2. Data and databases

The application of crop-simulation models to problems in the real world depends not only on the availability of models and application software, but also on the availability of information that make it possible to run models for particular target regions. Therefore, it is important that the appropriate data needs, data collection and experimental procedures are specified so that data-handling structures and analytical approaches can be defined and developed.

A database is an integrated collection of data, or information that describes interrelated sets of persons, places, things and/or events (entities). Databases may also be called files. They generally comprise records, and individual items of information that can vary in size and complexity. There are several different types of databases, classified by the type of information they contain, how they are structured, or a combination of the two.

The three categories that describe databases, based on their contents, are textual, numeric, and graphic files. Textual files contain records whereas numeric databases contain very little such information, but have various fields of numeric data. Numeric databases differ from those containing mostly words in terms of need to perform complex calculations on the data in a field, rather than merely retrieving a piece of information contained in the text. Graphic or image databases are also called object-oriented databases.

Databases are described also by the way the information is structured. The two common structures are flat-file and relational databases. In flat files, the individual records are designed to hold and organise all the information on a topic. These records are contained in one database. In a relational database, multiple records in different files may be linked together – related – to organise the information.

The advantages of database processing are that duplication of data can be reduced and consistency of data can be improved. In addition, broader data sharing, and improved productivity in application development and maintenance, can be achieved.

Commercially available databases include ACCESS, ORACLE, and DB2.

3.2.1. Minimum data sets

Minimum data set (MDS) refers to the least requirement for running the crop model and validating its output. Validation requires weather data for the duration of the growing season, soil data, management, and data from the experiment.

A typical minimum weather data set includes latitude and longitude of the weather station, incoming solar radiation, maximum and minimum air temperatures, and rainfall, usually collected on a daily basis.

Desired soil data include soil classification, surface slope, colour, permeability, and drainage class. Soil-profile data by soil horizon include upper and lower horizon depths, particle size distribution (percentage sand, silt, and clay contents), one-third bar bulk density, organic carbon, pH in water, aluminium saturation, and root-abundance information.

Management data include dates when soil conditions were measured prior to planting, planting date, planting density, row spacing, planting depth, crop variety, irrigation, and fertiliser practices. These data are needed for both model validation and strategy evaluation.

In addition to soil and weather data, experimental data include measurements of crop growth, soil water and fertility. These are needed for model validation.

3.3. Phosphorus modelling

Phosphorus is an essential nutrient for plants and animals, and is the limiting factor for crop growth in many tropical soils because of low native P level and high P-fixation capacity. As it is costly to apply inorganic P fertilisers, it is important that factors affecting the availability of P from inorganic and organic sources are understood under various cropping systems and climatic conditions, so that results may be extrapolated from one region to another. Thus, new methodologies to enhance the efficiency of P inputs may be devised, with the ultimate goal of improving soil fertility and achieving agricultural sustainability. The objectives of this work were to build a database for validating the P submodel within DSSAT and to provide better P fertiliser recommendations for major food crops in developing countries. The results from this exercise may be used in the forthcoming Acid Soils Co-ordinated Research Project (D1.50.06).

The P submodel (module v 2.2) within DSSAT 3.5 was developed by the Michigan State University group [6, 7], in association with scientists from the International Fertilizer Development Center. It was developed to predict the yield potential of crops with the residual effects or annual additions of soluble P fertiliser or phosphate rock under various soil, climate, and management conditions. The P submodel was developed also to help in the decision-making process for farmers, extension agents, and researchers in developing countries, to evaluate scenarios for best crops, management conditions, and source, application timing and rates of P fertiliser.

The P submodel is not yet an official component of DSSAT 3.5. Further testing is in progress. It is a “plug-in” module, hence relatively independent of the main code. The P pools were initialised from fractions obtained during sequential P extraction with increasingly aggressive extractants, or from soil-P tests. The module has the ability to simulate crop rotations, with each component using P left over from the previous crop.

The P module works on a daily basis, by mass transfer from one soil-P pool to another, calculated as the concentration of P in the pool multiplied by a rate constant. The total supply of labile P in the soil and the total plant demand are calculated for every day of simulation. Soil supply is sensitive to water status, temperature, and root density. Plant demand depends on mass and the optimum P concentration in plant organs at each stage of development. If plant demand exceeds the soil supply, a feedback mechanism reduces the simulated plant growth. Stress factors in the model output allow the user to evaluate P stress at each developmental stage.

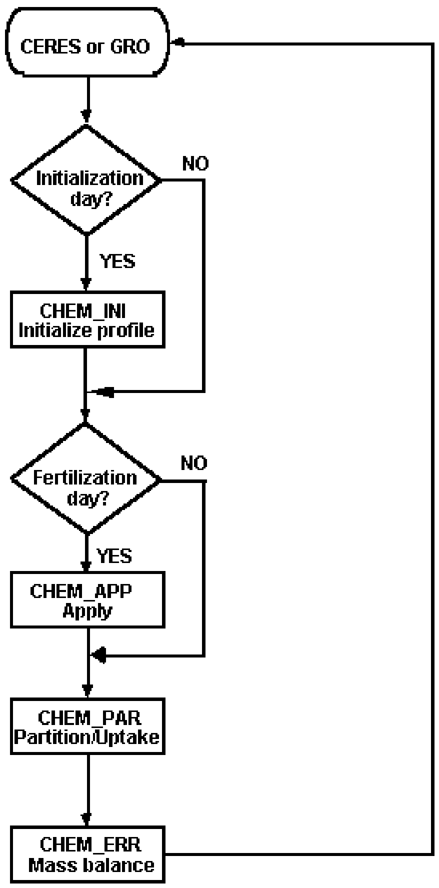

FIG.1. Flowchart of P module.

3.3.1. Programme flow and subroutines

Figure 1 shows the major steps of the P submodel; the module is as generic as possible so that it can be adapted easily for other chemicals.

Figure 2 shows mass flow among the various compartments of the central P module. The total supply of labile P in the soil is calculated for each day of simulation, as well as total plant demand. The labile P fraction can be estimated from soil-P tests. Several soil-test options are available. The fractions obtained during sequential P fractionation are according to Hedley et al. [8].

The P is partitioned into several pools. If plants are present, uptake is equal to either soil supply or plant demand, whichever is less. The total P is the sum of inorganic active, inorganic stable, organic active, organic stable, chemical in residues that decompose rapidly, chemical in residues that decompose slowly, chemical in the fertiliser pool, labile, and chemical in live plants. The total P in the profile should be the total P of the previous day plus the gains (fertiliser), minus the losses in erosion, runoff, and in harvested tissue.

3.4. Model testing

The model was tested using data from phosphate-rock trials in Venezuela and Thailand.

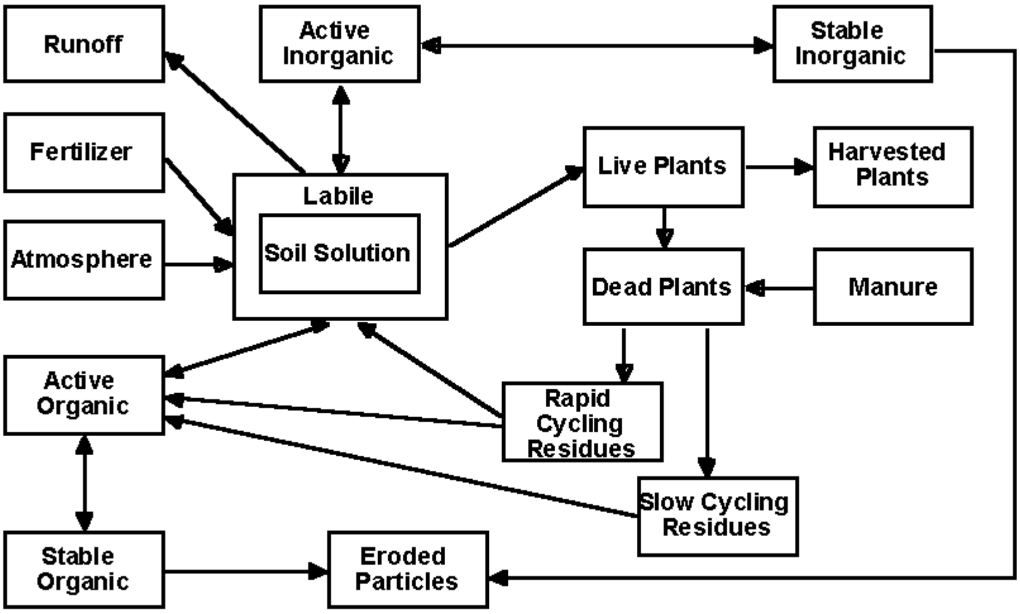

FIG. 2. Mass transfer among P pools.

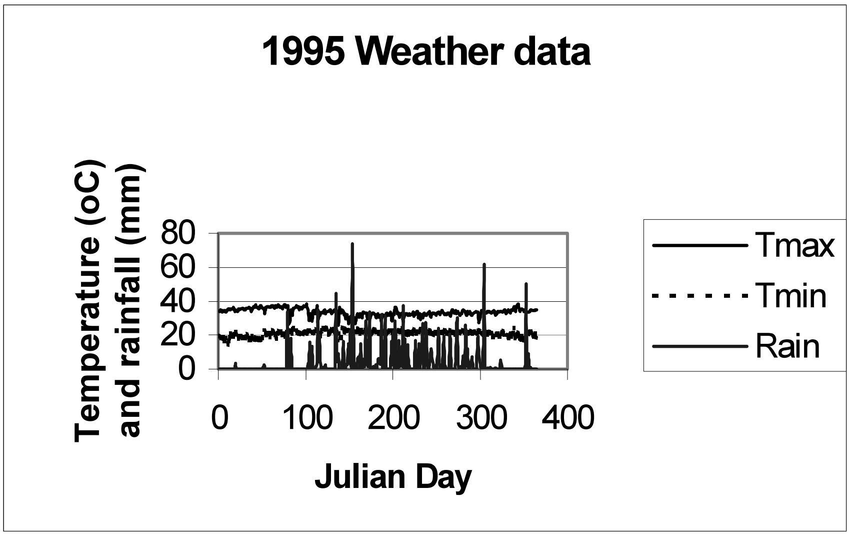

FIG. 3. Rainfall and temperature distributions for El Pao, Venezuela.

3.4.1. Venezuela

The data are those of Mr. Eduardo Casanova from experiments in El Pao, Venezuela. The field trials and the physical and chemical properties of the soils at El Pao are described elsewhere in this TECDOC. Briefly, the aim of the experiment was to evaluate the efficiency of P fertilisers using conventional and isotope techniques. The rock phosphates tested were: Riecito rock phosphate (RR) and acidulated Riecito [40% (RR40) and 60% (RR60)]. There were four P treatments (0, RR, RR40, RR60). The maize hybrid was PB8, at a density of 62,500 plants/ha. Basal fertiliser applications of 40 kg N/ha and 66 kg K/ha were made at planting with a side dressing of 87 kg N/ha 21 days later.

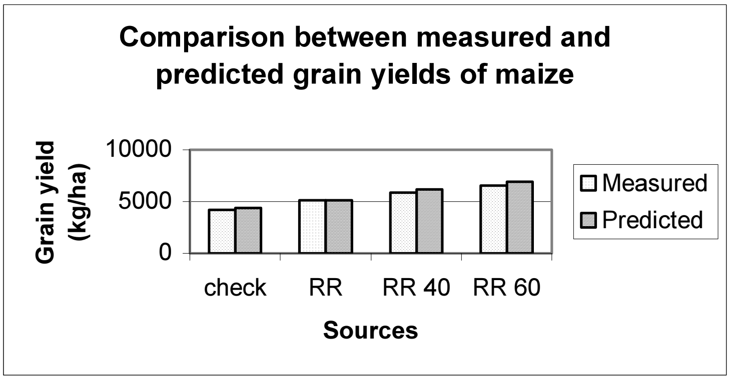

FIG. 4. Comparisons of measured and predicted maize yields at El Pao, Venezuela.

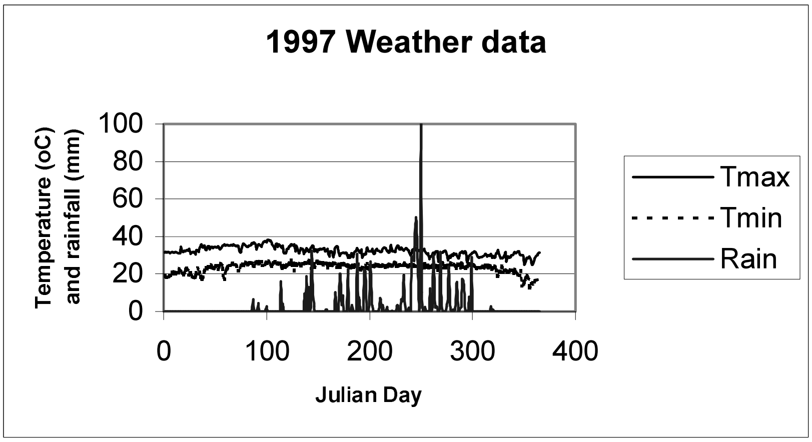

FIG. 5. Rainfall and temperature distributions for Lopburi, Thailand.

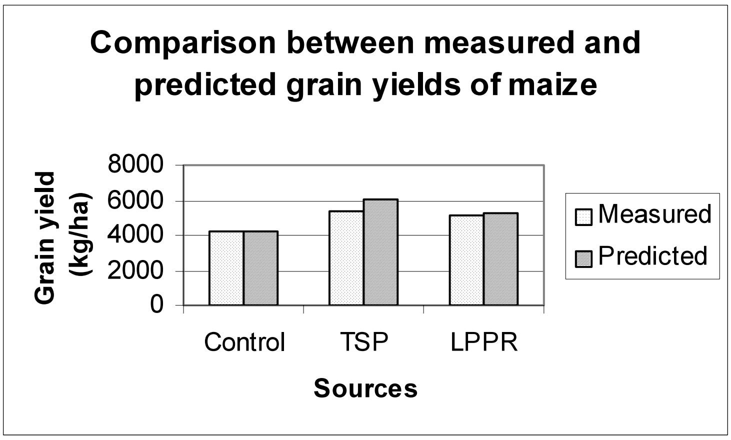

FIG. 6. Comparisons of measured and predicted maize yields at Lopburi, Thailand.

Figure 3 shows the temperature and rainfall distributions for 1995. A total of 1,411 mm of rainfall were recorded, mainly between April and October. The weather, soil, crop, fertiliser management and irrigation management (rainfed in this case) information were then put into the P submodel. The most difficult part of this work was determining the partitioning of the various P pools; the control treatments were used for calibration.

Figure 4 shows the model's performance for the different P treatments. Application of acidulated Riecito rock phosphate increased maize grain yield over the control; this was simulated successfully by the model.

3.4.2. Thailand

A soybean/maize rotation experiment was carried out in 1997, at Lopburi in the central plain of Thailand, by Ms. Jittiwan Mahisarakul. The objective was to evaluate the effectiveness of Thai and foreign sources of phosphate rock using TSP as a check: North Carolina phosphate rock, Algerian phosphate rock, Ratchaburi phosphate rock, Petchaburi phosphate rock, and Lumpoon phosphate rock. The Pakchong soil [9] is classified as an Oxic Paleustults, clayey, kaolinitic, isohyperthem. Basal 20 kg N/ha and 40 kg K_2O/ha were applied to the soybean, and basal 80 kg N/ha and 40 kg K_2O/ha were applied to the maize.

Figure 5 shows the rainfall and temperature distributions. The area is characterised by a dry season between November and March. Heavy rainfall is common in July and August. Figure 6 shows the measured and simulated maize grain yields for the control, TSP and local Lumpoon phosphate rock (LPPR). As in Fig. 4, the measured grain yield was corrected for the moisture content (14.5%) and the comparisons were encouraging. More model testing and sensitivity analysis of various components will be carried out.

4. CONCLUSIONS

Decision support systems such as DSSAT allow various factors that affect crop yields to be studied. However, the pre-requisite is a good minimum data set, which must be well planned and collected from the beginning of the experiment. Data from Venezuela and Thailand were used to test the P submodel within DSSAT, and close agreements were obtained between measured and simulated maize grain yields for phosphate rock treatments. One weakness of the P submodel is the need for detailed data on P-fractionation pools. The degree of detail implies that an expert system is needed to help initialise the various P pools and estimate transformation rates.

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TROPICAL ACID SOIL CASE STUDIES

RESTORATION OF SOIL FERTILITY AND IMPROVEMENT OF CROPPING SYSTEMS FOR SUSTAINABLE DEVELOPMENT IN THE HUMID SAVANNAHS OF THE IVORY COAST

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Abstract

In late 1998, FAO launched a Technical Co-operation Project to assist the government of the Ivory Coast in rural development by promoting agricultural production as the main source of economic growth, and by improving the management of natural resources. The sustainable development of the humid-savannah region and western highlands is being allotted primary consideration. The goal of the project is to replace traditional shifting cultivation with more-sustainable production systems. This paper describes the origins and scope of the problem and the research strategies being considered and employed. The project will be executed in three phases: constraint analysis and formulation of a pilot project, execution of the pilot project (1999–2003), and long-term extension (15 years) from 2004, based on the data generated in the pilot phase.

1. INTRODUCTION

At the request of the government of the Ivory Coast, FAO launched, in late 1998, a Technical Cooperation Project (TCP/IVC/7821) titled "Restauration de la fertilité des sols et amélioration des systèmes de culture pour le développement durable de la zone de savanes humides et de la région semi-montagneuse de l'Ouest." The project aims to assist the government of the Ivory Coast in implementing its Rural Development Strategy, which focuses on: (i) reducing existing regional disparities, (ii) promoting agricultural production as the main source of economic growth, and (iii) improving the management of natural resources in the country. In this context, the sustainable development of the humid savannahs and western highlands are of prime importance. To facilitate the achievement of this development goal, the government has created a High Commission for each of the two zones.

2. GENERAL INFORMATION

2.1. Importance of the problem

The savannah zone in the Ivory Coast comprises some 3.3 Mha of cultivated land (from a total area of 16 Mha) with a population of 2.1 million (80% rural). The western highlands cover 39,400 km^2 and has 1.5 million inhabitants. Socio-economic and agro-ecological factors that, over the last three decades, have resulted in serious degradation of the soil and low agricultural productivity, are as follows.

2.1.1. Traditional agricultural production systems

Generally, farmers in the Ivory Coast practise shifting cultivation, using annual fires to clear the bush. This traditional practice was economically and ecologically viable when land was abundant and the human population smaller, and bush-fallow periods lasted 15 years or more. Under increasing population pressure and scarcity of land, fallow periods are shorter, causing serious degradation of the natural resource base, stagnant or declining crop yields, food and nutritional problems and increasing poverty. The critical feature of this land-use practice is that nutrient outflows exceed inflows and lead to soil mining. Estimates for thirty-eight countries in sub-Saharan Africa (SSA) suggest that annual losses of macro-nutrients per hectare during the 1980s were 22 kg of N, 2.5 kg of P, and 15 kg of K.

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Long-term soil mining leads to loss of soil organic matter (SOM) with subsequent declines in nutrient-holding capacity, soil macro-structure, water-holding capacity and infiltration. For example, cultivation with low-input methods (no fertiliser) in the humid savannah zone of SSA can induce a 30% loss of SOM after 12 years, and 66% after 46 years, with rice yields declining from 1 ton/ha to 300 kg/ha. Crop residues, returned to the soil as practised under the present short-fallow system, are not sufficient to offset these losses. The challenge is to halt soil mining and restore fertility before yields become so low that cropping activities are abandoned.

2.1.2. Climate change

Decreasing rainfall in West Africa has resulted in annual-deficit increases from 150 mm in the 1960s to 400 mm in the 80s. Although it is not yet clear if this trend will continue, the rainfall deficit has significantly contributed to ongoing migration of human population and animals from the Sahel to the Ivory Coast and, within the country, from the savannahs towards the southern forest zones, and has led to changes in cropping patterns.

2.2. Agro-ecozones

The savannah in the Ivory Coast covers about two thirds of the national territory with some 3.3 Mha of cultivated land. The region has the following specific agro-ecozones:

(1) In the north, with unimodal rainfall pattern (<1200–1500 mm/yr), are three types of savannahs:
- North-eastern savannah (Bouna-Boundoukou-Tanda), semi-arid:
  - millet
  - sorghum and yam to the south
  - cotton becoming an important cash crop
  - livestock common;
- Northern savannah (Boundiali-Korhogo-Ferké), sub-humid:
  - cotton/maize predominant, however, with increasing rainfall deficit, maize is being replaced by sorghum and millet
  - yam
  - rice
  - fruit trees, mango, citrus, cashew, showing promise
  - animal traction common, often related to cotton cultivation;
- North-western savannah (Odienné), humid and undulating relief:
  - cotton, main cash crop, losing importance due to unfavourable financial returns
  - rice and maize are the main food crops.

(2) Central humid savannah (Savane Centre-Sud) with bimodal rainfall pattern (1200–1500 mm/yr), comprises the area around Bouaflé, Bouaké, Séguéla, Katiola, Dabakala, bordering on the forest/transition zone to the south and in its northern part there is a second growing period with precarious rainfall:
- Main production systems:
  - yam and cassava major food crops
  - rice
  - horticulture and aquaculture in the lowlands
  - potential for agro-forestry, fruit trees, and improved small-scale irrigation;

(3) Western highlands around Man and Touba, comprising 900 000 ha under unimodal rainfall (1500–2000 mm/yr). Humid-forest, mountain-forest and humid and sub-humid savannah zones meet:
- Due to merging agro-ecozones there is a mix of production systems:
  - cassava, maize and rice generally, the main food crops
  - cocoa, coffee and hevea are important cash crops.

3. CONSTRAINTS AND POTENTIAL OF THE SAVANNAH

The major agricultural problem that farmers face in the savannah zone is weeds. The length of the cultivation cycle in the shifting-cultivation system is largely determined by the degree of weed infestation, which, in turn, is dependent on the fertility of the soil. Soil fertility decreases rapidly after the fallow period through cultivation of nutrient-demanding crops such as rice, maize and cotton, often with no or very little fertiliser application. As a consequence, crop productivity decreases sharply due to rapid depletion of soil nutrients and increasing weed infestation.

Technical options presented below have been developed to a great extent by the research system within the Ivory Coast, but also in other countries of West Africa under similar agro-ecological conditions. According to their main impact, they have been presented at three levels: farmers' fields, farm, and community.

3.1. Constraints

3.1.1. Annual bush fires

As a labour-saving practice, most farmers use fire to clear the bush after the fallow period, and also to prepare fields for planting. This practice leads to loss of all the N in the biomass, two thirds of the K and one third of the P. Mineralisation of organic matter contributes to degradation of the soil structure and loss of water-retaining capacity.

3.1.2. Fallow

Leaving previously planted fields to return to bush fallow is the most important soil-fertility-restoring management technique used by farmers. During the past two to three decades, the fallow period has generally been reduced, from about 15 to as little as 2 years due to increasing population pressures and concomitant scarcity of land.

3.1.3. Soils

Generally, soils in the savannah are "sols ferralitiques," typically of low cation exchange capacity (CEC) and deficient in P. Cropping, coupled with N fertiliser application only, reduces soil pH (acidification), soil organic matter, and extractable cations.

3.1.4. Livestock

Although the savannah zone supports about 1 million head of cattle and 2 million small ruminants, the integration of livestock into cropping activities is weak; manure is only marginally used as fertiliser. It is estimated that 0.5 Mt/yr farmyard manure is produced, sufficient for about 100 000 ha of crops, equivalent to half the area under cotton.

3.1.5. Unbalanced cropping systems

In most crop rotations, legumes play a marginal role, therefore, contributing little to the N-economy of the soil. Major crops such as yam, often grown at the beginning of the cropping cycle after the fallow, use much of the reserves of P and K in the soil, and leaving little for subsequent crops. Since farmers apply virtually no fertiliser to food crops, with decreasing fallow periods, or even no fallow at all (in the north), such mining of nutrients leads to serious soil degradation and yields may become so low that cropping activities are abandoned.

3.1.6. Agro-economic constraints

Cotton is the only major export crop of the savannah zone; the other important cash crops, cocoa, coffee, hevea, pineapple, etc., are concentrated in the southern forest zone. This has specific disadvantages for the savannah zone:

- Following the devaluation of the FCFA in 1994, the price of food crops increased, but less than did the prices of export crops and of imported inputs. This has led to generally lower farm incomes, lower profitability from imported inputs and growing economic disparity between the savannahs and the forest zone,
- Since a major part of the food crops of the savannahs is home-consumed, the monetary base of the rural economy is weaker than in the forest zone, resulting in a disincentive to use expensive inputs, especially taking into account the lack of seasonal credits for food crops,
- The development of the savannah zone is strongly dependent on cotton, the major cash crop, which has an uncertain future:
  - being an input-intensive crop, it has benefited less than the export crops of the forest zone from the FCFA-devaluation
  - as a result, income from cotton is not particularly attractive to farmers, causing a general decline in production
  - CIDT is the only cotton company in the country that provides all necessary services to farmers from land preparation to processing; however, its pending privatisation creates some uncertainty with regard to farmer extension and farmer groups;
- Long distances to the main coastal consumer markets and export outlets, in and around Abidjan, are a major constraint, particularly with respect to perishable horticultural products, fruits, and roots and tubers,
- The input distribution and marketing network for general food crops are very underdeveloped,
- Modern farms with high value-added enterprises are concentrated mainly in the forest zone,
- Rural credit is a serious constraint, although not specific to the savannahs.

3.1.7. Socio-economic potential

Cotton production and processing, despite current weaknesses, are important assets for the region because of their capacity to develop and structure the rural economy, due mainly to the following factors:

- Provision of medium-term credit through CIDT for animal traction (about 90 000 animals on 180 000 ha),
- Creation of Farmer Groups and Unions, which constitute a potential basis for taking over certain tasks (input provision, credit, and marketing services) beyond narrow cotton production.

The region has an infrastructure of roads and feeder roads that is much better developed than in similar cotton-growing areas of neighbouring countries.

The unimodal rainfall pattern, with a marked dry season that is needed by some crops with high market potential (tree fruits, horticultural crops, groundnuts, etc.), is clearly advantageous over the more humid forest zone.

4. THE PROJECT

The primary goal of the project is to replace traditional shifting cultivation in the humid savannahs of the country by economically, ecologically and socially more-sustainable production systems. In order to achieve this development objective, the project focuses on the following main issues:

– Restoration of soil fertility through improved management of land and crops and more-efficient use of mineral and organic fertilisers,
– Crop diversification through more-efficient use of water resources using irrigation,
– Introduction of new cropping systems that have been successfully tested in countries with similar agro-ecological conditions,
– Adapting traditional land tenure to the market economy,
– Involving the private sector in all aspects of regional development, assisted by Government through the creation of a favourable environment.

The strategic framework of the project responds to the following needs:

– To take into account all aspects of soil-fertility restoration including areas concerned, cost of fertility restoration, and economic profitability and sustainability,
– To test all fertility-improving measures at the farm level in representative agro-ecozones of the humid and sub-humid savannahs before their extension at large,
– To identify major macro-economic constraints (e.g. marketing) that impede sustainable agricultural development in the savannah region.

The project will be executed in three phases: constraint analysis and formulation of a pilot project financed by FAO, execution of the pilot project (1999–2003) that will include a mid-term evaluation, and a long-term extension (15 years) starting in 2004 based on successful results of the pilot phase. The current diagnostic phase is expected to produce the following results:

– Methodological guidelines for the identification of constraints and test zones (agro-ecological zones and their fertility criteria) and the formulation of technological options for the improvement of soil and crop productivity,
– A document for a bankable pilot project,
– A regional development-program proposal with a particular focus on institutional support and crops with agro-industrial development potential (e.g. maize, soybean and groundnuts).

4.1. Available technologies

Available technologies, presented below, have been identified. They are designed to solve major technical production constraints, and have been derived from research and development work carried out in the Ivory Coast and similar agro-ecozones in West Africa. Most have not yet been adopted by farmers on a large scale and still need to be validated under, and adapted to, farmer conditions. They are grouped according to the level of intervention: farmer's field, farm, or community (watershed, irrigation perimeter, and village communal land).

4.1.1. Technology options at farmer's-field level

4.1.1.1. Weed control

Noxious weeds (*Imperata, Rotboellia*, etc.) are a general problem in the savannah for most crops, and can be controlled through animal traction, herbicides and/or cover crops. Cover crops such as *Pueraria*, and *Mucuna* have proven to be a low-cost technology to effectively suppress weeds in cropping systems, e.g. maize/pueraria, maize/mucuna and cotton/mucuna.

4.1.1.2. Fertilizer application

In the cotton-growing zone (northern savannah) where the utility of fertilisers is recognized, low to medium applications that are economically feasible for smallholders could be tested for cotton, upland and irrigated rice, maize and yam.

Application of phosphate rock is an option to improve the P-status of the generally P-deficient savannah soils.

4.1.1.3 Lowland rice

The specific problems of lowland rice are yellow mottle virus and iron toxicity. Rice varieties with resistance to the virus and to iron toxicity are available and need to be provided to farmers.

4.1.1.4. Urban and peri-urban horticulture

Dry-season urban and peri-urban horticulture suffers from problems related to the infestation of soils with nematodes and bacteria (e.g. *Pseudomonas*) and from unbalanced fertilisation. Improved crop rotations and nematicides together with balanced fertilisation can improve the situation.

4.1.2. Technology options at farm level

4.1.2.1. Livestock/agriculture integration

In the livestock zone (northern savannah) improved farmyard manure production and use is possible by a) stabling and/or fencing for overnight containment of livestock, b) mixing manure with NPK or SP and dissemination of licking stones.

4.1.2.2. Improved fallow

Reduction of the fallow period results in lower soil fertility and proliferation of noxious weeds, and requires also that farmers manage the fallow. Short improved fallow periods of 2 to 5 years under legume crops can improve the fertility status of savannah soils:

– Tree legumes (*Acacia auriculiformis* in the north and north central and *Acacia mangium* in the forest transition zone,
– Herbaceous legumes (*Pueraria phaseolides, Mucuna utilis, Crotalaria anagyroides)*,
– forage legumes (S*tylosanthes* spp. with grain crops, *Cajanus cajan* pure stand).

4.1.2.3. Improved crop rotations

Increased cultivation of grain legumes, such as groundnut and niébé, is needed.

4.1.2.4. Perennial crops

Perennial crops, e.g. hevea and coffee, can improve soil productivity. In the central savannah, coffee is usually intercropped during the first 3 to 4 years. Other options are the association of coffee with *Glyricidia sepium* for shade, and interplanting of hevea and coffee. In the humid savannah, cashew, mango and teak hold promise as commercial tree crops. Oil palm is being introduced in the humid west and central zones.

4.1.3. Technology options at community level

Implementation of technical solutions that address constraints at the community level (bush fire, irrigation, and livestock grazing), requires collective and co-ordinated action and management of the village community.

4.1.3.1. Erosion control

Water-erosion control is essential in the densely populated areas of the savannah. This can be achieved through construction of simple contour bunds, and stone lines that can be strengthened with perennial crops, such as coffee and banana.

4.1.3.2. Small-scale irrigation in lowlands

Iron toxicity can be controlled through the construction of up-stream drainage canals that are stabilised and utilised by perennial fruit crops, such as banana and mango.

4.1.3.3. Control against livestock and bush fire

Farmers need to protect their fields against bush fire and livestock incursion, particularly when they are establishing improved fallow or horticultural and perennial crops. This can be achieved by constructing “productive” live fences, such as cashew, citronnier, and *Gmelina*. These need to be protected for the first 5 years until they are resistant to bush fire.

4.1.3.4. Traditional tree cropping

In the northern savannah zone, indigenous trees such as karité and néré play an important role as food crops, and *Faidherbia albida* as fodder for livestock. Increased planting, protection, and marketing of products of these traditional species need to be supported.

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IMPROVING THE MANAGEMENT OF INFERTILE ACID SOILS IN SOUTHEAST ASIA: THE APPROACH OF THE IBSRAM ACID-SOILS NETWORK

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Abstract

The IBSRAM *ASIALAND* Management of Acid Soils network aims to improve the understanding of the broad range of biophysical and socio-economic production limitations on infertile acid soils of Southeast Asia, and to lead to development and implementation of sustainable land-management strategies for these important marginal areas. The main activities of the network are in Indonesia, Myanmar, Philippines, and Vietnam, with associated activity in Thailand, and minor involvement in Brunei, Cambodia, Laos, and Malaysia. The main experimental focus is through researcher-managed on-farm trials, to improve the management of phosphorus nutrition with inorganic and organic amendments. A generic design is used across the eight well characterised sites that form the core of the network. The results will be analysed across time and across sites. Improved methods for laboratory analyses, experimental management, socio-economic data collection, and data analysis and interpretation are critical components. Three important initiatives are associated with the core activities. These aim to establish a broader network on maintenance of quality laboratory analyses, to assess the potential for implementation of improved strategies through farmer-managed on-farm trials, and to improve our understanding of, and ways of estimating, nutrient budgets for diverse farming systems.

1. INTRODUCTION

There is no doubting that significant pressures exist on agricultural systems of the world, and therefore on land resources, to increase production, particularly in developing countries. These pressures arise from a combination of population growth [1], the need to improve the living standards of the poor, particularly their nutritional standards [2], and dwindling reserves of quality arable land [3]. It is vital that highly productive agricultural systems are maintained, but, increasingly, improved management of marginal lands is critical to increased and sustainable agricultural production. Marginal areas are underused where better are available and, in consequence, significant areas of quality agricultural land have been degraded through poor management practices [4]. Although the driving forces behind the need for increased agricultural production and the factors that limit production on marginal lands differ among regions, the need for improved management of marginal lands exists in many parts of the world, particularly in developing countries and certainly in Southeast Asia.

The development of sustainable land management systems for marginal soils requires an understanding of the particular production limitations, of methods for overcoming these limitations, and policies to implement changes. A network approach to solving these problems can yield a wider set of biophysical and socio-economic conditions, and thus a better understanding of the underlying processes, improved intra- and inter-regional (South-South and North-South) transfer of knowledge and experience, and greater institutional capacity building. Understanding the operations of the IBSRAM acid-soils network in Southeast Asia may prove useful in establishing a new IAEA/FAO Co-ordinated Research Project for acid soils.

2. THE CONSTRAINTS OF INFERTILE ACID SOILS

The low fertility of marginal soils can be due to inherent infertility or can result from mismanagement. As such, the need to improve the fertility of inherently infertile soils or to restore the

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fertility of degraded soils can be considered as the capitalisation or recapitalisation of the natural resources.

Most of the marginal soils of Southeast Asia, and of the tropics and sub-tropics in general, are marginal because of inherently low fertility or poor water supply, or both. The majority of these infertile marginal soils are acidic, particularly in upland areas. The acid upland soils of the tropics and sub-tropics are inherently infertile as a result of nutrient deficiencies, especially of P, Ca, Mg, and Mo, or toxicities, especially of Al and Mn. Correction of these disorders is often difficult, but failing to address them exacerbates the problem through further nutrient depletion and acidification. In contrast, correction of these constraints and proper management can yield productive and sustainable farming systems.

Although there can be many problems in acid soils, in most cases deficiencies of P and N limit agricultural production; overcoming these problems generates the greatest improvements. Sustainable N-replenishment strategies, particularly for low- to medium-input systems on marginal soils, can rely on biological N_2-fixing processes, with limited need for chemical fertilisers. A similar approach is not possible for P. It is likely that improved P-management strategies will continue to rely on fertilisers, albeit with as much biological supplementation and recycling as is feasible [5, 6].

Deficiency of P is widespread in soils of the tropics and sub-tropics. Most estimates suggest that more than 2 Gha are affected [6, 7, 8]. Such deficiency may be due to low-P-status parent material, weathering, loss by erosion and surface run-off, and long-term mismanagement, i.e. imbalance between nutrient input and removal in the harvested crop.

It is clear that improved management of these soils must involve adaptation of farming systems, with greater reliance on organic sources of nutrients combined with judicious use of inorganic fertilisers, particularly P. Although there is a large body of research work on P, knowledge gaps exist. There is reasonably good understanding of management of P with inorganic amendments, less detailed information exists on management with organic forms, and data on the interactions of organic and inorganic forms are limited. Even where the processes are understood, methods for efficiently matching management strategies to particular farming systems are limited. Practical recommendations are required that improve the synchrony of P supply and plant demand, through management of organic and inorganic amendments. A major aim of the IBSRAM acid-soils network is to reduce these knowledge gaps through high-quality applied research.

Clearly, P and N are not the only problems. When management strategies have been established to improve the P and N fertility of soils, the deficiencies of other nutrients may, or, in time, will, limit production. Consequently, the initial focus on P and N management must be expanded to an integrated plant-nutrient management approach.

3. THE IBSRAM NETWORK

Critical to developing and assessing the issues of improved management is the use of multidisciplinary and interdisciplinary approaches within the biophysical and socio-economic contexts. An expected outcome of this approach is a significant improvement in the capacity of all the collaborators, as individuals, as institutions, and as groups of institutions, to undertake quality collaborative research, development, and implementation, towards sustainable land management.

The objective of the IBSRAM *ASIALAND* Management of Acid Soils network is to contribute to the process of improving management of infertile marginal soils, with a particular focus on improved management of P in the acid upland soils of Southeast Asia. This is undertaken through collaboration with partners in the national agricultural research and extension systems (NARESs) of Vietnam, Philippines, Indonesia, Myanmar and Thailand, with advanced research institutes (ARIs) in Australia and New Zealand, and with other research and development agencies in the region.

A systematic approach is needed to tackle the complex of problems that can cause low productivity in these marginal infertile acid upland soils. Such an approach has been taken in the IBSRAM acid-soils network. The modus operandi of the network is to operate with a core set of institutions on a core set of initiatives, with a number of important related initiatives undertaken by a subset of these and other institutions.

Prior to 1996, the focus of the network was on ameliorating the toxic effects of Al and low pH, however, since then, the focus of the core of the network has been on establishing researcher-managed on-farm trials – concentrating on P management – designed within the biophysical and socio-economic constraints of the particular agroecosystems.

A significant part of these core activities is being undertaken in association with a project through the University of Queensland (UQ), under the leadership of Dr. Pax Blamey, and funded by the Australian Centre for International Agricultural Research (ACIAR). This project, entitled "Management of phosphorus for sustainable food crop production on acid upland soils in Australia, Philippines and Vietnam," operates with collaborators at the National Institute for Soils and Fertilisers (NISF) in Vietnam, the Bureau of Soil and Water Management (BSWM) and the Central Mindanao University (CMU) in the Philippines, and the Queensland Departments of Natural Resources (QDNR) and Primary Industry (QDPI) in Australia. The core set of collaborators extends beyond those associated with the UQ-ACIAR project to include the Centre for Soils and Agroclimate Research (CSAR) and the University of Gadjah Mada (UGM) in Indonesia, and, in Southern Shan State of Myanmar through a PhD student based at Massey University (MU), New Zealand, the Land Use Division of the Myanmar Agriculture Service (LUD-MAS).

The core of the network operates with three separate but integrated sub-projects: establishment of quality analytical and experimental methodologies, the development and implementation of appropriate field experimentation concentrating on inorganic and organic-P management, and the thorough assessment of socio-economic characteristics of the farming systems and of the particular treatments being used. In this approach, it is recognised that sound scientific methods and principles must be used in the interpretation of any improved crop growth that might be achieved. In addition, the results of field experiments will be implemented and extended successfully to other sites only if the results take full consideration of the socio-economic context.

3.1. Core field experiments

A generic experimental design was developed for adaptation and implementation by all collaborators in the core of the acid-soils network. The field experiment was designed to assess responsiveness to P, including combinations of inorganic organic amendments, and, in some cases, to assess response to lime. Having a reasonably standard design facilitates comparison of results across sites, with sufficient flexibility in treatments to maintain local relevance. Each collaborator selected particular treatments on the bases of biophysical constraints at the site and market conditions, and other economic and social limitations. The responsiveness to P is established with sources that are readily available in both the chemical and market senses. These include triple superphosphate (TSP), single superphosphate (SSP), and SP 36 – a phosphate fertiliser produced in Indonesia that contains 36% P_2O_5, or 16% P (Table I, I1). The inorganic/organic combinations included these same sources plus forms of inorganic P that are less available in the chemical sense, such as fused magnesium phosphate (FMP) and phosphate rocks from North Carolina (NCRP), Christmas Island (CIRP), and the Peoples Republic of China (CRP) (Table I, I2). These sources of inorganic P were chosen on the basis of what was available to farmers, or likely to become available. The organic sources were chosen on the basis of what was available, or may become available, for transfer within or importation from outside the farming system (Table I, O1, O2). The treatments were chosen after detailed discussions with researchers and surveys of farmers, farm suppliers, and local agro-industries.

The majority of the trials are located on farmers' fields previously assessed as representative of a major soil type and agroecosystem in the area. The experiments in Myanmar and Australia are located on research stations for reasons of access and management.

TABLE I. INSTITUTIONS COLLABORATING IN THE CORE OF THE ACID-SOILS NETWORK, AND THE TREATMENTS USED

Country	Province/State	Institution	Inorganic amendments		Organic amendments	
			I1	I2	O1	O2
Vietnam	Hoa Binh	NISF	SSP	FMP	Corn[a]	FYM[b]
Vietnam	Nghe An	NISF[c]	SSP	FMP	Corn	FYM
Philippines	Isabela	BSWM	TSP	NCRP	Chicken[d]	Tricho[e]
Philippines	Bukidnon	CMU	SP	NCRP	Chicken	Stylo[f]
Indonesia	Jambi	CSAR	SP-36	CIRP	FYM	Stylo
Indonesia	S. Kalimantan	UGM	SP-36	CIRP	Chicken	Stylo
Myanmar	S. Shan State	MU/MAS	TSP	CRP	FYM	Titho[g]
Myanmar	S. Shan State	LUD-MAS	TSP	CRP	Corn	Compost
Australia	Queensland	QDNR/QDPI[h]	TSP	NCRP	Lablab[i]	Rhodes[j]

[a]Corn residue. [b]Farmyard manure. [c]Includes *Tithonia diversifolia* as a third organic amendment. [d]Chicken manure. [e]Compost produced with the fungal agent *Trichoderma harzianum*. [f]*Stylosanthes guianensis*. [g]*Tithonia diversifolia*. [h]Includes a number of other organic amendments. [i]*Lablab pupureus.* [j]Rhodes grass (*Chloris gayana*).

3.2. Site characterisation

An essential component of running good field experiments, particularly multi-location experiments, is careful characterisation of the sites. Firstly, this is an essential part of treatment design. Secondly, it is done to ensure that the site is homogeneous, or that any heterogeneity can be used during analysis of results. Thirdly, site characterisation is essential for interpretation of data, to enable comparison of results from different sites, and for the development of relatively site-specific management recommendations. As the number and diversity of sites increases, the importance of characterisation for full interpretation of results becomes more evident. A range of techniques was used to characterise the sites.

Several techniques are available for analysis of soils and determination of P status in particular, therefore, the standard extraction methods regularly used, and with which the greatest amount of data have been generated, are recommended for each laboratory. The main soil-P methods used in the network are the Olsen, Bray II, or Bray I methods. For comparisons across sites, however, it is desirable that the same methods are used. For this reason, all collaborators are encouraged to use their customary method and a common technique or set of techniques. For the purposes of these field trials, all collaborators were encouraged to use the modified bicarbonate technique [9]. The longer extraction time (16 h) and wider soil:solution ratio (1:100) may be more useful for relatively low-P soils and where organic P may be more important.

As low availability of P in soils may be due to low P content and/or severe P-fixation, it is unlikely that a single extraction method will suit all soils or all farming systems to provide sufficient information for accurate interpretation of results. As such, a more universal approach to understanding P response requires measurement of both intensity and quantity factors – the ability of soil to supply P in the short term and medium- to long-term P-supply capacity. To support the standard extraction methods, P-sorption characteristics are assessed to better understand the quantity factor. In addition, since there is particular interest in the cycling of P in various organic and inorganic pools as affected by treatment, a limited set of soil samples has been collected for measurements of P fractions using a modification of the technique of Hedley et al. [10].

Representative surface and sub-surface soil samples were collected and analysed and used in pot experiments. Decisions on rates of P fertiliser used to assess the P responsiveness of the soils at each site were made from analyses of available P and P sorption, and the growth of corn seedlings in pots supplied with different rates of P. The available P and sorption capacities of the soils at the experimental sites differed markedly. For instance, in the Philippines are the fairly low-sorbing Isabela, with an estimated 67 mg P sorbed per kg of soil, at a soil solution concentration of 0.1 mg P L^{-1}, and the higher-sorbing Bukidnon, with 188 mg P kg^{-1}.

A broad set of analyses of the bulked soil samples from each site and measurement of the growth of corn seedlings in element-omission trials were used to assess the status of major nutrients and indicate likely basal applications. For most sites, the trials indicated deficiencies mainly of N and P, with less critical insufficiencies of other nutrients. Together, these analyses and pot experiments improved the capacity to select treatment P rates and basal, non-treatment, fertiliser application levels.

Although variability in soils is the reality with which farmers must cope, minimising heterogeneity, or at least understanding the variability, is important in the experimental context. Site uniformity was assessed, particularly where greater heterogeneity was observed or expected. For instance, at Bukidnon, Philippines, a maize crop was grown on the area in which the experiment was to be located and used to assess heterogeneity. Top-soil samples (0-15 cm) were collected from 4 × 4 m grids, and sub-soil samples (15-30 cm) collected from one-quarter of these. Soil samples were analysed for pH and available P. The height of the corn crop was measured at 33 days after germination as were grain yields, for each grid at maturity. A topographical map was developed to determine the best layout for the experiment. The resultant selection was fairly homogeneous and any major variability was documented for possible use in co-variate analyses. Similar approaches were used at other sites, as deemed necessary.

3.3. Quality of amendments

In order that results can be interpreted accurately, it is essential that there are sufficient data to characterise all amendments. To this end, samples of all fertilisers must be analysed, using appropriate methodologies, to determine total and available nutrient contents. For phosphate rocks, this can involve total and citrate-soluble P, as well as more-detailed analyses of the degree of chemical substitution, etc. At least initially, analyses of phosphate-rock samples used in the network have been limited to total and citrate-soluble P.

The analyses of organic amendments present far greater problems. Firstly, moisture content of the material as added must be measured. Secondly, the total content of inorganic elements must be determined, and thirdly, the content of particular organic compounds can be measured [11, 12]. All of these factors influence rate of breakdown of, and thus nutrient release from, residue. An alternative to estimating breakdown by thorough chemical analyses is to measure breakdown in litter bags or in in-vitro systems [13]. To date, analyses have been limited to inorganic nutrients. However, as with fertilisers, samples of organic amendments are stored for subsequent analyses.

3.4. Field-experiment results

At all sites, as expected, there were significant responses in corn yields to applications of available P sources, although extent of the responses and yields differed. As an example, there was a five-fold increase in maize yield in response to application of P as SP-36 (up to 95 kg P ha^{-1}) in the first corn crop at Jambi, Indonesia. It was noted that the maximum yield was low; growth was limited by low rainfall, and acquisition of nutrients other than P from the infertile soil may have been restricted due to reduced root exploration under the dry conditions.

Combinations of inorganic and organic sources produced large differences between treatments. Response to the more available forms of P fertiliser (TSP, SSP and SP-36) were greater than to the less-available forms (FMP and the various phosphate rocks). With subsequent crops, differences between the treatments were less marked. Greater residual value appeared to compensate for lower initial availability.

Highly available organic sources, such as chicken manure, resulted in greater yields than lower quality farmyard manure and other organic treatments, such as corn residues. The initial responses to under-sowing corn with *Stylosanthes guianensis* were poor as the stylo offered too much competition, especially when drought conditions increased the sensitivity of corn to competition for water. Even then, however, leaf colour suggested that the stylo treatment improved N nutrition. This treatment was included as a result of evidence for improved corn growth when planted into a well managed stand of stylo, combined with farmer interest in quality forage for livestock. Management of the stylo is critical so as to maintain ground cover and limit competition during crop growth, particularly the earliest stages, and still produce enough legume biomass to improve soil fertility and, if required, forage for livestock. With improved management of the stylo, in terms of frequency and severity of cutting, decreased competition resulted in increased benefits to the corn. There is scope for further improvements in management.

More data are required from subsequent crops to more accurately assess responses to P, to determine the relative effectiveness of inorganic and organic sources, to appraise the combined effects of organic and inorganic sources, and the residual values of various sources. Careful characterisation of the soils, the fertilisers, and the organic sources is essential to allow more complete understanding of the dynamics of responses across sites and years.

3.5. Improvement of laboratories

Good site characterisation, accurate interpretation of experimental results, and appropriate matching of recommendations to particular farming systems, require good-quality laboratory analyses. Many of the laboratories in the region, and within the network, have severe limitations in undertaking basic soil and plant analyses, with limited capacity to monitor the quality of analyses. A significant component of network activities aims to improve laboratory facilities and their use. To varying degrees in the different institutions, equipment has been provided, facilities upgraded, staff trained and quality-assurance programmes initiated. In many cases, an important component of improving laboratory facilities has been in terms of upgrading layout, management, and maintenance of current resources. Improving laboratory facilities and monitoring the quality of analyses are an on-going activity within and beyond the network.

The importance of high-quality laboratory analyses is recognised in one of the related initiatives outside the core activities. The aim of this initiative, undertaken in collaboration with a

Bangkok-based scientist from the Institut de Recherche pour le Developpment (IRD) and the Thai Department of Land Development, is to establish a network for the improvement and maintenance of laboratory analyses throughout the region; the Southeast Asian Laboratory Network (SEALNET). The aim of SEALNET is to foster improved analyes of soil, plant, water, and fertiliser in Southeast Asia. Laboratories in Brunei, Cambodia, Indonesia, Lao PDR, Malaysia, Myanmar, Philippines, Thailand, and Vietnam, and from ARIs and IARCs that collaborate with NARESs in agricultural research and development in this and other regions, have been involved. After a survey of laboratory practices and indications of significant support for the establishment of such a network, a workshop was held in December 1998 to develop a standard set of methods (neither too restrictive nor too comprehensive), to work towards the preparation of a detailed cookbook-style laboratory manual, and to further development the network. It is planned that the laboratory manual will form the basis of a series of training courses for laboratory technicians and managers, with follow-up visits to help participating laboratories implement changes in methods and to establish improved quality-assurance programmes with effective intra- and inter-laboratory comparisons to maintain standards.

3.6. Socio-economic analyses

Socio-economic information is essential during the identification of appropriate treatments and to assess their potential impact. Crop yields, soil characteristics and plant-nutrient uptake need to be assessed to evaluate the treatments. However, the development of appropriate strategies for sustainable land management by farmers requires additional economic analyses, and evaluation of social acceptability of proposed strategies and likelihood of broad implementation.

Analyses of field experiments revealed large differences in the relative economic benefits of different treatments at different sites. The recent economic crisis resulted in significant devaluation of many of the currencies in the region, affecting the absolute and relative costs of inputs and farmers' incomes. This emphasises the need to include sensitivity factors in such economic analyses, at least to the point of worst- and best-case scenarios, if not more complex stochastic analyses.

Another problem in such economic analyses is presented when the market for particular inputs or products has not developed, thus supply, pricing, and market-access factors have to be speculated upon. Economic analyses are a critical step in developing sustainable land-management practices, however, they must be implemented with due care.

3.7. On-farm farmer-managed evaluations

Direct comparison of a limited number of management strategies in farmer-managed trials is an important step in assessing biophysical and socio-economic impacts of these strategies and their acceptability to farming communities. In addition, such farmer-managed trials are very useful as extension exercises and to identify problems in, or potentials for, implementation and the requirement for policy intervention.

Another initiative outside the core activities of the network is underway in five provinces of Indonesia: a series of on-farm, farmer-managed evaluations. These form the *SebarFos* Upland Agriculture Improvement Project. They are being conducted by a number of agencies within the Indonesian Agency for Agricultural Research and Development (AARD) in partnership with the Potash and Phosphate Institute (PPI) – East and Southeast Asian Program, based in Singapore, and the collaboration of the acid-soils network and two upland farming projects supported by GTZ, with some financial support from Christmas Island Phosphates. Two of the detailed researcher-managed, on-farm experiments of the core of the acid-soils network, in Jambi and South Kalimantan provinces, are located in the same villages as two of these *SebarFos* studies; the other sites for farmer trials in the *SebarFos* initiative are in the provinces of Lampung, West Sumatra, and West Kalimantan.

In each of the five provinces, at least ten farmers are involved. The hypothesis is that the application of a large amount of reactive phosphate (approximately 150 kg P ha^{-1}, or 1 t ha^{-1} of phosphate rock), in combination with improved and locally adapted germplasm for whichever crop is used, and appropriate soil-conservation measures, is a strategic intervention for the development of improved farming systems. As most of the soils have some P-sorption capacity, most applied P remains within the zone of application. Except on very sandy soils with little or no sorption capacity, P-leaching losses are small, but, without protective soil-conservation measures, P contained in enriched surface horizons is susceptible to loss by surface run-off and erosion. It may be argued that a large initial input of P is not the most efficient practice on an agronomic basis or even at the level of farm economics; however, part of the reason this approach is being assessed is as a strategic intervention in terms of policy implementation. It may be that the only way farmers can achieve a level of productivity from which they can manage their farming systems in a sustainable manner is to get a significant improvement in soil fertility through nutrient capitalisation of the soil resource with a one-off injection of support from government or non-government agencies. It is likely that such a one-off intervention will be more acceptable to such agencies than a longer-term management of intervention.

The *SebarFos* trials involve direct comparisons on large areas of farmers' fields between current practice and the improved strategy. Comparable monitor "windows" are located in each treatment for the collection of more-detailed soil and crop information, and samples to aid interpretation. During the first year in Pauh Menang village, in Jambi, the *SebarFos* strategy increased peanut pod yields by between 25 and 400%, with large increases in net income, even when the costs of all inputs were met in the first year. With significant residual value from the phosphate rock, there should be even stronger justification for this strategy when costs are spread over a number of years. Linking the core field experiments, designed with a sound scientific base, to these more-applied trials that are oriented towards implementation and policy issues, adds strength to both initiatives. Improving the connection between agronomic, economic, implementation and policy issues increases the prospects for research, development, and implementation to operate as a continuum rather than as discrete and unrelated activities.

3.8. Nutrient-balance studies

An important component of degradation of land resources is nutrient removal and loss. Although water and wind are major causes of degradation of agricultural soil, it is estimated that as much as 40% of cropland degradation has resulted from chemical losses, of which nutrients are the most important [4]. Nutrient-balance studies in sub-Saharan Africa [14] and Central America [15] indicate some alarming annual losses of nutrients at the regional, farm and field levels.

Another related initiative, outside the core of the acid-soils network, is a project on nutrient-balance studies in northeast Thailand (NBS-NET). Initial estimates of crude nutrient budgets, using simple balance of fertiliser inputs and product removals, largely based on secondary statistics, indicated some major losses of nutrients for various crops, albeit with large variations between farms [16]. Through a series of surveys and measurements, and with the possibility of limited field experimentation, NBS-NET is developing improved databases on nutrient balances in rain-fed rice-based cropping systems in northeast Thailand. Better measurements and estimates of all input and loss pathways are required to understand nutrient dynamics at a number of spatial domains. At the field and farm levels, the result will be improved fertility-management recommendations to farmers. At the provincial and country levels, they will improve the efficiency of fertiliser importation, production, and distribution. These nutrient budgets vary with crop, soil type, and farm diversity, but, in addition, they vary with non-farm income and other socio-economic factors, which are important part of the surveys. When the methodologies have been developed for surveying the cropping systems in northeast Thailand, they will be used in other areas in the acid-soils network.

3.9. Implementation of improved land-management strategies

The IBSRAM Management of Acid Soils network is using a broad range of approaches to improve the management of infertile acid soils, as outlined above. These approaches include researcher-managed field experiments that have a sound scientific basis, a range of biophysical and socio-economic surveys of primary and secondary data to better understand the characteristics of the resource-management domains, and farmer-managed field trials to help evaluate the possibilities for implementation and aid in the extension process. A major focus is to increase the capacity of individual collaborators and their institutions to undertake high-quality, relevant research in a broad range of biophysical and socio-economic disciplines. In many instances, this involves the adoption, adaptation, and/or development of improved methodologies.

Although the network does not focus on large-scale implementation of improved land-management strategies, we must be cognisant of the need for, and problems of, implementation. The detailed assessments of the biophysical and socio-economic characteristics of systems in these studies cannot be replicated during the implementation phase. More-easily measured surrogate indicators must be identified so that important characteristics that define the likelihood of success with particular land-management strategies can be identified without time-consuming and expensive measurements [5]. Improved understanding of the underlying processes of critical land-management issues must be used to develop surrogate indicators, and the results of the network must be prepared in a form that can be used by extension workers, as well as in a more scientifically oriented format.

4. USE OF ISOTOPE TECHNIQUES IN COLLABORATIVE NETWORKS

Isotope techniques are not being used in the current phase of the IBSRAM network, and it is unlikely that they should ever play a predominant role in such an applied research effort. However, there are a number of areas in which radio- and stable-isotope techniques could be of significant use in improving understanding of underlying processes. Many of these techniques have been used in the region and by research groups associated with, or part of, the network, however, relatively few of the NARESs have well established isotope facilities. Since it can be argued that these techniques should not be the major focus of such research networks, it is logical that the research skills of collaborators should be matched with well equipped isotope laboratories, rather than undertaking the expensive and largely unjustifiable task of improving isotope facilities in the NARESs. The section that follows includes a brief outline of possibilities for using these techniques in such applied research networks.

4.1. Characterization of soils and fertilisers

Implementation of improved land-management strategies requires characterisation of the agroecosystems. Effective fertility recapitalisation needs good understanding of the soils and of the amendments. Simple methods will have to be developed for broad-scale use by extension workers and farmers, but these surrogate indicators will be developed only through detailed correlation studies. Isotope techniques can assist in more fully understanding P-sorption and -desorption characteristics of soils and P-release rates of different sources, particularly phosphate rocks. Such studies will be restricted largely to laboratory and glasshouse experiments.

4.2. Nutrient availability

The availability and uptake of nutrients, from organic and inorganic sources, can be assessed using direct and reverse-labelling techniques, and with multiple-isotope techniques, for the same and different elements. Likely isotopes include ^{15}N, ^{32}P, ^{33}P, ^{35}S, and ^{34}S. Such studies can be used to assess overall and temporal differences in the nutrient-supply capacity of different sources, and temporal and spatial differences in nutrient acquisition by plants. As the cost of buying and analysing stable isotopes decreases, so multi-element studies under realistic field conditions will become more common [17].

4.3. Soil organic matter dynamics

There is great need to increase our understanding of organic-residue and soil organic matter dynamics. The use of C-isotope techniques can aid in this quest. Studies using natural variations in ^{13}C and ^{12}C between plants with different photosynthetic pathways have revealed useful information on C-pool dynamics that cannot be appreciated by simple measurement of total C or other pool-fractionation techniques. Carbon inputs labelled with ^{14}C or ^{13}C have been used to follow the breakdown of specific organic amendments. Whilst the use of ^{14}C-labelled material must be restricted to a limited range of situations, primarily in the laboratory or glasshouse, the development of efficient and cost-effective methods for labelling material with ^{13}C may increase field studies on residue and soil organic matter breakdown, particularly where natural-abundance techniques are not applicable. In addition, these isotope methods should be combined with more appropriate measurements of active soil C [18].

4.4. Residue breakdown

Increasingly, the management of residue quality is seen as a critical part of achieving synchrony of nutrient release and increasing amounts of soil organic matter. There is scope to label residues with isotopes of C and important plant nutrients so as to monitor accurately release rates and improve our understanding of the chemical and physical factors that control the breakdown of residues and how they interact with soil and environmental factors.

4.5. Nutrient inputs and losses

Nutrient budgets are a useful tool for assessing an important component of the sustainability of land-management systems. Although some parts of the nutrient budgets, such as inputs of fertiliser and residues, are easily measured or estimated, other parts are more difficult to determine. There several areas in which the use of isotope techniques may play an important role in improving the accuracy of nutrient budgets, in particular: (i) ^{15}N natural-abundance techniques to estimate N inputs from BNF, (ii) ^{15}N techniques, mainly with enriched sources, to estimate denitrification, (iii) radio- and stable-isotope techniques for measuring nutrient (^{15}N, ^{34}S, ^{35}S, ^{33}P, ^{32}P, etc.) and C (^{13}C) movement down the soil profile and in solution samples, and (iv) isotope (e.g. ^{137}Cs) techniques for measuring erosion losses and sediment transport.

4.6. Soil and plant moisture

Lack of moisture can be a major constraint in many marginal soils of the tropics and sub-tropics, even if only for relatively restricted periods. Soil-moisture measurements based on isotope technology in neutron moisture meters (NMMs) can provide invaluable information on the distribution of water in a soil profile. The increased use of time domain reflectometry (TDR), with advantages in accuracy of measurement in surface layers, and multiple-site and time measurements with multiplexing, is proving to be an attractive alternative to isotope-based techniques.

In addition to ascertaining limitations for plant growth, dynamic measurement of fluxes of water in the soil profile, whether by NMM or TDR, is important for understanding leaching processes, especially when coupled with measurements of nutrients in soil and solution samples from the profile.

In certain rather specialised situations, ^{18}O and ^{2}H can be used to identify particular sources of water being used, most frequently in drier climates in which plants can get access to very different sources of groundwater.

Major variations in C isotopes in plant tissues result from different photosynthetic pathways, and smaller differences arise from other biochemical and physiologic processes, including N metabolism and water use. $\delta^{13}C$ data can be used to identify differences in water-use efficiency, although this is probably of greatest use in plant breeding and selection programmes, rather than in more-applied studies of moisture limitations in marginal soils.

5. CONCLUSION

The suite of activities within, or associated with, the IBSRAM acid-soils network constitutes a wide range of strategic and applied research, involving biophysical and socio-economic analyses. The modus operandi of the network is such that there is significant benefit to each of the collaborators and their institutions, through enhanced research and development capacity, and greater use of the research and development output by interpretation across the different agroecosystems being studied. The result of this collaboration should be soundly based strategies for improved management of the less fertile lands of the region, with a clear understanding of the potential for implementation, the process of implementation and extension, and the likely impact on the sustainability of farming communities.

Although isotope techniques are not used in the network, it is clear that they can play an important role in increasing the understanding of processes. Equally, it is clear that such techniques cannot dominate these applied research networks, but must form part of the important link that allows research output to be used for development and implementation of sustainable land-management strategies.

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