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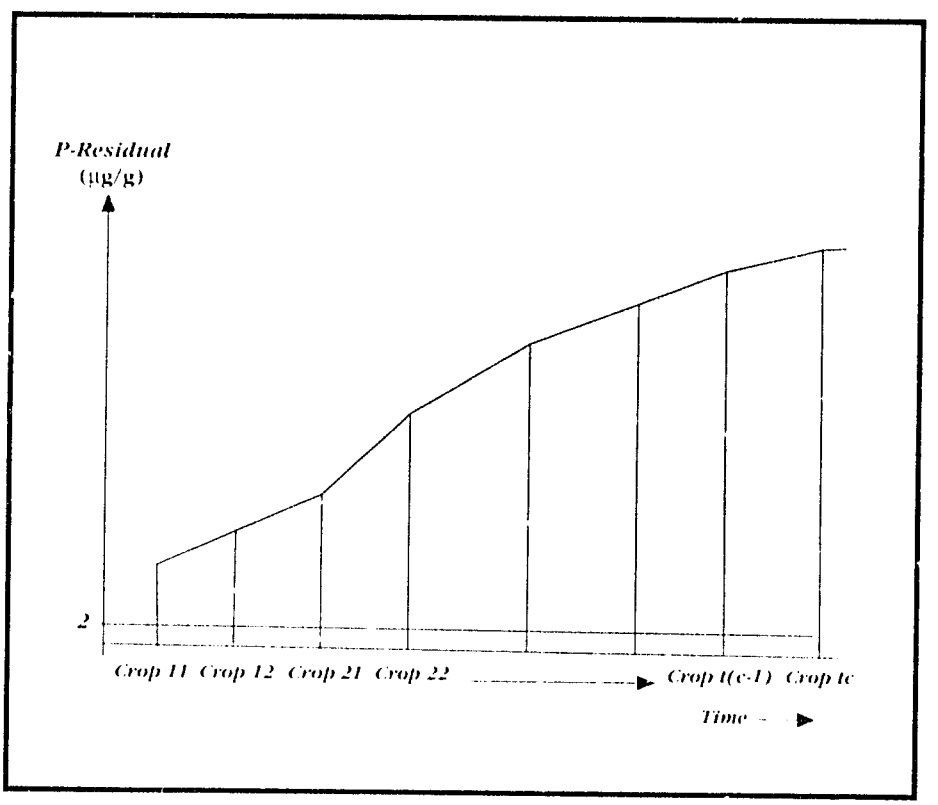
Proceedings of the TropSoils

Phosphorus Decision Support System Workshop

March 11-12, 1992 Texas A&M University College Station, TX



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Phosphorus Decision Support System Workshop

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Workshop Participants:

Russell Yost, *PDSS Principal Investigator*, University of Hawaii
Andre Bationo, IFDC/ICRISAT, Niger
Fred Cox, North Carolina State University
Mamadou Doumbia, Texas A&M University
Jose Espinosa, Potash and Phosphate Institute, Latin America
Roger G. Hanson, TropSoils Management Entity
Deborah Hellums, IFDC, Alabama
Lloyd R. Hossner, Texas A&M University
Stephen Itoga, University of Hawaii
Anthony S.R. Juo, Texas A&M University
Patrick Jomini, Industry Commission, Australia
Timothy McBride, TropSoils Communications Coordinator
Kazi Memon, Texas A&M University
Arthur Onken, Texas A&M University
W. Shaw Reid, Cornell University
Andrew Sharpley, USDA-ARS

Workshop Organized By:

University of Hawaii, Honolulu, HI

TropSoils
The Soil Management Collaborative Research Support Program
Cornell University, North Carolina State University, Texas A&M University, University of Hawaii, USAID

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Soil Management Collaborative Research Support Program
Box 7113
North Carolina State University
Raleigh, North Carolina 27695-7113

For distribution, contact:

Russell Yost
University of Hawai
Department of Agronomy & Soil Science
Honolulu, HI 96822, USA

or

Timothy McBride
TropSoils Communications Coordinator
North Carolina State University
Raleigh, NC 27695, USA

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Edited, designed and produced by: Sharon Balas

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Foreward

Phosphorus is one of three primary nutrients required for the function of biological systems and especially plant growth; the others being nitrogen and potassium. It is also one of the essential plant nutrients that limit sustainable crop production in tropical soils. For over a decade, the Soil Management Collaborative Research Support Program (CRSP), internationally known as *TropSoils*, has researched phosphorus in the soil-plant relationship for sustainable production on three continents. These TropSoils activities have facilitated collaborative efforts among international colleagues addressing the time-honored problem of how phosphorus research on one site can provide phosphorus management options to farmers at sites around the world.

Now the challenge facing us is to capture these phosphorus fertilization technologies and develop them into a computer-based information system that can be used by decision makers, both expert and non expert, at many levels, in the private and public sector, from farmers to extension agents to government agencies. TropSoils took the lead in knowledge-based research with its support of the development of ACID4 and ADSS, both an expert or decision support system (DSS), designed for the amelioration of soil acidity. ACID4 and ADSS demonstrated the feasibility of a systems approach to this problem.

In 1989, with the University of Hawaii as the lead CRSP institution, an intra-institutional project, combining the efforts of researchers at the Universities of Hawaii, North Carolina State, Cornell and Texas A& M, was formed to develop the Phosphorus Decision Support System (PDSS). The developmental purpose of PDSS was to capture in electronic form decades of phosphorus research and experience and use these data in solving current phosphorus problems at specific sites. The PDSS focus is to provide accurate and efficient detection and remedy of phosphorus deficiencies in crop production and phosphorus excesses that may be detrimental to natural resources.

The TropSoils Phosphorus Decision Support System Workshop, held at College Station, Texas, on March 11-12 1992 was organized to bring together key research collaborators in order to move toward the final completion of PDSS. Its goal was to review the status of phosphorus diagnosis and recommendation technology, identify diagnosis and recommendation research needs, review software development, identify remaining knowledge modules and plan project completion. The papers presented at the PDSS Workshop are compiled in these Proceedings.

Roger G. Hanson
Director, Management Entity
Soil Management CRSP
Box 7113
North Carolina State University
Raleigh, NC 27695-7113, USA
April 1992

The Diagnosis Of Phosphorus Deficiency And Predicting Phosphorus Requirement

R. Yost
University of Hawaii, Dept. of Agronomy and Soil Science
A. B. Onken
Texas A&M University, Research and Extension Center
F. Cox
North Carolina State University, Department of Soil Science
S. Reid
Cornell University, Department of Agronomy

Introduction

The purpose of this paper is to provide an overview of the diagnostic and recommendation structure of the Phosphorus Decision Support System (PDSS) and to present this structure for discussion and approval during the workshop. The PDSS is being developed by scientists of the TropSoils Program (including Cornell University, North Carolina State University, Texas A&M University, and the University of Hawaii). The project objective is to build on the experience of the ACID4 and ADSS expert systems, which were developed to aid decision-making regarding the management of lime and soil acidity in Ultisols and Oxisols. The PDSS is intended to both solve problems where: 1) P may be limiting crop production or 2) where excessive P has been applied and P fertilization should be suspended.

Soil phosphorus (P) is often deficient in highly weathered soils of the tropics. This is a natural consequence of the presence of aluminum and iron oxides resulting from extensive weathering and has been repeatedly documented (Fox and Searle, 1978; Manu et al., 1991; Sanchez and Uehara, 1980; Wade and Widjaja-adhi, 1988). Most soils, even those initially deficient in P, accumulate P when applications exceed removals. This is apparently the cause of high P levels in paddy rice (Widjaja-adhi, personal communication, 1991). That these two extremes can occur in fields of close proximity is a weakness in P management strategy. But, probably the major weaknesses in the strategy are the cost, inconvenience, lack of precision, and sometimes the sheer impossibility of assessing P availability for the subsistence farmer. Consequently, fertilizer decision-making can result from past practice, peer farmer influence, or desire to ensure adequate nutrition by knowingly over fertilizing.

The uncertainties in predicting P status complicates the detection of both deficiencies and excesses. As a consequence, deficiencies exist undetected while in other situations excesses occur, which increase costs and may lead to degradation of natural resources by water body contamination.

Structure of PDSS

Diagnosis

One of the goals of the PDSS project is to improve the ease and accuracy of diagnoses of deficiencies and excesses by making a more thorough use of information about the soil and cropping history and by making the system easier to use. We are attempting to do this by using various sources of information such as:

1. Past cropping history: previous crop yields and their comparison with genetic potential or regional averages or expectations.

2. Whether fertilizer had been applied in the past and whether soils of the region are known to need added P or would be expected to need P based on texture, nature of the soil mineralogy, and acidity status.

3. Presence of crop deficiency symptoms or other indications of disorder from direct plant observation.

4. Quantitative data such as plant analysis and extractable P measurement of available P from the field in question.

In addition to considering these sources of information in isolation, we want to weight these sources of information according to their reliability and then join them together to conclude an overall diagnosis (Appendix I). The diagnostic procedure will arrive at one of three conclusions: 1) P is deficient; 2) P is not deficient; and 3) there is insufficient information to conclude either sufficiency or deficiency. We are, therefore, separating the diagnosis from the recommendation stage in the P management problem-solving (Fig. 1). We believe there are several advantages to separating these steps:

1. The diagnosis process can probably be most effective if it can consider a variety of information in achieving the diagnosis, because the diagnosis can be based, within certain limits, on the observations and data that the farmer has available – rather than on a rigid set of analyses that must be performed before any results or interpretation will be made.

2. The diagnosis process may be successful even when it is not completed. If the few available observations are suggestive of a problem, the diagnosis can be successful if it points out that the current data are insufficient to make a diagnosis, and if it indicates what additional information is needed for a conclusive diagnosis.

3. The diagnosis process is best if it does not involve considerable expense. The cost and inconvenience of obtaining definitive data for a diagnosis are often deterrents to making a diagnosis at all. In practice, many agriculturists will not perform a diagnosis unless there are some indications that a potentially serious problem exists. The higher the cost and greater the inconvenience in acquiring the data the longer the agriculturist will wait before deciding to act.

Recommendation

The recommendation process, in contrast, requires substantially more information than a diagnosis; in addition to extractable P, there must be some estimate of how much of the added

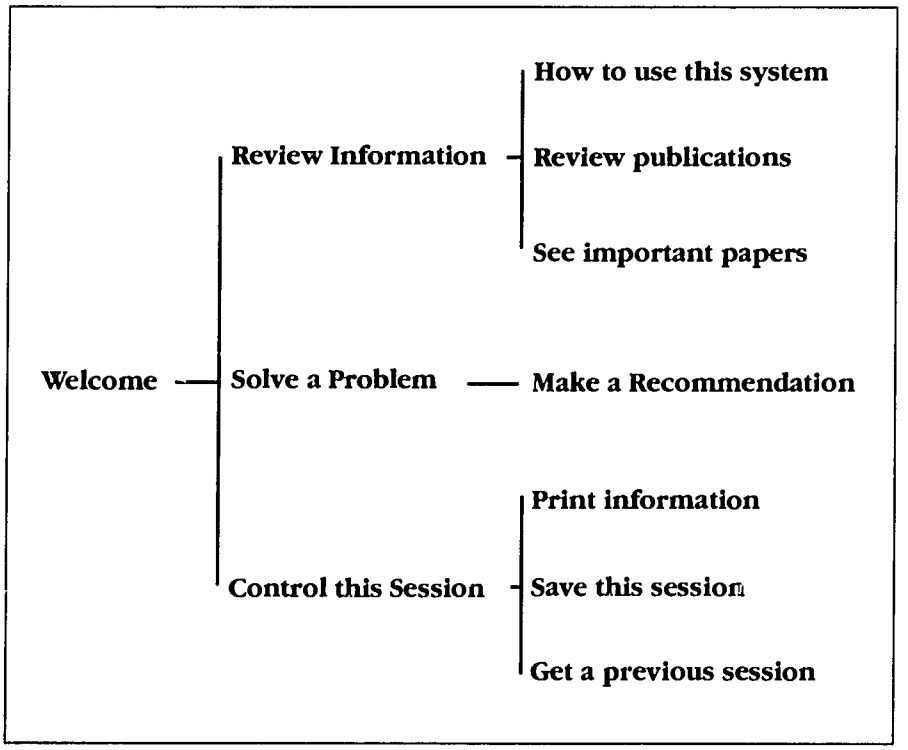

Figure 1. Introductory screen for PDSS.

phosphate remains available to the crop. The extractable P must be calibrated – meaning that the functional relationship between the amounts of added P and the increase in extractable P must be determined. A calibration is usually accomplished by multi-locational, multi-year experiments (Evans, 1987). We propose attempting to predict the calibration of soil test P using frequently measured soil properties.

The PDSS is intended to implement the best diagnosis and recommendation methodology, in a form usable by those with little training, but with responsibility for agricultural development planning or for extending modern agricultural technology to enhance food production and stability while protecting the environment.

Implementing Diagnosis and Recommendation

Sources of Information for a Diagnosis

Diagnosis by PDSS makes use of three main groups of information: 1) farmer knowledge of the specific field, its history, and visual observations of plant or soil; 2) existing regional knowledge (e.g., are the soils in the region known to be P deficient?); and 3) interpretations of nutrient concentrations in plant and soil materials taken from the field. These groups of information are combined to arrive at an overall diagnosis of likelihood of a P deficiency, no deficiency, or that the information provided is inconclusive.

Farmer Knowledge of the Field

Typical major crops and yields vary with region. Regional norms for crops are used as reference yields against which to compare previous yields (Table 1). These yield estimates were obtained from TropSoils annual reports and communication with TropSoils collaborating scientists. If the previous yields were as much or more than the regional norm we will conclude that there is no serious P deficiency, even without measuring plant and soil nutrient concentrations. This inference is probably valid only for the crop following the one whose yields were considered. Longer term predictions require soil property information. High yields, however, do not exclude the possibility of excessive nutrient application. Determining when nutrients have been or are applied in excessive amounts and plant and soil analyses will probably be required.

Crop yields that are low in relation to the regional norm may be due to many factors. Consequently, the user must be queried about other possible factors. We presently ask whether insects, diseases, drought, and inadequate cultural practices are possible causes for low yields. Low yields alone are not particularly diagnostic of P deficiency, unless all of the other yield reducing factors appear absent. It is recognized that other yield reducing factors are often present when P deficiency exists. The present focus of PDSS is P diagnosis, but multiple deficiencies are frequent and are being considered for future work.

The cropping history information also includes determining whether N, P, or K has been added.

Crop Observations /Symptoms

These are a second category of diagnostic knowledge. Observations include whether the plant has yellowing of upper or lower leaves, yellowing of leaf tips or interiors, purpling of leaf tissue together with narrow leaves and narrow stems. The presence of these symptoms suggests P deficiency, but their absence does not indicate nutrients are present in sufficient quantities.

Table 1. Crop yields which are sufficiently big to indicate that it is very unlikely that P is deficient (first approximation).

Region	Maize	Soybean	Rice	Cowpea	Peanut	Cassava	Sorghum	Millet	Inf. Source[1]
	Mg/ha								
Brazil/ Cerrado	6.0	3.0	2.0	1.0	1.5	10	na	na	
Brazil/ Manaus	4.0	2.0	2.0	1.0	1.5	10	na	na	
Niger	1.5	na	na	na	na	na	1.0	0.75	
Mali	–	–	–	0.75	–	–	1.2	0.75	Doumbia
Sitiung Indonesia	4.0	0.8-1.0	2.0	1.0-1.2	1.0	10	na	na	Dierolf
NE Thailand	2.0	–	–	–	–	10	–	na	Vityakon, Vichiensanth

Personal communications.

Table 2. Plants whose presence is associated with low P or high acidity or low fertility.

Region	Local name	Scientific name	Suggests:
Indonesia	alang alang	Imperata cylindrica	low P
Central & S. America	molasses grass/ capim gordura	Melinis minutiflora	low P, acidity
Nigeria, W. Africa	not known	Melastoma	low P, infertility
Mali/Niger	striga	Striga hermonthica	low fertility

Indeed, there are numerous cases of dramatic yield increases to P when no symptoms were present.

Another type of observation that can be useful in identifying P deficient conditions is the presence of plants usually associated with low P and high soil acidity (Table 2). Taken alone, such observations are inconclusive, but when no other information is available, they are useful. When taken together with other observations, a hypothesis that P deficiency is possible can be generated.

Existing Regional Knowledge

Sometimes there is regional or local knowledge of soils that are P deficient. In certain cases regional surveys of soil P status show that without added P one can be almost certain that P will be deficient. Such a situation occurs in the vast Cerrado of Brazil (Lopes, 1977) and in a survey of P status in West Africa presented by Manu et al. (1991). In these regions it seems that one can assume that the soils are P deficient if they have not been phosphated. Similarly, it appears that unless previously fertilized, chances are that Alfisols, Ultisols, and Oxisols will be P deficient as well. Exceptions do exist – Onne, Nigeria, for example, is an acid Al-toxic Ultisol but has a very high level of available P. Soil taxonomy, together with knowledge of previous cropping and fertilization history, is thus useful in pointing out soils that probably are P deficient and in giving an approximate soil clay mineralogy.

Plant and Soil Analyses

Quantitative measures of nutrient content in plant tissue and in soils are usually considered the most definitive information in nutrient diagnosis. While such data are more quantitative than the observations mentioned earlier, they, too, are subject to error and do not always override the visual observations. When the various groups of information are consistent they lead to rather conclusive results. They triangulate and lead to better overall decision-making than any group alone, even if the data are plant and soil analyses. But when these data are in conflict, a re-examination of the data sources is needed.

Tentative critical values for plant analysis results are given in Table 3. These values may differ with cultivar, stage of growth, or plant age, and plant part. Hence some caution should be used when interpreting the data. The usual interpretation is that plant analysis values greater than the values in the table suggest nutrient sufficiency, while values substantially less are probably associated with plants that are deficient in the particular nutrient.

Table 3. Critical levels of plant nutrients in various crops.

Crop	N	P	K	Ca	Mg	S	Zn	Fe	Mn	Cu	B	Ref†
	%					mg/kg						
Maize	2.9	.23	1.9	.4	.25	na	15	15	15	5	10	1
Sorghum	2.5	.25	1.8	.2	.15	.15	10	65	10	3.6	10	1
Soybean	5.8	.43	2.2	.9	.32	.24	50	126	35	12	42	2
Cowpea	4.0	.49	1.6	.1	.2	.25	44	na	na	na	na	2
Rice	2.5	.1	1.0	.15	.1	.1	10	70	20	6	3.4	2
Millet	1.9	.18	1.8	.11	na	na	na	na	na	na	na	2
Cassava	5.1	.25	1.1	.4	.26	.32	na	na	100	na	17	2
Peanut	3.5	.25	1.5	.5	.25	.15	20	30	20	4	20	2

Tissue sampled: Maize — ear leaf at tasselling; Sorghum — second blade below apex for macronutrients and various tissues for micronutrients.

†*References: 1 – Jones et al. (1990); 2 – Plucknett and Sprague (1989)*

Diagnosis of Excessive P

The diagnosis of excessive P uses much the same information as required for deficiency diagnosis, only in different ways. Some criteria for excessive P are:

1. Plant analysis concentrations of P much in excess of the critical level (e.g., P concentrations in excess of one percent).

2. Soil analysis, such as extractable P, in the excessive category (usually 3x or more of the critical value).

Phosphorus Fertilizer Recommendations

Developing fertilizer recommendations requires more information and data than does diagnosing a P deficiency or excess and usually requires the following information: 1) the existing extractable P level; 2) the buffering coefficient for converting applied P to extractable P; and 3) the critical level of extractable P for the intended crop. Considerable expertise is required when one or more of these quantities is not known. Our approach to making fertilizer recommendations begins with determining what information in known, whether it is sufficient to infer or approximate the minimum information for a recommendation from the above variables, and if not sufficient, what are the best alternatives to obtain the necessary information.

Existing Extractable P Level

A measure of the extractable P level for the field in question is usually necessary. Few alternatives are available to estimate the existing extractable P level. If, however, absolutely no information is available, one might assume a low level of extractable P. In cases where data are

absent, it might be useful to compare profits and benefits to P application for the case where extractable P is very low and where it is very high and P is or is not applied. This technique can be used to evaluate the benefits of obtaining the necessary data for an accurate recommendation.

Buffering Coefficient

Extractable P is used differently in making a recommendation than when making a diagnosis. For a diagnosis, extractable P levels are compared with the critical level to arrive at a "yes" or "no" answer to the question, "Is P deficient?" When developing a recommendation, the numerical value of extractable P is needed to estimate, "By how much must extractable P be increased in order to reach or exceed the critical extractable P value?" The calibration of extractable P is the process of determining how much P is required given the level of extractable P. Evans (1987) says:

> *A properly calibrated soil test should permit information in two categories:*
> 1. *Identify the degree of deficiency or sufficiency of the element.*
> 2. *Identify how much of the element should be applied if it is deficient.*

He also suggests that calibration should be a continuing process because of changes in management and technology.

Traditionally, calibration for extractable P has been generated from multi-year, multi-soil field experiments where the response of a particular crop to fertilizer level is measured in relation to extractable P. Often an entire experiment is required for each site, which has a single initial extractable P level. Multiple sites are then necessary for a wide distribution of extractable P levels. The calibration can be accelerated by factorial experiments where a response curve is developed in relation to graded levels of extractable P. Because the costs of such multi-year experiments are quite high and require considerable infrastructure and financial support, these calibration experiments are becoming increasingly difficult to justify.

Table 4. Estimates of buffering coefficients using laboratory incubation (Hunter) and by fitting equations to multiple year field data (b_1 and b_2) (Lins, 1987) and predicted from soil clay content (Hunter pred, b_1 pred).

Clay (pred) —%—	Hunter[1]	b_1[2]	b_2	Hunter (pred)	b_1
68	0.0554	0.04	0.0008	0.07	0.04
63	0.1119	0.1	0.0001	0.1	0.07
57	0.1319	0.05	0.0003	0.14	0.1
27	0.3883	0.27	0.0003	0.33	0.25
12	0.3911	0.31	0.0007	0.43	0.32

[1] *Hunter's incubation method (add P in solution, allow to dry at laboratory conditions for four days, measure extractable P).*

[2] *b_1 and b_2 represent the amount by which extraciable P was increased by P fertilization (b_1 - linear; b2 - quadratic coefficients).*

Table 5. A range of soils and their buffering coefficients as documented by various authors.

Soil	% Clay	Extractant	Initial $P(b)_0$	b_1	b_2	k	Ref.
Georgeville		Mehlich1	7[1]	0.02	0.0002	0.271	Cox et al., 1981
Portsmouth		Mehlich1	51[1]	0.32	0.0008	0.128	Cox et al., 1981
Batcombe		Olsen	16[1]	0.19		0.181	Cox et al., 1981
Oxisol	63	Mehlich1 (1:10)	3.5[1]	0.021	0.0003	0.152	Lins et al., 1985
Oxisol	27	Mehlich1 (1:10)	6.2[1]	0.246	0.0006	0.383	Lins et al., 1985
Entisol	12	Mehlich1 (1:10)	11.0[1]	0.256	0.0011	0.246	Lins et al., 1985
Oxisols, Entisols	12-68			(predicting b_1) b_1=0.43924-0.0050228clay(%) - 0.011887pH R^2=0.884			*fr.* Lins diss. p.134, 1987
Oxisols, Entisols	·12-68	Mehlich1 (1:10)		(predicting b_1) b_1=0.38023-0.005006clay(%) R^2=0.923			*fr.* Lins diss p.134, 1987
Maile (Hydrudand)		Truog	7.46[2]	0.059	0		Tamimi & Matsuyama, 1990
Hawi (Eutrudand)		Truog	50[2]	0.109	0		"
" "	13	Bray P1		0.286[1]	0		Kang & Osinamc, 1979
Kandiudult		mod. Olsen	2.9	0.2153	0		Wade et al., 1988
" "	77	mod. Olsen	2.78	0.0535	0		Wade et al., 1988
" "		Mehlich 1	3.0	0.046	0		Wade et al., 1988
Nigeria	14	Bray P1		0.286	0		Kang & Osirame, 1979
Italy (pH5.9-7.9)	4-54	Olsen-P	1.7-8.7[3]	0.12-0.57	0		Indiati et al, 1991
Africa (Oxisols, Alfisols, Vertisols, Mollsols, and Ultisols)	4-83%	Bray P1	equation	Log(Bray1) = 0.5594 + 0.0154*clay +0.1117*OC +			

" "		Truog	equation	0.03*ecec Log(Truog) = 2.629 + 0 .02*clay - 0.32*pH + 0.0205*ecec		Johnston, 1991
Typic Calciorthoxid (Breda) (275mm rainfall)		Olsen-P	2.66	0.683		Johnston, 1991 Matar, 1988
Vertic Chromoxerert (Jinderess) (470mm rainfall)		Olsen-P	2.52	0.706		Matar, 1988
Chromoxerertic Rhodoxeralf (Tel Hadya) (350mm rainfall)		Olsen-P	2.92	0.784		Matar, 1988
'Highly weathered'	varying	'labile P'	equation (180d w/wet- ting & drying)	-0.047log(clay%) + 0045P(labile P in mg/kg) - 0.053OC(%)+0.39		Sharpley et al. ,1984
'Highly weathered'	varying	'labile P'	equation (180d)	-0.19log(clay%) + 0.70		Sharpley et al., 1989
"	"	"	equation (30d)	-0.30log(clay%) + 0.68		"
Oxisol	76	Bray P1	equation (field)	12.41* exp(0.013*P)		Smyth & Cravo, 1990
"	"	Mehlich1 (1:10) (maize: 6 mg/kg; cowpea: 8 mg/kg)	equation (field)	3.13*exp(0.016*P)		"
NE Thailand	5	Olsen-P		22 mg P/kg (critical for maize)		
NE Thailand	5	Bray P2		27 mg P/kg (critical for maize		Suwanarit, 1985
Typic Umbraquult (Portsmouth)		Mehlich1 (1:4 ratio)	field	20	0.477	McCollum, 1991

Extractable P = $b_1X + b_2X^2$, where X is applied P, usually expressed in kg P/ha.
Extractable P = $P1exp(-kT)$, where P_1 is extractable P at time T_0 and T is the time, in years, after the initial measurement. Here larger values of k indicate lower residual effects. Researchers often do not include crop removal of P in computing this value, as pointed out by McCollum (1991).

[1] *Extractable soil P expressed in kg/ha, applied P expressed in kg P/ha.*
[2] *Extractable soil P expressed in ppm, applied P expressed in lbs P/A.*
[3] *Extractable soil P expressed in mg/kg, applied P expressed in mg P/kg.*

Laboratory Incubation

Buffering coefficients have also been estimated with laboratory incubations (Hunter, 1974; Sharpley et al., 1984; Sharpley et al., 1989; Johnston et al., 1991; and Indiati et al., 1991). Lins (1987) estimated buffering coefficients by laboratory incubation and by fitting predictive equations to data from yields, extractable P, and applied P from a field study conducted for several years. The estimates were relatively similar (Table 4) suggesting that incubation methods might be helpful in estimating buffering coefficients if they are not available or cannot be predicted from available data. The method used (Hunter, 1974) has been developed with such purposes in mind. As a research need, we would like to see whether this incubation method can estimate field scale buffering coefficients of the type developed by Lins (1987). Research data used for this purpose would also be useful in predicting buffering coefficients from basic soil properties.

Predicting P Buffering Coefficients

Several buffer coefficients and equations that have been developed to predict P buffering coefficients are shown in Table 5. Equations have been developed by Sharpley et al. (1984;

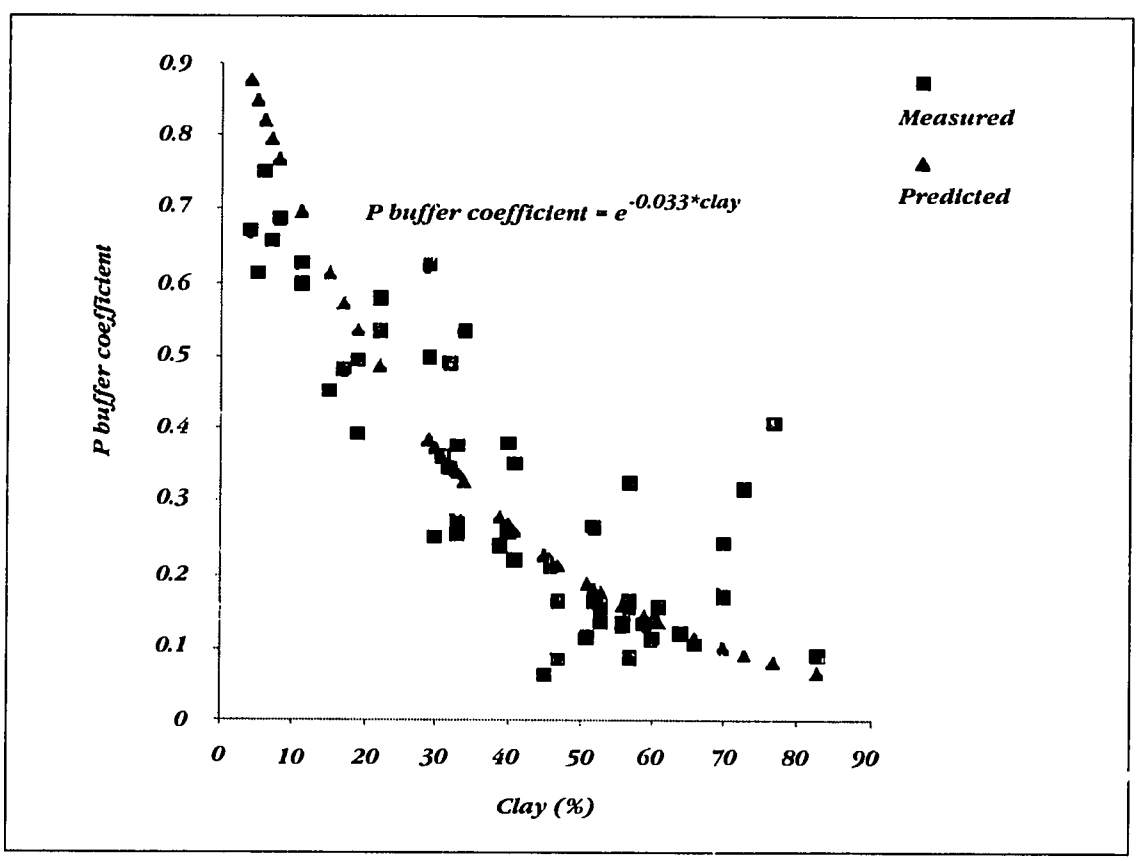

Figure 2. Predicting P buffer coefficient for soils of S. Africa (Johnston et al., 1991). (Data analyzed by F.R. Cox, North Carolina State University.)

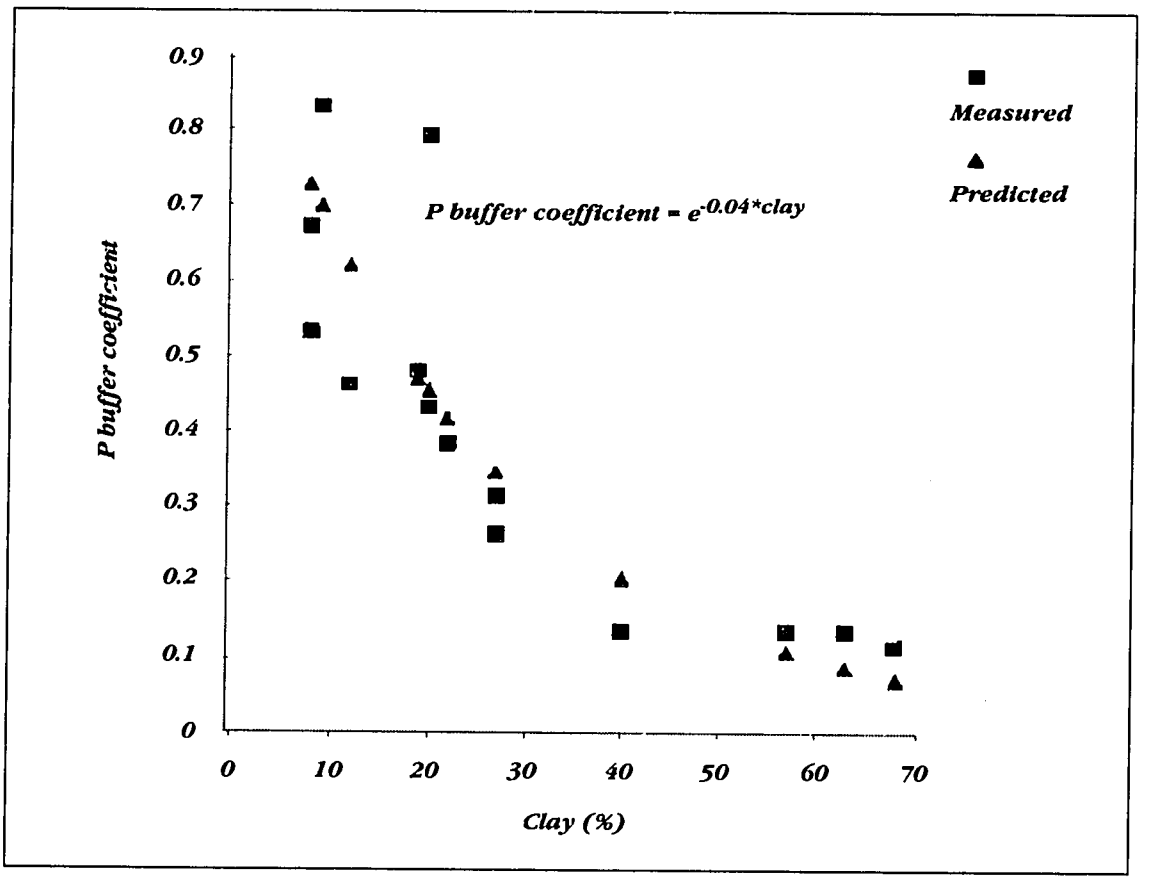

Figure 3. Predicting P buffer coefficient for soils of North Carolina and Brazil. (Data analyzed by F.R. Cox, North Carolina State University.)

1989), Johnston et al. (1991), and Indiati et al. (1991) that predict P buffering coefficients from commonly measured soil properties.

One hypothesis of the PDSS work is that estimates of P sorption, in the absence of specific data, can be approximated by estimates of the sorption intensity (amount of P sorbed per unit area) and the sorption area (amount of sorption area). We suggest that one of the reasons that measures of clay content have proven useful in predicting P requirement (Lins et al., 1985) is because the percentage of clay reflects the amount of surface available for sorption. Dr. F.R. Cox has recently compared various predictions of buffering coefficients based on clay percentage (Figs. 2 and 3). These results suggest that further studies on using clay percentage as a proxy to predict buffering coefficients may be worthwhile.

The other variable that we suggest is important is sorption intensity. The sorption intensity is thought to be related closely to the mineralogy of the soil – in particular to the density and concentration of hydroxyls on the soil clay surface.

Our hypothesis is that variables that permit us to predict the quantity of A hydroxyls on the soil (those primarily involved in P sorption) will be useful in predicting the P buffering coefficient. We propose this question as a research need.

Critical Level of Extractable P

We have reviewed an extensive study of P requirements for soybean in Brazil by Lins (1987), who observed that the critical level for soybean varied from 6 to 23 mg P/kg as soil clay content decreased from 63 to 12 percent. Fitting an equation to the relationship, the results are:

$$P_{critical} = 26.568 - 0.30325 \cdot \text{clay (\%)}: \text{ adjusted } R^2 \text{ of } 0.97.$$

We suspect that these equations will not be valid for all situations because of soil mineralogy differences, but this factor is surely necessary in order to estimate the number of A hydroxyls on the absorptive surface. Lins' results indicated that a different equation was needed for gibbsitic soil. If the above approach is taken, then some means of quantifying the mineralogical differences in exposed A hydroxyls is needed.

We propose using Lins' approach to diagnose and recommend, as a strategy to better manage nutrient P to both increase production in situations of P deficiency and to reduce applications of P where the levels are already excessive. This is probably not the ultimate approach, but it has advantages in being based on a testable theoretical assumption that P sorption is due to sorption by A hydroxyls and by better quantifying the number of A hydroxyls on the soil, improved prediction and understanding of P sorption for practical agriculture will occur. In addition, this approach will hopefully stimulate more mechanistic and process-oriented approaches in managing soil and fertilizer P.

Phosphorus Accumulation

Another exploratory effort of the PDSS program is to attempt to use the rate functions developed for recommendations to explore effects of management of P in the future, which would provide some of the data needed to evaluate sustainability of production and environmental concerns related to P buildup and help design management strategies that are more economically sound. Matar (1988) adapted the approach of Cox et al. (1981) to include the reduced extractable P due to crop removal:

$$P_t = P_{eq} + [(A + BF) - P_{eq})\exp(-k_1 t) - TPU \qquad (1)$$

where P_t is the extractable P at any one time (kg P/ha), P_{eq} is extractable P at the equilibrium state, which is a function of soil properties, climate, and cropping system, A and B relate the increase in extractable P that occurs when P is applied (A is the intercept and B is the slope of the regression line – the P buffer coefficient of the soil), F is the amount of fertilizer P added, k_1 is the loss constant per month of P immobilization in soils, and TPU is the total P removed from the soil in mg/kg. As others have found, the relation between P added and $NaHCO_3$-P was linear within the range of usual application rates (0-52.5 kgP/ha). Matar's model includes several assumptions: 1) P uptake is proportional to the level of available P in the soil at any one time t; 2) both native P and added P are equally available; and 3) no replenishment of $NaHCO_3$—P from the solid-phase P occurred.

Previous and most current P management is based on measurement of current P status through soil tests, at best, or without any knowledge of extractable P, at worst. In many of the regions where P management is important to ensure productivity and economic viability, soil testing is not feasible on a regular schedule. Where annual or biannual sampling is not possible,

the quantity of available P may accumulate. Also, presumably, where P levels were once adequate, but fertilizer P could not be added, extractable P levels would eventually decrease.

In an effort to make reasonable predictions of the extractable P when direct measurement is not possible, we suggest a simplified simulation model that includes the following components (Appendix II):

1. Use of the buffering coefficient to estimate by how much added P will increase extractable P.

2. Estimate crop removal of P based on yield and how residue is handled.

3. Consider the long term sorption or conversion from available P to unavailable P.

4. Predict extractable P status by querying the user about their management and yields over extended periods of time (5-10 years).

By bringing together these elements of P management, the goal of the simulation is to provide some plausible estimate of the status of available P under alternative P management strategies. The approach is similar to that suggested by Matar (1988) for semi-arid regions and builds on suggestions by Wolf et al. (1987) for humid regions by including soil properties and by considering situations where experimental field experiments have not been conducted.

Economic Evaluation of Recommendation Alternatives

Jomini (1990) and Jomini et al. (1991) describe an analysis of economic factors relating to the soil levels of P, cost and availability of rock phosphate, and soluble P materials in an economic analysis that considers risk and uncertainty in yields. The approach is unique in that it dynamically considers fertilizer P carryover, possible states of nature, and the farmer's economic condition. This analysis will be presented at the workshop so need not be described here. At present, the economic analysis proposed seems ideally suited to link with the PDSS system, so the economic consequences of fertilization can be evaluated before the final recommendation is given.

Research Needs

So far research needs have been identified for the following three coefficients:

1. A method of predicting the critical level of P for soils that vary in mineralogy (density of A hydroxyls, which are the primary source of P sorption).

2. A method of predicting buffer coefficients that includes the major factors associated with P sorption in soils.

3. A method of predicting residual effects based on fundamental soil properties. It is clear that soils such as the Andisols provide less residual effect than do soils with crystalline clay mineralogy.

If these three prediction methods were available, the PDSS would be able to generate P recommendations in the majority of soils of the humid tropics.

Appendix I. A Current Method of Combining Evidence of a Phosphorus Deficiency

Diagnostic Strategy

I. Overall View

If last crop yield above it's threshold, then no problem. (NProb)
If last crop yield below F * it's threshold, then problem. (Prob)
Compute Confidence factors for

1. Cropping History.
2. N observations symptoms are present (yellowing lower leaves, yellowing tips and midrib first, and no serious drought in previous three weeks). Then if intended crop is maize, millet, rice or sorghum, have problem with confidence 60%.
3. P observations symptoms (purple leaves, narrow stems and leaves). confidence 60%
4. Soil analysis. (P and K: <= 80% critical level) confidence 70%.
5. Plant analysis. (N, P, K, Ca, Mg, and S: <= 75% critical range) confidence 60%.
6. Acidity. (Critical aluminum saturation· >=120% of critical Al sat) confidence 70%.

If MAX of these confidence factors is >= 50% then conclude Problem.(Prob)
else conclude no problem. (NProb)

7. If MAX of these confidence factors is <50% then the data are insufficient for a diagnosis.

II. Cropping History Confidence Factor

	Fertilized		Didn't Fertilize	
	Comments	No Comments	Comments	No Comments
above 100% of threshold then	0	0	0	0
80% to 100% of threshold then	10%	20-30%	20%	40%
below 80% of threshold then	20%	40-60%	40%	70%
below 50% of threshold	95%	95%	95%	95%

Use this table for each year's datum. Combine the data using a 4,2,1 weighting scheme. i.e.

Crop Confidence = (4*C1 + 2*C2 + C3) / 7 {if we have three years data}
(2*C1 + C2) / 3 {if we have two years data}
C1 {if we have one year of data}

If any of the crops are maize or soybean, then multiply confidence factor by 80%. (i.e., reduce likelihood of deficiency.)

Appendix II. Outline of a Proposed Simulation to Help Anticipate P Accumulation and Buildup

Algorithm for Estimating Soil Residual P

Defined Variables:

CLAY = Clay content [in %]
AL = Aluminum content [in %]
AMPAL = Amorphous Aluminum oxide [in %]
AMPFE = Amorphous Iron oxide [in %]
WP15 = soil moisture at 15 bar water potential [in %]
OM = Soil organic matter content [in %]
BD = Soil Bulk Density [g/cm^3]
SA = Sorption Area [in m^2]
SD = Sorption Density [in _g/m^2]
CEC = Cation Exchange Capacity [in cmol$_c$/kg]
c(t) = number of crop per year
FRC = P-fertilizer recommendation factor
ECF = Extr. P correction factor
EP(t,c(t),i) = Amount of extr. soil P at year t, crop c(t), and state i, [in mg/kg]
state i (i= 0,1,2) _ state 0 = the state where P-fert. has not been applied
state 1 = the state where P-fert has been applied, before cropping
state 2 = the state after cropping or at harvest.
TP(t,c(t),i) = Total soil P at year t, crop c(t), and state i, [in mg/kg]
RP(t,c(t),i) = The amount of the residual soil P at year t, crop c(t), and state i
= Total P _ Extr. P (includes both reversible and irreversible), [in mg/kg]
DP(t,c(t)) = change in the amount of estimated P accumulation [in mg/kg]
PFR(t,c(t)) = The rate of P-fertilizer in year t, applied prior to crop c(t), [in kg/Ha]
PUP(t,c(t)) = Estimated P-uptake in year t, and crop c(t), [in mg/kg]
PP(t,c(t)) = Amount of P in the plant tissue at year t, crop c(t), [in mg/kg]
PSB1(t,c(t)) = Amount of P-sorbed by soil at year t, during crop c(t) when the crop is still growing, [in mg/kg]
PSB2(t,c(t)) = Amount of P-sorbed by soil at year t, during non-cropped interval between successive crop c(t), [in mg/kg]
CR$(t,c(t)) = Kind of crop commodity planted at year t, crop c(t).
CRY(t,c(t)) = Crop yield at year t, crop c(t) [in kg/Ha]
CL(t,c(t)) = The length [in months] of crop c(t)
TI(t,c(t)) = The time interval between crop c(t)s, [in months]

Initializing Variables:

INPUT clay content or default value _ CLAY
INPUT AL-content or default value _ AL
INPUT amorphous aluminum content or default value _ AMPAL
INPUT amorphous iron content or default value _ AMPFE

```
INPUT soil moisture at 15 bar potential or default _ WP15
INPUT soil organic matter content or default _ OM
INPUT soil bulk density or default value _ BD
INPUT P-fertilizer recommendation factor _ FRC
INPUT Extractable-P uptake correction factor _ ECF

/* Estimating sorption area and sorption density */

SA = function(CLAY, OM, ...)
SD = function(SA, CEC,...)

/* Estimating P Accumulation */

FOR t = 1 to t

    INPUT number of crop at year t _ c
    c(t) = c

    FOR c(t) = 1 to c

    INPUT kind of crop commodity at crop c(t) _ CR$(t,c(t))
    INPUT the length (in months) of crop c(t) _ CL(t,c(t))
    INPUT estimated time interval for the next crop _ TI(t,c(t))
    IF TI(t,c(t)) = "" THEN TI(t,1) =...= TI(t,c) =     {12_(CL(t,1)+...+CL(t,c))}/c

    NEXT c(t)

    INPUT initial extr. soil P or default _ EP(1,1,0)
    INPUT initial total. soil P or default _ TP(1,1,0)

        FOR c(t) = 1 to c

    /* For Crop c(t)th at year tth */

    INPUT the rate of P-fertilizer  or default _ PFR(t,c(t))
    INPUT Expected crop yield or default _ CRY(t,c(t))
    INPUT measured P-tissue content or default  _ PP(t,c(t))

    EP(t,c(t),1) = EP(t,c(t),0) + ((1/(2*BD))*PFR(t,c(t))*FRC
    PUP(t,c(t)) = PP(t,c(t))*CRY(t,c(t))*ECF
    PSB1(t,c(t)) = f{EP(t,c(t),1),SA,SD,Crop,Time}
    EP(t,c(t),2) = EP(t,c(t),1) - PUP(t,c(t)) - PSB1(t,c(t))
    IF TI(t,c(t)) < 1 THEN PSB2(t,c(t)) = 0
    ELSE PSB2(t,c(t)) = function{EP(t,c(t),2,SA,SD,Time}

    IF t=1 and c(t)=1 THEN EP(1,1,0) = EP(1,1,0): RP(t,c(t),0) = TP(t,c(t),0) - EP(t,c(t),0):
    RP(T,c(t),2) = RP(t,c(t),0) + PSB1(t,c(t))
    ELSE EP(t,c(t),0) = EP(t,c(t),2) - PSB2(t,c(t))
    RP(t,c(t),0) = RP(t,c(t),2) + PSB2(t,c(t)

    /* Estimating Residual P at year t, and at crop c(t), at state 2 */

    RP(t,c(t),2) = RP(t,c(t),0) + PSB1(t,c(t))
    DP(t,c(t)) = RP(t,c(t),2) - RP(t,c(t),0)

    NEXT c(t)

NEXT t
```

/* PRINT Result as the following format */

Year (t)	Crop c(t)	Initial P P(t,0)	Initial P+P-fert. P(t,1)	Final P P(t,2)	Est. Residual P DP(t,c(t))
1	1				
	.				
	.				
	c				
.	1				
	.				
	.				
	c				
t	1				
	.				
	.				
	c				

/* PLOT the Result in Graphic form */

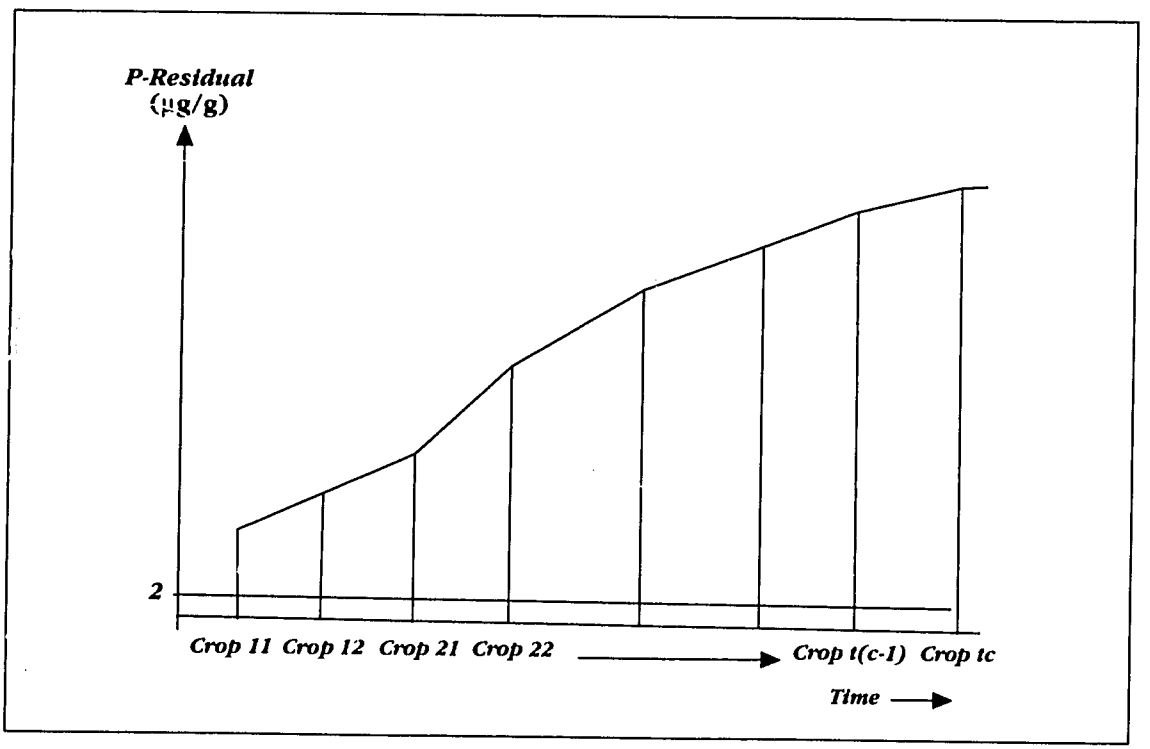

Figure 4. Example of a graphic plot of simulation results where P is accumulating in the soil.

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Contact Person:

Russell Yost
University of Hawaii
Department of Agronomy and Soil Science
Honolulu, Hawaii 96822
Telephone: (808) 956-7066
Fax: (808) 956-6539
Electronic Mail: (BITNET) rsyost@uhunix.bitnet
(CGNET) CGI055

Soil Phosphorus Status And Use Of Different Calibration Tests To Predict Phosphorus Requirement And Response Of Selected Crops Of West Africa

A. Bationo
IFDC/ICRISAT, Niger
A. Manu
Texas A&M University, Department of Soil and Crop Sciences/TropSoils
A.U. Mokwunye
Director, IFDC Africa

Abstract

Phosphorus (P) deficiency is a major constraint to crop production on soils in West Africa. The low adsorption capacities of these soils, however, means that moderate amounts of P amendments are required for optimum crop production. Although farmers in the region lack adequate capital for the purchase of commercially imported P fertilizers, an economic alternative could be the use of locally-mined phosphate rock in ground or partially acidulated forms. Calibration studies are necessary for cost effective recommendations for P application; yet most of these studies have been carried out in the temperate regions using water soluble P fertilizers. On selected unfertilized soils of West Africa, Bray P1, Bray P2, Mehlich1 and Olsen performed equally well in assessing P availability. High correlations were also obtained when the same four methods were used on soils fertilized with water soluble P fertilizers. The efficiency of these methods in extracting P was dependent on the solubility of the PR source. P sufficiency levels obtained using Bray P1 on soils receiving water soluble P fertilizers were 6.6 mg kg^{-1} for pearl millet in the northern Sahelian zone and 7.5, 9.7 and 10.7 mg kg^{-1} for cowpea fodder, pearl millet grain, and total biomass of sorghum, respectively. P recommendations were made based on the relationship between extractable P and quantities of P applied.

It was observed that crop rotations and levels of organic matter in the soil can have a significant influence on P calibration.

Introduction

Soils of West Africa are generally deficient in phosphorus (P) and it is one of the major constraints to sustainable crop production in the region (Bationo et al, 1986). P deficiency increases from slight in the wetter southern zone to severe levels in the dryer areas of the north. In the northern zone, crop response to N fertilizers could be minimal, or sometimes completely nonexistent, until P requirement has been satisfied (Traoré, 1974).

Although the beneficial effects of P fertilizers are well known, lack of adequate capital limits

the use of imported commercial P fertilizers by many West African farmers. However, another economic alternative is native phosphate rock (PR), large deposits of which occur in this region. Due to their low solubility and reactivity, the direct use of PR in West Africa has not been found to be very attractive by farmers. However, technologies have been developed for the production of partially acidulated PR to increase its agronomic effectiveness (Schultz, 1986).

Several soil testing procedures have been developed in order to estimate amounts of P that are proportional to those that can be utilized by crops. Based on these test results, recommendations are made for amounts of P required for optimum crop yields. These tests have generally been developed and carried out on temperate soils and recommendations have been made for the application rates of commercially available water soluble fertilizers. It has been reported that critical soil test P levels are influenced, to a large extent, by soil texture, with high critical levels being associated with sandy textured soils while heavier textured soils are characterized by low critical soil P levels (Cox, 1991).

Unfortunately very limited P calibration work has been done on West African soils either using water soluble P fertilizers, ground PR or acidulated PR as a base (Bationo et al; 1991).

This paper discusses the following:

1. Assessment of P status and factors influencing P availability in selected West African soils.
2. Comparison of different testing methods on soils that have received commercial water soluble P fertilizers, ground PR and partially acidulated PR.
3. Establishment of P sufficiency levels and recommendations for P applications required for optimum production of selected crops.
4. The effect of crop management practices on P calibration.

Materials and Methods

Site Selection

In order to identify the nutrient needs of the important crops within the major agroecological zones of West Africa, IFDC established nine benchmark sites along a south-north transect for agronomic research. Along this transect, rainfall decreases from 1,500 mm at Amouchou in Togo to 560 mm at Sadoré in Niger. The major agroecological zones traversed along this transect are the Sahel, Sudan Savanna, Northern Guinean Savanna, Southern Guinean Savanna and Derived Savanna. Nine sites (soils) along this transect were sampled for this study. Soil from an irrigated rice paddy was added as the tenth soil (Fig. 1).

Laboratory Analyses

The surface soils were air-dried and crushed to pass a 2 mm sieve. Soil pH was determined in H_20 and KCl using a 2:1 solution: soil ratio. Exchangeable Al and total acidity were measured using the method described by Maclean (1982). Exchangeable bases were displaced with 1N NH_4OAc. Ca and Mg were determined by atomic absorption spectro-photometry and K and Na were determined using flame photometry. Organic carbon was determined by the method of Walkley and Black (1934).

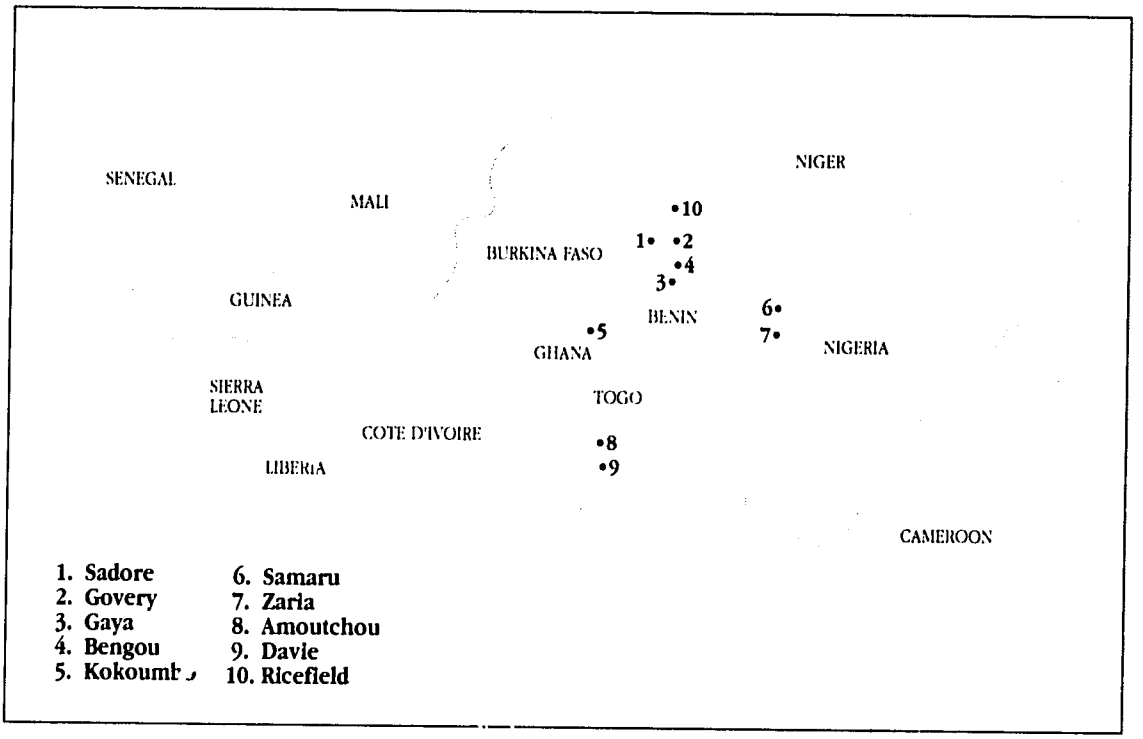

Figure 1. Location of sample sites in West Africa.

Total P was determined after wet digestion with perchloric acid. Extraction for available P was done using the Bray P1 extractant. P in solution was analyzed by the molybdate blue method as described by Olsen and Sommers (1982). Phosphorus sorption characteristics were determined using the method of Fox and Kamprath (1970).

Poorly crystalline and free Fe and Al oxides were determined by oxalate extraction (Schwertmann 1973) and citrate-dithionite extraction (Jackson 1958), respectively. Iron and aluminum were measured by atomic absorption spectrophotometry.

P - Incubation Studies

In order to determine the fertilizer P equivalent of these soils, 50 g samples were incubated with an aqueous solution containing O and 2500 mg P. Soils were kept at field capacity for three weeks, after which the amount of available P in each soil was determined using the Bray P1 extractant.

P - Calibration Studies

Representative soils were taken from plots on which different P fertilizer sources and rates have been applied over several years. Samples were analyzed using five soil testing methods: Bray P1 and P2 (Bray and Kurtz 1945), Mehlich1 (Nelson et al., 1953), water extraction (Sissingh, 1971) and Olsen (Olsen et al., 1954).

Table 1. Physical and chemical properties of some selected IFDC Benchmark soils (0-15 cm) from West Africa.

	Sadoré	Gobery	Gaya	Bengou	Kokombo	Zaria	Samarou	Amouchou	Davie	Rice Field
Soil Type	Entisol	Alfisol	Alfisol	Alfisol	Alfisol	Alfisol	Alfisol	Alfisol	Ultisol	Vertisol
Climatic zone[a]	S	S	SS	SS	NGS	NGS	SGS	SGS	DS	S
Rainfall (mm)	560	620	800	800	800	1055	1055	1360	1500	NA
Organic matter (%)	0.130	0.334	0.499	0.618	0.679	0.787	1.170	0.875	1.29	5.910
pH H_2O	4.95	5.75	4.95	5.15	6.20	4.05	5.45	6.65	5.45	5.10
Exchangeable acidity (Cmol(+)kg^{-1})	0.38	0.08	0.51	0.06	0.00	0.34	0.07	0.02	0.03	0.39
Effective cation exchange capacity (Cmol(+)kg^{-1})	0.66	0.73	1.22	1.86	2.57	2.54	3.38	2.50	3.54	14.88
Total P (mg kg^{-1})	60	75	159	106	62	172	192	76	68	411
Available P (mg kg^{-1})	3.70	3.22	3.81	3.39	2.65	12.96	2.59	3.70	7.41	25.90
Fe-oxalate (mg kg^{-1})	153	113	372	205	219	805	865	303	306	3265
Al-oxalate (mg kg^{-1})	148	114	299	183	102	374	244	126	340	70
Fe-Dithionite (mg kg^{-1})	4800	425	14600	5000	5250	7775	6125	1525	9950	5175
Al-Dithionite (mg kg^{-1})	84	364	1136	557	450	1062	695	287	59	804
Clay (%)	4.5	3.5	10	9	6	14	12	5	14	44
Sand (%)	89	90	76	61	85	39	38	85	75	19
Maximum P sorbed (mg kg^{-1})	75	51	127	60	28	128	97	35	74	464
P.ad 2 ppm[b] (mg kg^{-1})	24	20	31	15	14	29	21	12	23	40
Fertilizer equivalent (mg kg^{-1})[c]	1.25	1.22	1.33	1.37	1.24	2.65	1.8	1.34	1.51	5.68

a *S = Sahel, SS = Sudan Savanna, NGS = Northern Guinean Savanna, SGS = Southern Guinea Savanna, DS = Derived Savanna.*

b *Pad. 2 ppm: phosphorus to be adsorbed in order to have .2 ppm P in the soil solution at equilibrium and is defined as P external requirement.*

c *Fertilizer equivalent is quantity of P needed to increase Bray P1 by 1 mg kg^{-1}.*

Table 2. Simple correlations (r) between selected soil fertility parameters (n = 10).

	ECEC	pH (H_2O)	Clay
Organic matter	0.99***	-0.16	0.97***
Effective cation		–	–
Exchange capacity (ECEC)		-0.14	0.97***

*** *Significance at the 0.0005 level*

Phosphorus sufficiency levels, defined as the amount of extractable P required to obtain 95 percent of the maximum yield, were estimated using linear or non linear regression models.

Results and Discussion

General Soil Characteristics

Soils were sandy to sandy loam in texture except the rice paddy soil which had a clayey texture (Table 1). Soils exhibited a wide range in acidity going from acid (pH 4.1) to almost neutral (pH 6.7). Exchangeable acidity was very low. It should be noted, however, that the

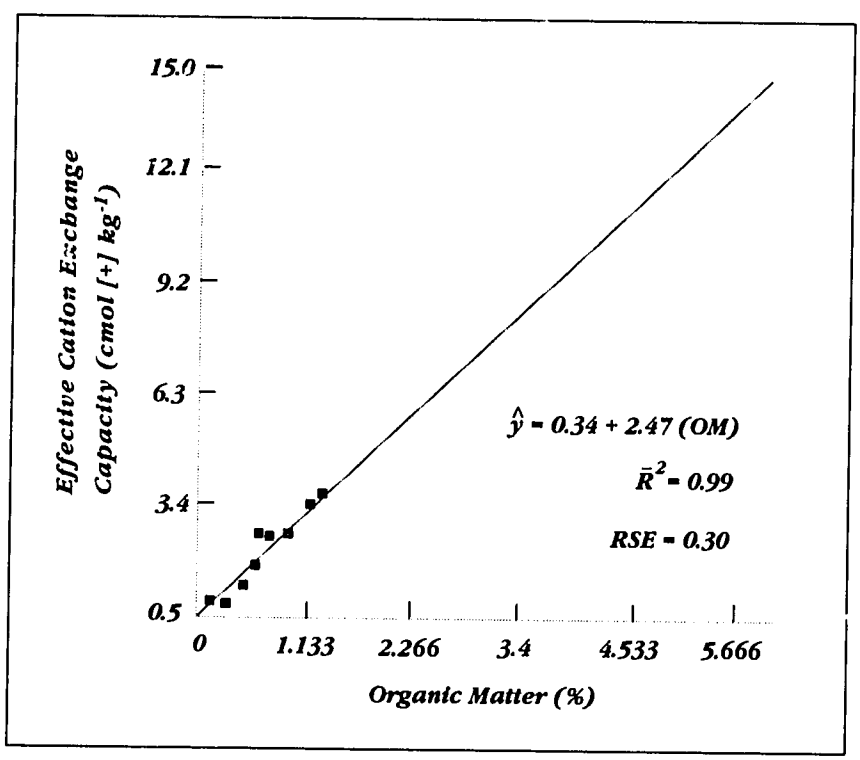

Figure 2. Relationship between effective cation exchange capacity and organic matter of selected West African soils.

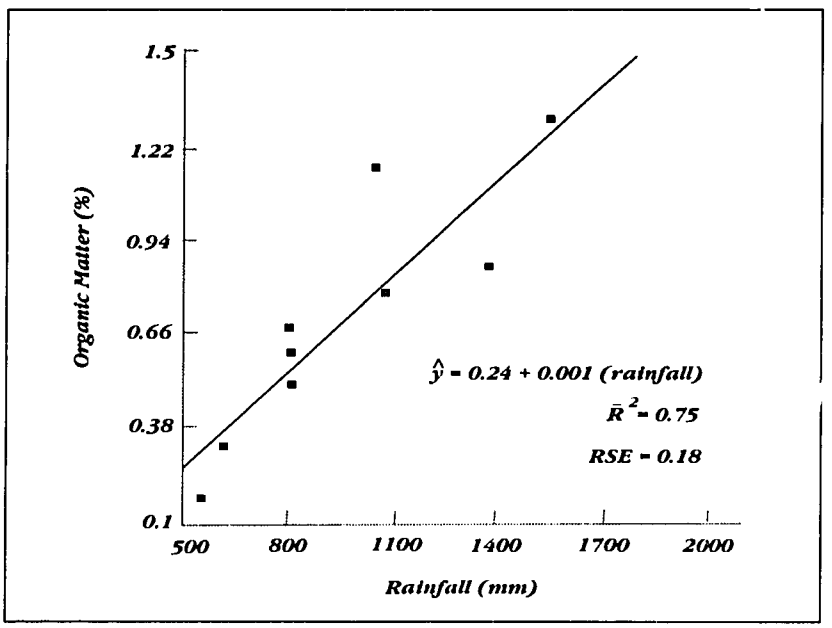

Figure 3. Relationship between organic matter content and rainfall of selected West African soils.

transect did not traverse the highly weathered acidic granitic Ultisols which occur in the high rainfall areas of West Africa.

Organic matter (OM) levels and effective cation exchange capacity (ECEC) were generally low, with the exception of the rice soil which had OM and CEC values of 5.9 percent and 14.9 cmol(+) kg^{-1} respectively. Strong interrelationships existed between some soil fertility parameters (Table 2). Organic matter was highly correlated with ECEC (Fig. 2), clay content (r = 0.97***), and rainfall (Fig. 3).

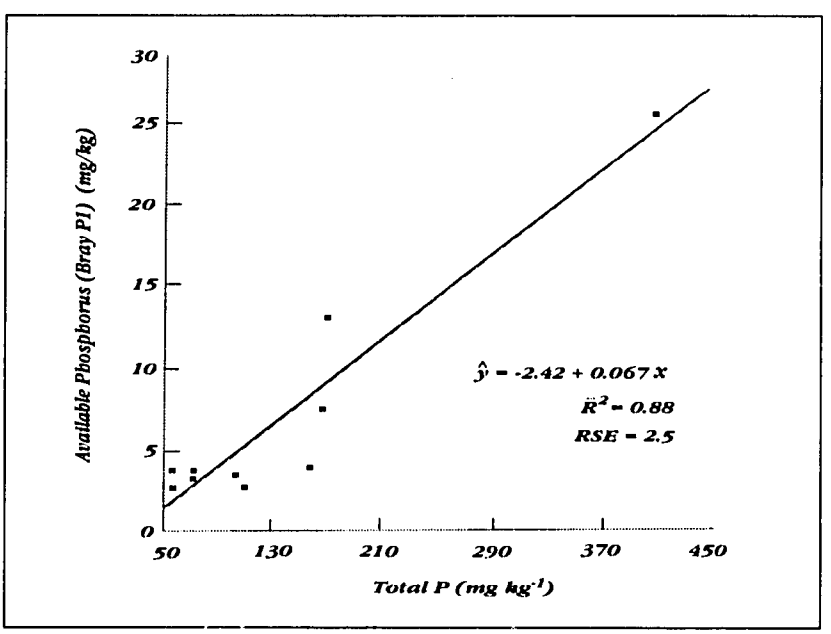

Figure 4. Relationship between available phosphorus and total phosphorus of selected West African soils.

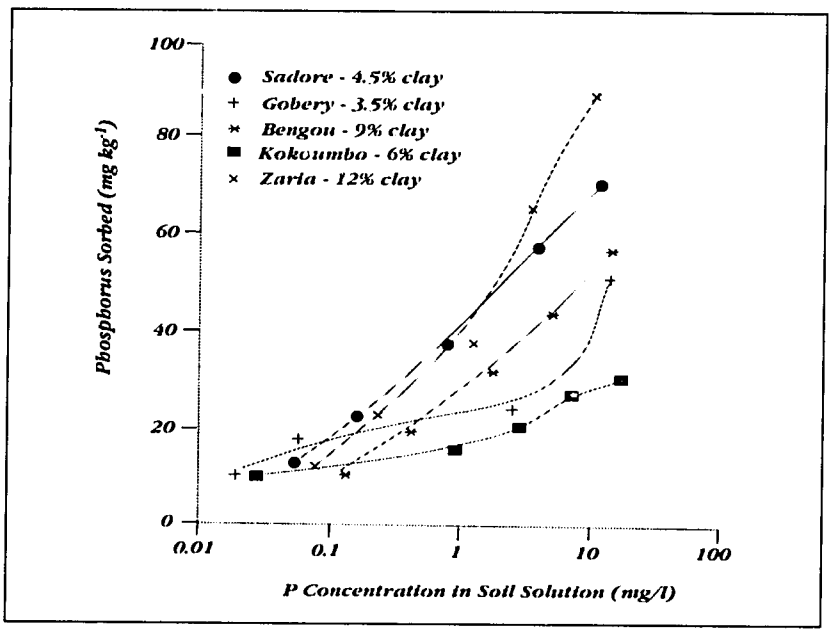

Figure 5. Relationship between phosphorus sorbed and phosphorus in soil soultion at equilibrium for selected West African soils.

Phosphorus Parameters

With the exception of the Vertisol, available P levels in the soils were generally below critical levels required by most crops. Total P amounts ranged from 60 to 192 mg kg^{-1} and a very strong relationship existed between total P and available P levels in the soils (Fig. 4).

P sorption characteristics were determined by fitting the sorption data to the Langmuir equation and P sorption maxima (b) was calculated. The P external requirement, which is the

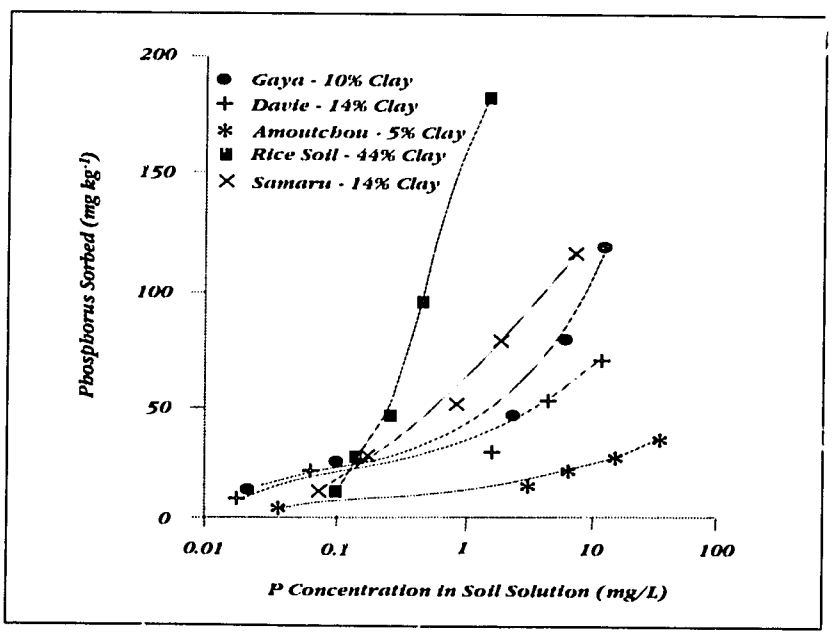

Figure 6. Relationship between phosphorus sorbed and phosphorus in soil soultion at equilibrium for selected West African soils.

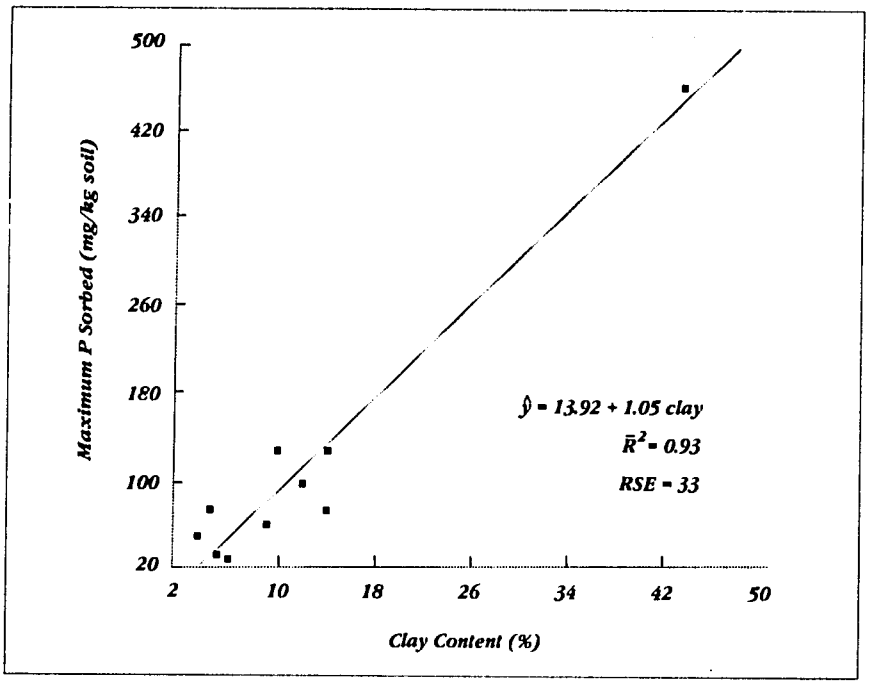

Figure 7. Relationship between maximum P sorbed and clay content of selected West African soils.

critical level of P required in the soil solution to obtain the maximum yield, was determined from the sorption curve (Figs. 5 and 6).

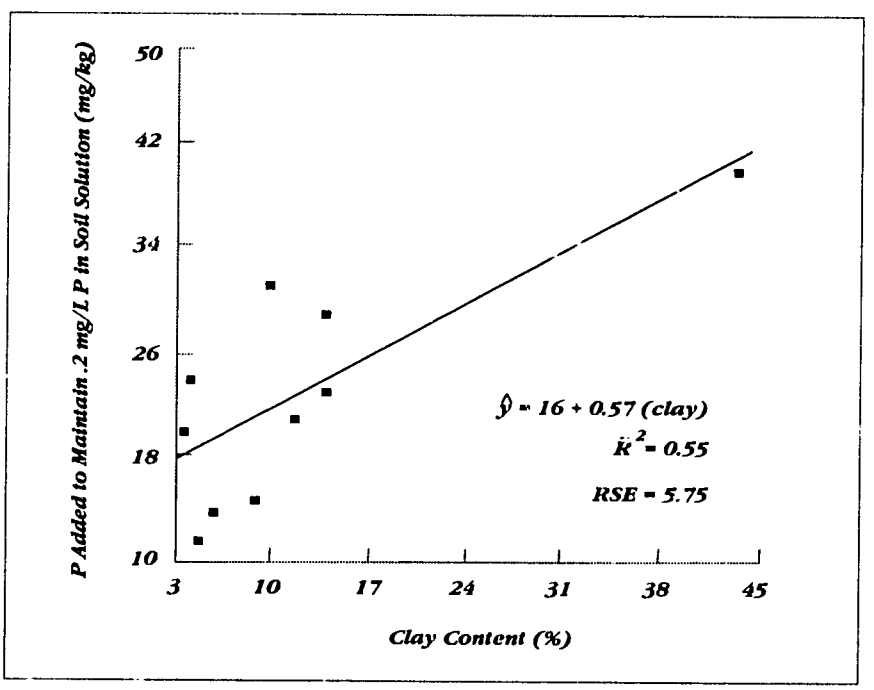

Figure 8. Relationship between P added to maintain .2 ppm P in soil solution and clay content of selected West African soils.

Fertilizer equivalent, which can be defined as the quantity of P needed to increase Bray P1 by 1 mg kg^{-1} (Peck et al., 1971), was determined from the laboratory incubation studies.

Due to the clayey texture of the Vertisol, high values of P sorption maximum, P external requirement, and fertilizer equivalent were obtained (Table 1). For the rest of the soils, P sorption maxima ranged from 28 to 128 mg kg^{-1} while P external requirement and fertilizer equivalent ranged from 12 to 31 mg kg^{-1} and 1.25 to 2.65 mg kg^{-1}, respectively.

Total P, Bray P1, P sorption maxima, P external requirement and fertilizer equivalent in the soils were highly correlated with organic matter, clay and the poorly crystalline Al and Fe phases as observed by Manu et al. (1991).

Figures 7, 8, and 9 show the relationships between clay and the following P parameters: P external requirement, P sorption maxima, and fertilizer equivalent, respectively. These results are in agreement with the findings of Fox and Searle (1978) and Juo and Fox (1977) who observed that the clay contribution to P sorption was related to the specific surface area of Fe and Al oxides. Ellis and Truog (1955) on the other hand, related P adsorption to the exposed edge site Al and Fe on clay surfaces. This interrelationship not only suggests the potential control of the availability of P by the poorly crystalline Al and Fe phases, but could also influence the potential reactivity of P.

Soil Calibration Studies

Soil Testing Methods

The different soils selected were analyzed with the different soil testing procedures. Table 3 gives the minimum and maximum extractable P values obtained from these analyzes. Table 4 gives the simple correlation coefficient for the five soil testing procedures. The high r values for Bray P1, Bray P2, Olsen, and Mehlich1 suggest that these methods were equally efficient in

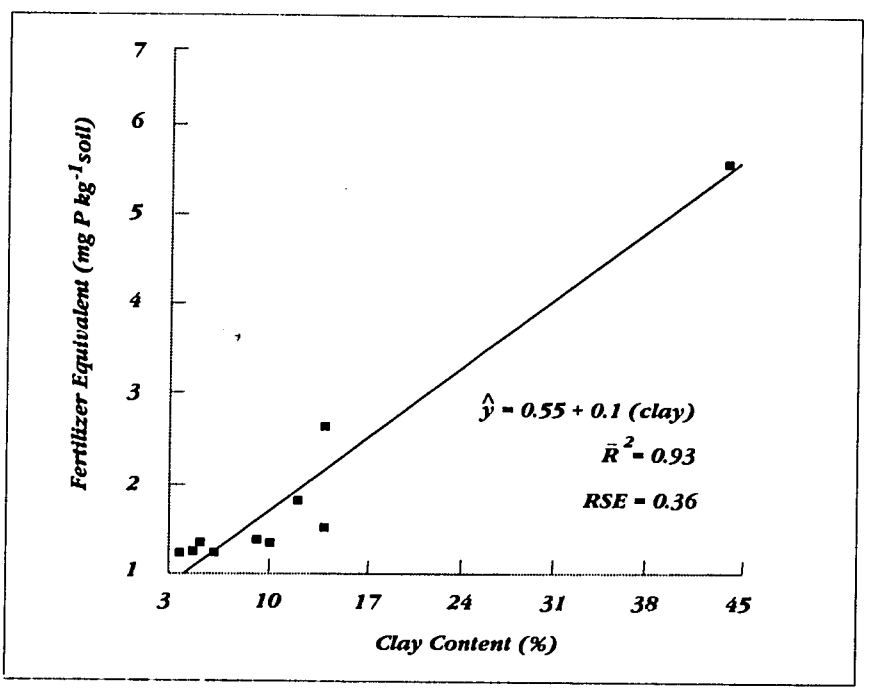

Figure 9. Relationship between fertilizer equivalent and clay content of selected West African soils.

Table 3. Minimum and maximum values of ex-tractable P with different soil test procedures on selected West African soils.

	Extractable P	
	Minimum	Maximum
	mg kg⁻¹	
Bray P1	2.59	25.90
Bray P2	4.56	64.40
Mehlich1	1.43	12.00
Olsen	2.98	37.40
WEP(1:10)	0.77	2.31
WEP(1:20)	1.31	4.33

Table 4. Simple correlations relating P extracted using five soil testing methods on different soils of West Africa.

	Bray P2	Mehlich1	Olsen	WEP(1:10)	WEP(1:20)
Bray P1	0.98	0.96	0.91	0.83	0.82
Bray P2	0.92	0.97	0.75	0.79	
Mehlich1	0.79	0.82	0.77		
Olsen	0.67	0.75			
WEP(1:10)	0.94				

Table 5. Simple correlations relating soil properties P sorption and availability indices.

	Total P	Bray P	B[1]	Pext[2]	Fertilizer equivalent
Organic matter	0.93***	0.91***	0.95***	0.67***	0.95***
Clay	0.98***	0.94***	0.97***	0.78***	0.97***
Al OXA	0.99***	0.96***	0.98***	0.87***	0.96***
Fe OXA	0.94***	0.93***	0.98***	0.74	0.99***
Al Dithio	0.52	0.41	0.43	0.74	0.37***
Fe Dithio	0.23	0.03	0.09	0.47	0.03
Total P	1.00	0.96***	0.96***	0.84***	0.95***
Bray P1		1.00	0.93	0.79	0.97***
B[1]			1.00	0.85***	0.97***
Pext[2]				1.00	0.765
Fertilizer equivalent					1.00

1 *B = P adsorption maximum*
2 *Pext = P external requirement*
*** *Significance at the 0.0005 level*

Table 6. Chemical analyses of some WASAT phosphate rocks.

	Kpeme (Togo)	Parc-W (Niger)	Kodjari (Burkina Faso)	Tahoua (Niger)	Tilemsi (Mali)
	%				
Total P	15.7	12.4	11.1	12.2	12.5
Citrate-solute P	1.31	.13	0.92	1.09-1.18	1.84
CaO	51.3	40.0	33.5	39	14.4
F	4.0	3.4	3.1	2.8	3.1
Al_2O_3	1.1	1.5	4.0	2.1	2.1
Fe_2O_3	1.3	1.0	4.1	10.3	6.1
MgO	0.05	0.13	0.29	0.20	0.52
Na	0.23	0.13	0.09	0.15	0.57
K_2O	0.04	0.13	0.43	0.12	0.1
SiO_2	0.03	0.005	–	0.005	0.007
CO_2	4.6	23.0	25.7	11.7	9.4

determining plant available P (Table 5).

Two contrasting soils from the IFDC Benchmark transect were selected to test the efficiency of different soil test procedures with different types of fertilizers (Tables 6, 7). Ranges of available P extracted by the different methods are given in Tables 8 and 9. Simple correlation coefficients

Table 7. Chemical analysis of partially acidulated phosphate rock of WASAT.

Rock source	Level of acidulation[a] (%)	Type of material	Total P	Wt. (%) WSP[b]	Wt. (%) CSP[c]
Parc-W (Niger)	25	Granular[d]	10.47	2.4	1.2
Parc-W (Niger)	40	ROP[e]	9.5	4.0	0.9
Parc-W (Niger)	50	Granular[d]	8.9	4.4	0.8
Tahoua (Niger)	25	Granular[d]	11.0	1.7	1.2
Tahoua (Niger)	50	Granular[d]	9.9	2.9	1.3
Kpeme (Togo)	25	Granular	12.6	3.2	1.5
Kpeme (Togo)	50	Granular	11.0	5.1	0.9
Kodjari (Burkina Faso)	25	Granular	9.0	2.0	1.6
Kodjari (Burkina Faso)	50	Granular	5.2	3.5	1.3
Tilemsi (Mali)	15	Granular	23.1	2.6	2.2
Tilemsi (Mali)	30	Granular	10.5	2.4	1.2

[a] *Where 100% indicates the amount of H_2SO_4 required for preparation of Single superphosphate.*
[b] *WS - water soluble.*
[c] *CS - solute in neutral ammonium citrate solution.*
[d] *Analysis reported on minum 6- plus 14-mesh (Tyler).*
[e] *ROP indicates nongranular (run of pile).*

Table 8. Minimum and maximum available P values obtained with five soil testing procedures in a soil treated with PRs, PAPRs and water soluble fertilizers, Zaria, Nigeria, 1991.

	PR		PAPR		Water soluble fertilizers	
	Minimum	Maximum	Minimum	Maximum	Minimum	Maximum
	mg/kg⁻¹					
Bray P1	8.54	14.29	8.80	15.32	8.80	22.09
	14.95	43.65	14.95	45.11	14.95	42.19
Mehlich	7.08	28.66	7.08	25.07	6.91	20.28
WEP	11.06	1.80	1.06	1.93	1.08	2.41
Olsen	5.33	9.60	5.60	10.00	5.74	16.67

for available P obtained with the five soil test procedures were computed for each of the fertilizer types (Tables 10 and 11).

In Gaya, which is in the Sudano-Sahelian zone, soils were fertilized with ground phosphate rock (PR) from Tahoua and 50 percent acidulated Parc-W phosphate rock (PAPR). In Zaria (Northern Guinean Savanna) phosphate rock from Togo, in ground and partially acidulated forms, was used. Triple and single super phosphate were used as water soluble P fertilizers at both sites.

With the exception of the water extraction procedure, r values were very high for the water soluble fertilizers at both sites. This suggests that the other four soil testing methods were equally efficient in determining plant available P on soils fertilized with TSP or SSP. It was observed however that r values for PR and PAPR were similar at Gaya while r value for PR were lower than those of PAPR at Zaria. This could be attributed to solubilities of the different rock phosphates. As observed by Bationo et al. (1990) and Mokwunye and Pinto (1991), Tahoua PR has a better agronomic effectiveness compared to Togo PR.

Determination of Sufficiency Levels and Recommendations for Amounts of P Required for Optimum Crop Production

It has been established that Bray P1, Bray P2, Mehlich 1 and Olsen performed equally well in determining plant available P when soils were fertilized with TSP or SSP. Bationo et al. (1991) and Beidari et al. (1991) found Bray P1 to be the soil testing method most suitable to the soils in the subregion. Phosphorus sufficiency levels for optimum yields of millet, cowpea, and sorghum were therefore determined based on P amounts extracted using the Bray P1 method.

Figure 10 shows the relationship between P extracted from plots receiving different sources and rates of P over seven years in the Sahelian zone at Sadore, Niger. At all levels of application, plots receiving water-soluble P fertilizers, TSP, SSP, and SSP minus nitrogen (SSP-N), had the highest amounts of extractable P in the soil after seven years. This was followed in decreasing

Table 9. Minimum and maximum available P values obtained with five soil testing procedures in soil treated with PRs, PAPRs, and water soluble fertilizers for pearl millet (A) and cowpea (B) production, Gaya, Niger, 1991

	PR				PAPR				Water soluble fertilizers			
	Minimum		Maximum		Minimum		Maximum		Minimum		Maximum	
	mg/kg											
	A	B	A	B	A	B	A	B	A	B	A	B
Bray P1	2.34	3.24	9.03	8.66	2.34	2.97	8.84	7.00	2.34	2.63	10.31	9.02
Bray P2	3.16	3.80	13.08	15.80	3.16	2.89	14.58	12.02	3.16	3.16	14.58	11.30
Mehlich (mg/kg)	0.89	1.11	6.17	4.28	0.89	1.11	6.89	6.16	0.89	0.89	6.22	5.49
WEP (mg/kg)	0.02	0.02	0.34	0.47	0.02	0.04	0.31	0.23	0.02	0.04	0.31	0.49

Table 10. Coefficients of simple correlation (r) for five soil testing methods in a soil treated with PRs PAPRs, and water-soluble fertilizers of pearl millet (A) and cowpea (B) fields, Gaya, Niger, 1991.

	PR								PAPR								Water soluble fertilizer							
	Bray P2		Mehlich 1		WEP (1:1)		Olsen		Bray P2		Mehlich 1		WEP (1:1)		Olsen		Bray P2		Mehlich 1		WEP (1:1)		Olsen	
	A	B	A	B	A	B	A	B	A	B	A	B	A	B	A	B	A	B	A	B	A	B	A	B
Bray P1	0.98	0.91	0.94	0.86	0.78	0.80	0.96	0.85	0.93	0.95	0.82	0.90	0.69	0.50	0.81	0.92	0.99	0.93	0.91	0.85	0.40	0.56	0.95	0.86
Bray P2			0.93	0.73	0.78	0.86	0.95	0.86			0.91	0.92	0.62	0.37	0.86	0.87		0.93	0.85	0.39	0.43	0.96	0.89	
Mehlich 1					0.68	0.54	0.90	0.81					0.53	0.42	0.89	0.79					0.19	0.56	0.95	0.82

Table 11. Simple correlation (r) for five soil testing methods in a soil treated with TPRs, TPAPRs, and water-soluble fertilizers Zaria, Nigeria, 1991

	PR				PAPR					SSP				
	Bray P1	Bray P2	Mehlich	Olsen	WEP(1:10)	Bray P1	Bray P2	Mehlich	Olsen	WEP(1:10)	Bray P1	Bray P2	Mehlich 1	Olsen
WEP(1:10)	0.63	0.84	0.77	0.72		0.80	0.76	0.75	0.84		0.80	0.79	0.77	0.87
Bray P1		0.87	0.63	0.87			0.89	0.72	0.90			0.97	0.91	0.96
Bray P2			0.89	0.88				0.92	0.77				0.92	0.93

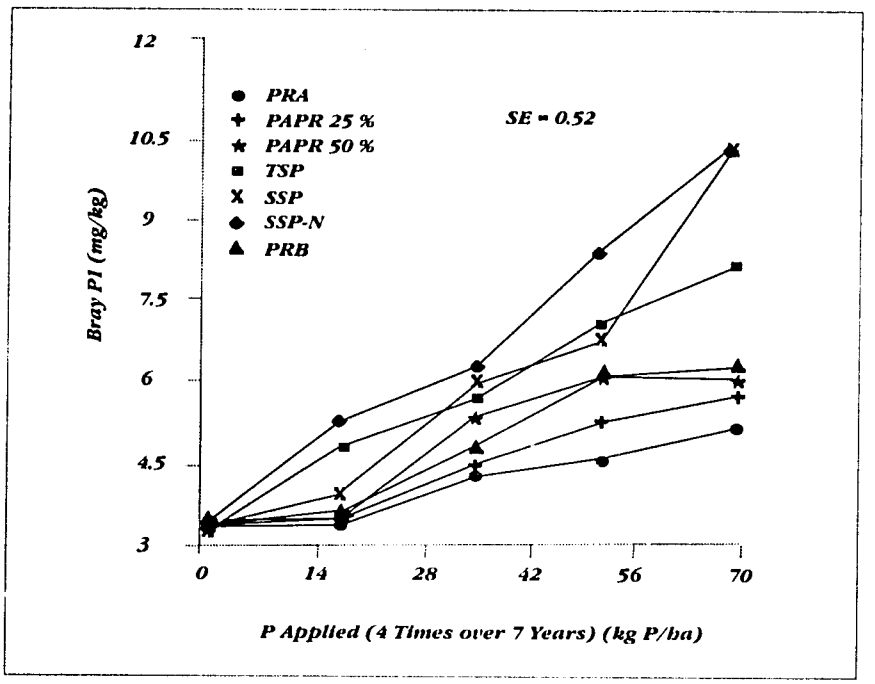

Figure 10. Relationship between different sources and rates of phosphorus on phosphorus availability (Bray P1), Sadoré, Niger, 1988.

order by P extracted from Parc-W rock phosphate acidulated at 50 percent (PAPR 50%), Parc-W rock phosphate acidulated at 25 percent (PAPR 25%), basally applied ground Parc-W rock phosphate (PRB), and ground Parc-W rock phosphate applied annually for seven years (PRA). Yields of pearl millet grain and total biomass followed similar trends as shown in Figures 11 and 12.

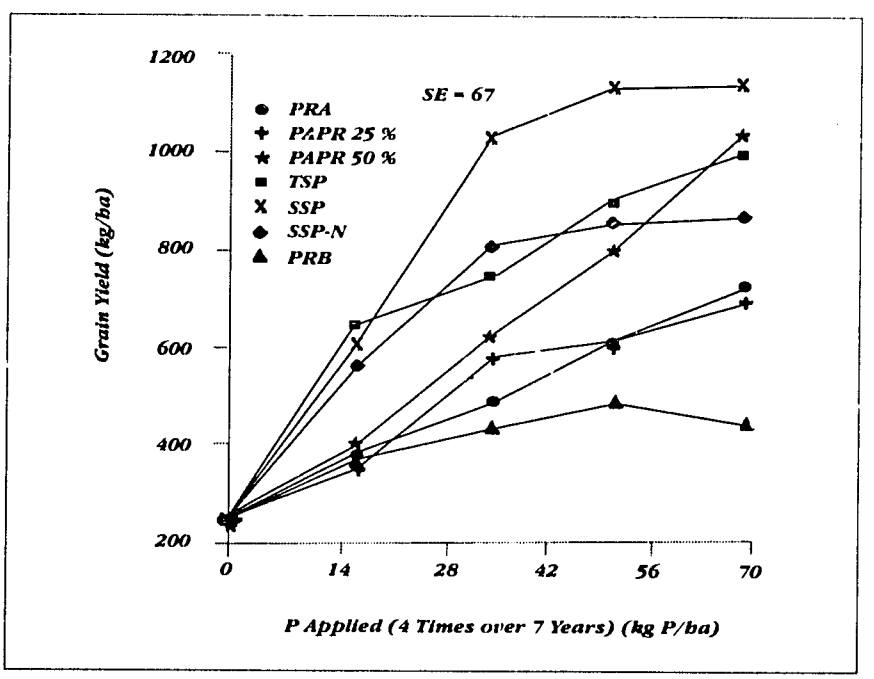

Figure 11. Relationship between different sources and rates of phosphorus on pearl millet grain yield, Sadoré, Niger, 1988.

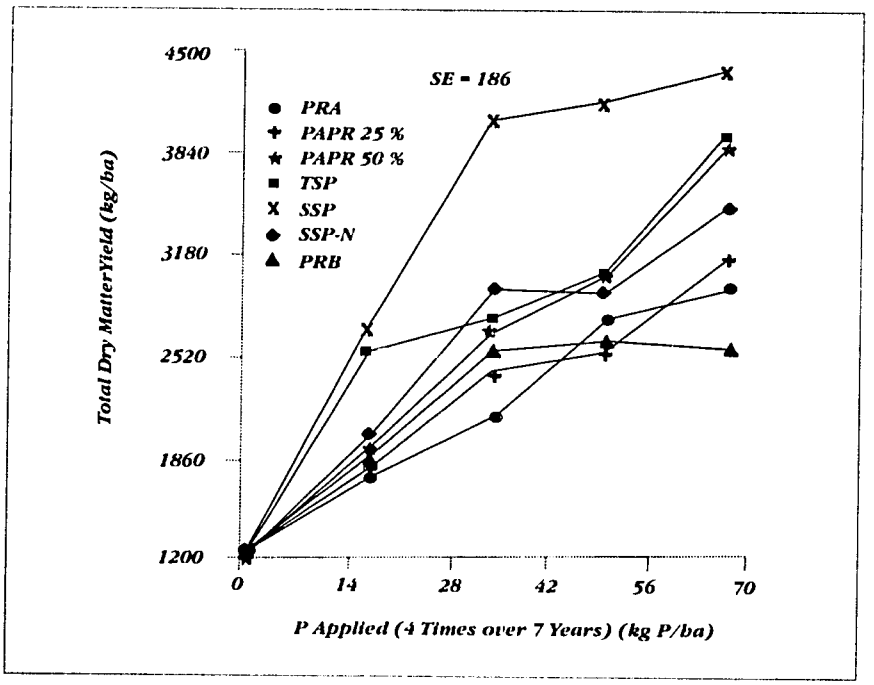

Figure 12. Relationship between different sources and rates of phosphorus on pearl millet total dry matter yield, Sadoré, Niger, 1988.

Phosphorus sufficiency levels were estimated for the SSP treatment by studying the relationship between relative yield (as percent of the maximum yield of grain and total biomass obtained) and extractable P. The amount of extractable P required to obtain 95 percent of the maximum yield (P sufficiency level) was 6.6 mg kg^{-1} for both millet grain and total biomass (Fig. 13).

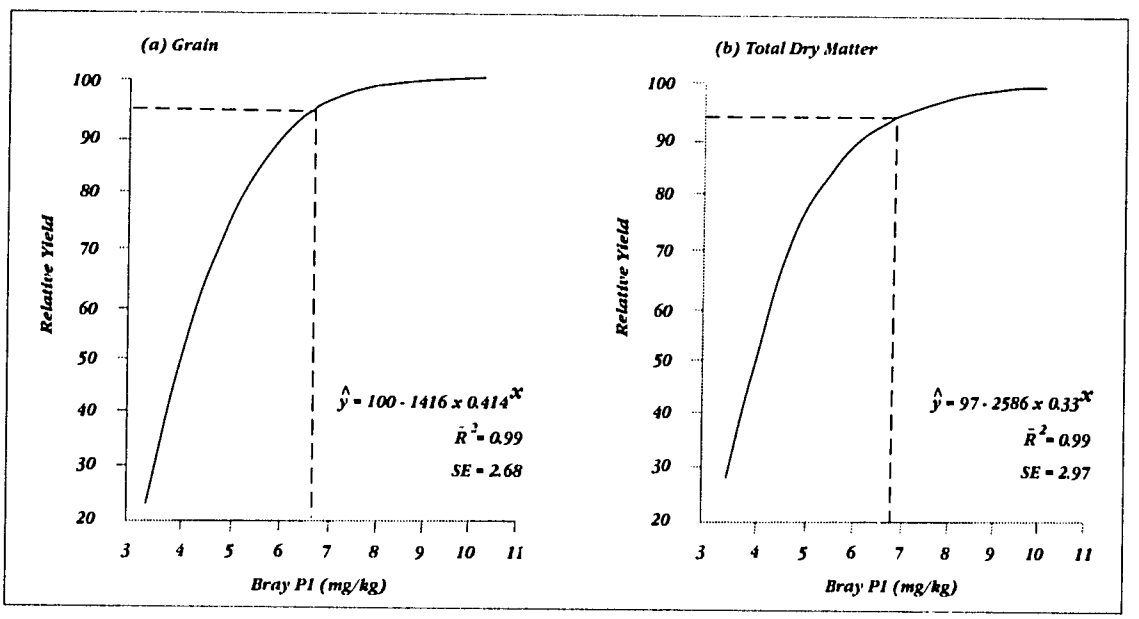

Figure 13. Relationship between relative yield of pearl millet grain (a) and total dry matter (b) yields with Bray P1, Sadoré, Niger, 1988.

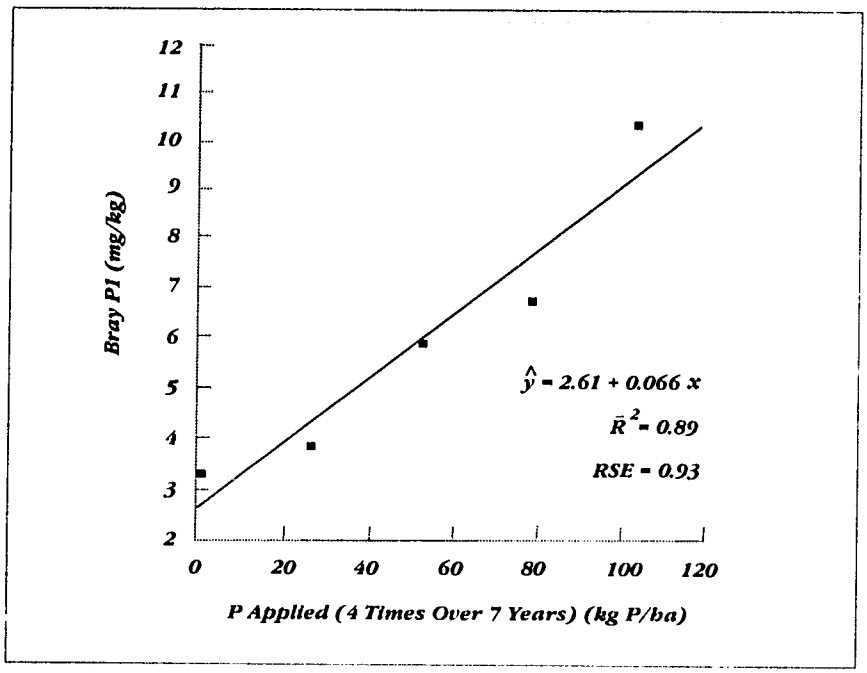

Figure 14. Relationship between Bray P1 and P applied, Sadoré, Niger, 1988.

A simple linear regression model was used to establish a relationship between extractable P and amounts of P (kg/ha) to be applied (Fig. 14). Recommendations for the amount of fertilizer required to attain the sufficiency level could then be made based on the figure.

The efficiency of water soluble P sources, SSP and TSP was compared with that of ground

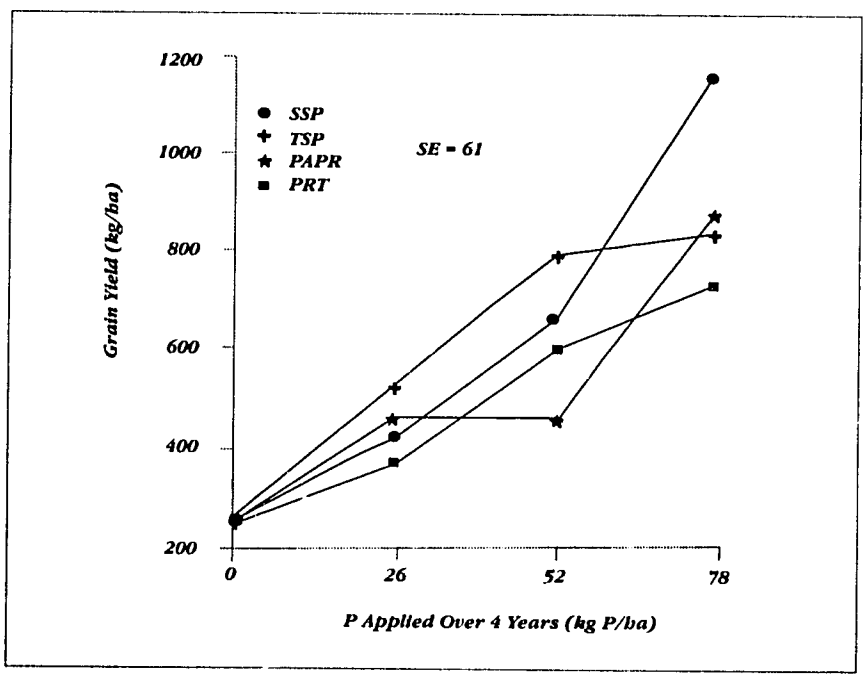

Figure 15. Relationship between pearl millet grain yield and different sources and rates of phosphorus, Gaya, Niger, 1991.

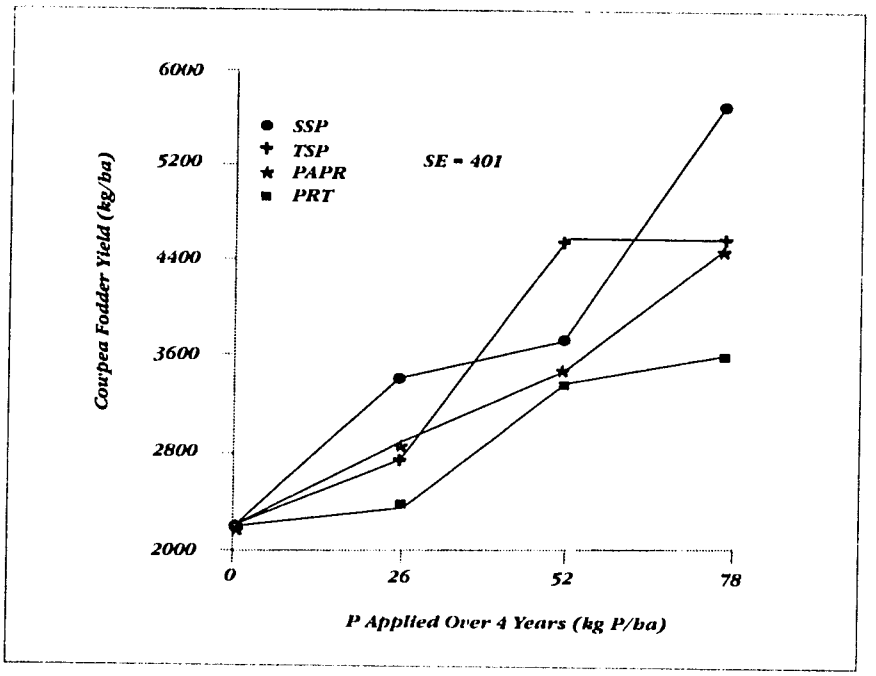

Figure 16. Relationship between cowpea fodder yield and different sources and rates of phosphorus, Gaya, Niger, 1991.

Tahoua rock phosphate and Parc-W rock phosphate acidulated at 50 percent on soils of the Sudano-Sahelian zone at Gaya. Yields of plots receiving the SSP treatment were superior to those receiving other P sources. SSP was subsequently used in the calibration and recommendation (Figs. 15 and 16). In the same agroecological zone at Bengou, Niger, P sufficiency levels were

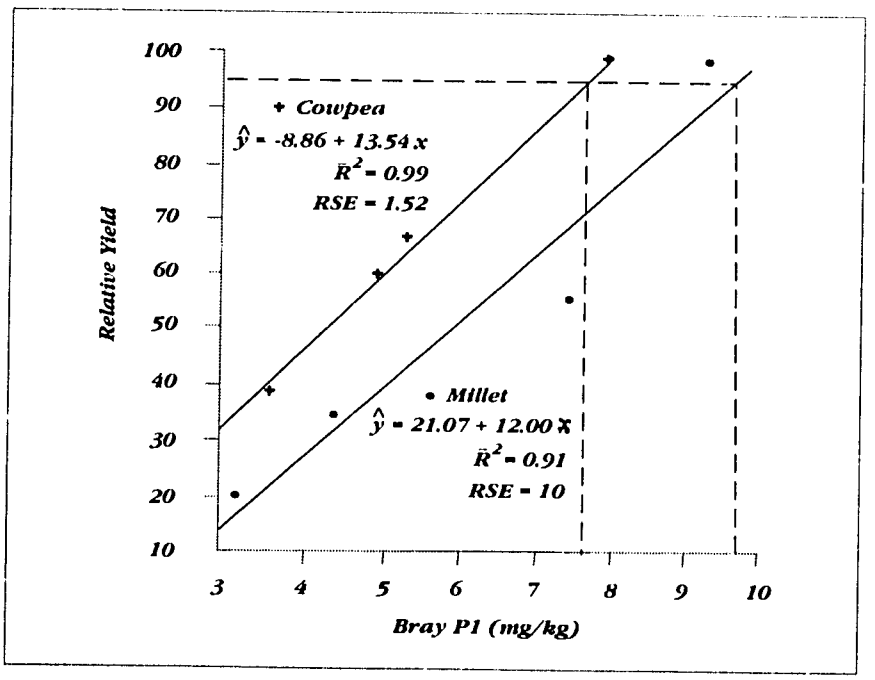

Figure 17. Relationship between relative yield of pearl millet grain yield and cowpea fodder yield and available phosphorus Bray P1, Gaya, Niger, 1991.

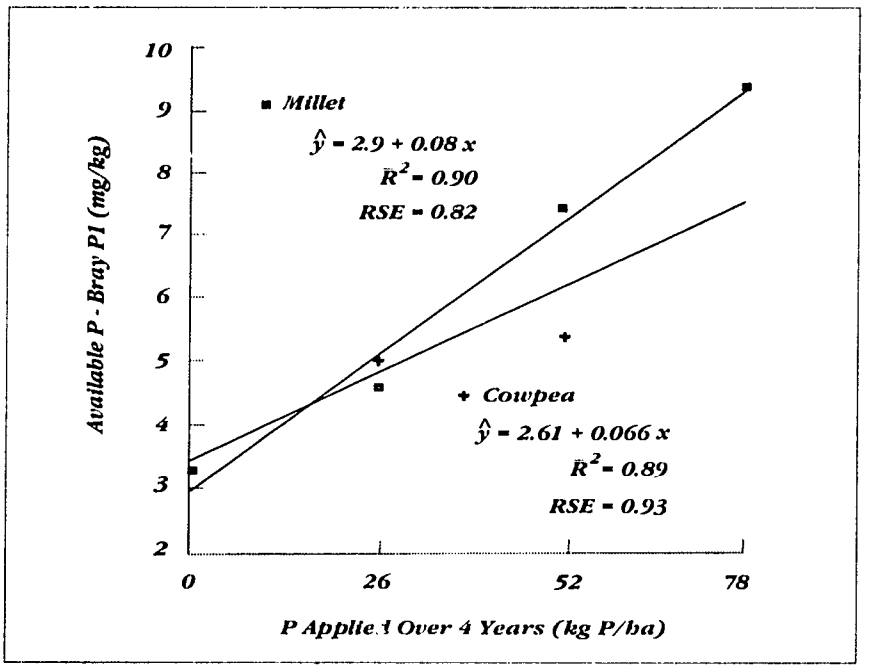

Figure 18. Relationship between available phosphorus for pearl millet and cowpea and P applied over four years, Gaya, Niger, 1991.

also determined. SSP was used as the P source and sorghum as the test crop.

In the Sudano-Sahelian zone the relationship between relative yields and P extracted was best explained by a linear regression model. It was observed that maximum yields of pearl millet grain, cowpea fodder and sorghum grain were obtained with the maximum P applied, but not

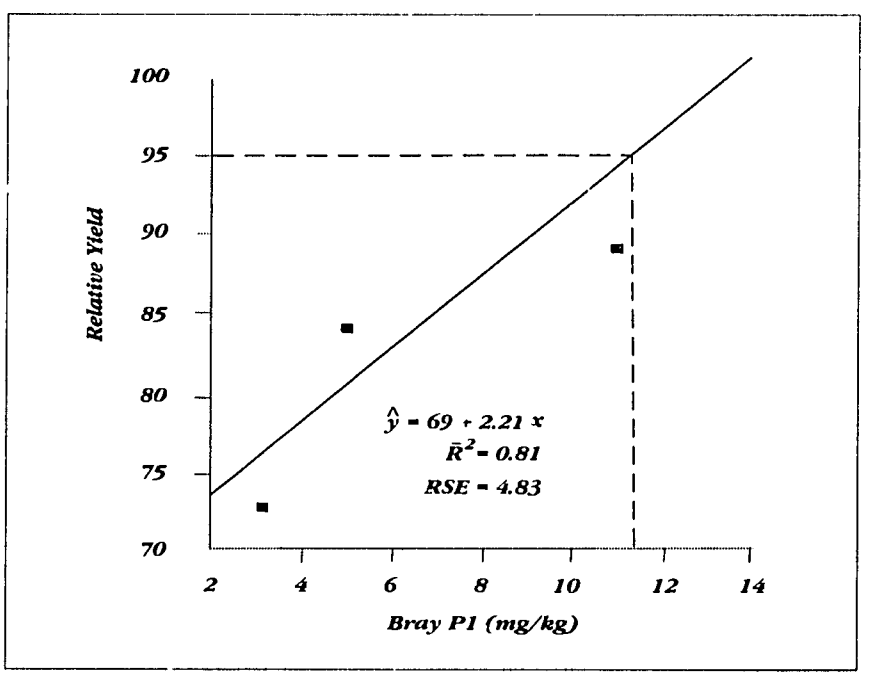

Figure 19. Relationship between sorghum total dry matter relative yield and available phosphorus (Bray P1), Bengou, Niger, 1990.

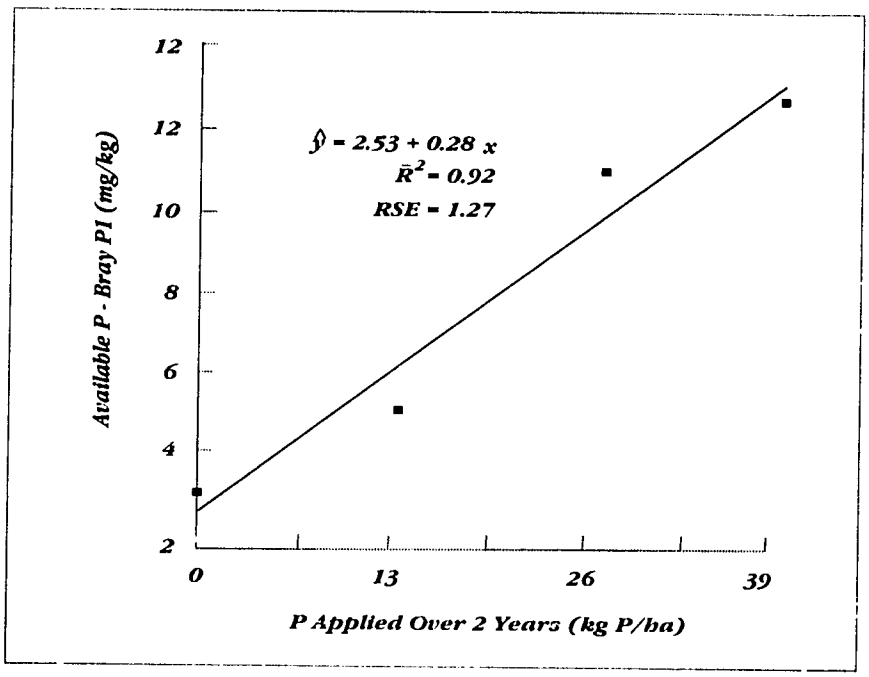

Figure 20. Relationship between available and applied phosphorus. Bengou, Niger, 1991.

many observations were made after the maximum yield was obtained, as was observed in the Sahelian zone. P sufficiency levels for cowpea fodder and millet grain production were 7.5 and 9.7 mg kg^{1} respectively (Fig. 17). The lower P sufficiency level for cowpea compared to millet could possibly be due to the ability of the legume to efficiently utilize occluded iron-bound and calcium-bound P as has been observed for other legumes (Gardner et al., 1983; Ae et al., 1991).

Contrary to observations of Cox (1991), P sufficiency levels for pearl millet production in the sandy Sahelian soils were slightly lower than the sandy loam soils of the Sudano-Sahelian zone.

Recommendations of P rates required for optimum millet and cowpea production in the Sudano-Sahelian zone could be made using Figure 18. The relationship between relative yield of sorghum total dry matter and Bray P1 extractable P is shown in Figure 19 and recommended P rates can be obtained from Figure 20.

Influence of Management Alternatives on P Calibration and Recommendations

Crop response to P fertilizers could be a function of several biotic and abiotic factors. It is thus imperative that the cropping and management histories be known before any meaningful and cost effective recommendations can be made.

As an illustration, a trial was established in the Sudano-Sahelian zone at Tara, Niger, to assess the effect of four types of rotations on millet yields after four years. The cropping systems were: fallow-millet-fallow-millet (F/M/F/M), cowpea-millet-cowpea-millet (C/M/C/M), continuous millet (M/M/M/M) and groundnut-millet-groundnut-millet (G/M/G/M). Sufficient levels of P, in the form of SSP, was applied in all the rotation systems. At all N levels, highest millet dry matter yields

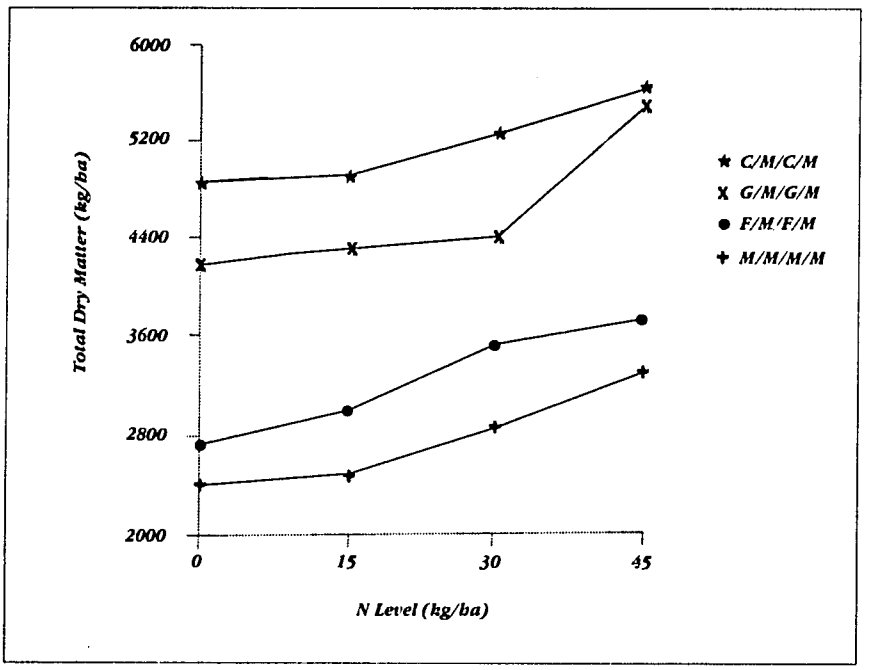

Figure 21. Effect of nitrogen and different cropping systems on pearl millet total dry matter yield, Tara, Niger, 1991.

were obtained under C/M/C/M rotation as shown in Figure 21. This was followed in descending order by G/M/G/M, F/M/F/M, and M/M/M/M.

It has been demonstrated by Bationo and Mokwunye (1991) that the use of P fertilizers alone could not sustain millet production over the long term. However, maintenance of adequate levels

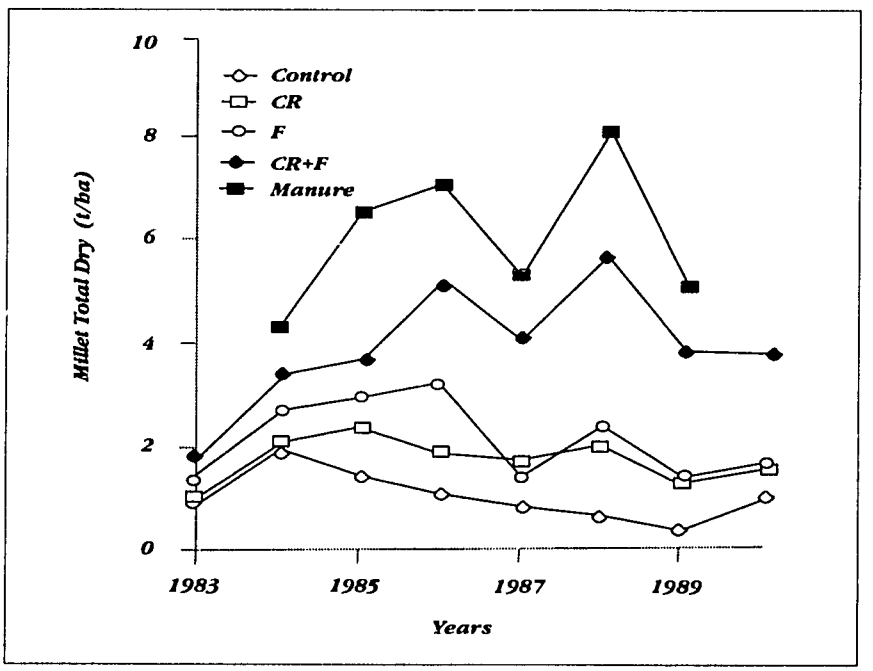

Figure 22. Pearl millet total dry matter yield as affected by different managements over years.

of organic matter, either through application of manure or crop residue, promoted sustainable production of millet (Fig. 22). These data clearly indicate that the base relative yields of crops to be used in P soil test calibration models could be influenced by different management and cropping histories.

Conclusion

Characterization of selected West African soils sampled along a transect extending from the Sahelian in the north to the Derived Savannah agroecological zone in the south showed that:

1. Soils generally have sandy to sandy loam textures
2. Fertility indicators of organic matter and effective CEC were generally low and highly correlated
3. Plant P availability indices including Bray P1, P fertilizer equivalent, and external P requirement were also very low.

These P parameters were highly correlated with clay and organic matter and poorly crystalline iron and aluminum oxides. Results of calibration studies indicated that Bray P1, Bray P2, Mehlich1 and Olsen performed equally well in assessing P availability. However, the efficiencies of these extractants were found to be related to the solubilities of different phosphate rocks.

Phosphorus sufficiency levels and P amounts required to obtain optimum yields for pearl millet, cowpea, and sorghum were found to be low. This could be due to the low clay contents and poor buffering capacity of these soils.

Management alternatives such as organic matter recycling and cereal rotations with legumes could have a strong influence on P calibration and recommendation. This suggests that multi-parameter modeling is necessary for cost efficient P calibration studies.

It should be emphasized that P calibration in the region is in its infancy and further research is required.

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Contact Person:

Andre Bationo
IFDC/ICRISAT
BP 12404
Niamey, Niger

Telephone: 227-72-25-29
Fax: 227-73-43-29
Telex: ICRISAT 5406NI

Phosphorus Status And Sorption In Sandy Soils Of The Sahel Region Of West Africa

M.D. Doumbia
Texas A&M University, Department of Soil and Crop Science
M. Ouattara
INRAN, Scientific Director
L.R. Hossner
Texas A&M University, Department of Soil and Crop Science
A.B. Onken
Texas A&M University, Research and Extension Center

Abstract

The purpose of this paper is to discuss research data on phosphorus (P) status and sorption in soils of little clay content from Mali and Niger in order to determine the P fertilization factor (or the amount of P fertilizer necessary to increase soil test P to the critical level) for TropSoils.

Phosphorus recommendations in most of these regions were made by diagnosing deficiencies in greenhouse or pot studies. Response curves were then made in selected field plots to determine rates required to correct deficiencies. Economic considerations, however, excluded recommendations of rates based on crop species and yield goals.

Surface sandy soils of the Sahel regions of West Africa have low P sorption (a mean of 22.9 $\mu g\ g^{-1}$) and buffering capacities. However, P sorption in these soils increases with depth by a factor of 2.5. Phosphorus sorption was most influenced by clay content, organic matter content, exchangeable acidity, Bray-I P, and free Fe content.

A rate of 15 mg P kg^{-1} of soil provided adequate P for optimum sorghum (Sorghum bicolor) growth and dry matter yield (greenhouse) in Plinthic Paleustalfs. An application as low as 2.5 mg of P kg^{-1} of soil not only prevented symptoms of poor early growth, but produced a significant dry matter increase in the greenhouse. The critical P requirement for sorghum or millet (Pennisetum americanum) appears to be about 11 mg P kg^{-1} of soil.

Models such as Jomini's could be amended with factors such as erosion and soil management and used in the determination of P fertilizer necessary to increase soil test P to the critical level.

Introduction

Among the major constraints to crop production in Sahelian Africa are: 1) extremely deficient levels of P and N; 2) limited available soil water; 3) spatial variability in stand establishment; and 4) soil acidity. The two most important factors for increasing agricultural productivity in the Sudano-Sahelian Zone of Africa are the improvement of soil fertility and better management of rainfall (Day and Aillery, 1989). Stroosnijder (1981) found that nutrient deficiencies resulted in

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usable water being left in the soil by native vegetation in the Malian Sahel. A similar conclusion was reached by Payne et al. (1987) for sandy soils of Niger. Stroosnijder (1981) concluded that application of nutrients could result in increasing crop production five-fold in the southern Sahel under natural rainfall conditions. Ssali and Mokwunye (1986) found that nitrogen and P are the most frequent limiting nutrients in these soils. In addition, many authors have examined Sahelian soils for P sufficiency as it influences crop growth and yield (Nye and Greenland, 1960; Enwezor and Moore, 1966; Goldsworthy, 1967; Pichot and Roche, 1972; Poulain, 1976; Pieri, 1986) and found that P was the most deficient and plant growth limiting nutrient in these soils. Jones and Wild (1975) documented that P deficiency could be so acute that plant growth stopped once the seed reserve of P had been depleted.

The ability of soils to supply P to crops depends on: 1) the concentration of P in soil solution (intensity factor); 2) the quantity of solid phase P that acts as a reserve (quantity factor); and 3) the rate of renewal upon depletion of soil solution P (rate factor) (Olsen and Khasawneh, 1980). In addition, several soil characteristics influence the availability of applied phosphate to crops. Very few studies, however, have investigated the effects of these factors and soil characteristics on plant response to applied P in the Sahel region of West Africa.

The objectives of this paper are to: 1) review P diagnosis and recommendations in Mali; 2) compare P adsorption characteristics of selected soils of Niger; 3) discuss sorghum response to P in Plinthic Paleustalfs of the Cinzana station (greenhouse); and 4) make recommendations for P soil test calibration in the Phosphorous Decision Support System (PDSS).

Phosphorus Diagnosis and Recommendations in Mali

Research conducted to improve soil fertility in Mali was exclusively carried out, until 1977, by the French institute, IRAT. The improvement of soil fertility in Mali as well as in many other regions of Sudano-Sahelian Africa followed principles suggested by Chaminade (1965). These principles are as follows:

1. Deficiencies are first diagnosed through greenhouse or pot studies using test-plants. Using this procedure, Traoré (1972) found that most soils of Mali are deficient in P. With the same procedure, Doumbia (1990) found that P deficiency was more acute than that of N in Grossarenic and Plinthic Paleustalfs of the Cinzana station.

2. Response curves are established in field plots to determine the rate required to alleviate the deficiency. This rate may be referred to as *corrective* as it usually brings the soil fertility to a level satisfactory for crop growth and yield. Pieri (1986) found that an application of 18 to 31 kg P ha^{-1} was adequate to alleviate P deficiency in most soils of West Africa.

3. A rate based on crop species and yield goals is recommended. This *maintenance* rate is often omitted for economic considerations. For example, Pieri (1973) reported a ratio of 4:1 between the price of 1 kg of triple superphosphate (TSP) and that of 1 kg of sorghum or millet. The ratio is 1.5:1 for a cash crop such as cotton (*Gossypium hirsutum*). One kg of P_2O_5 (as TSP) should provide a yield increase of 8.8 kg of sorghum grain or 3.2 kg of cotton and be economically sound (Pieri, 1973). For this reason, the *corrective* rate of P was recommended for most crops in most soils of Mali. The rate was set at about 20 kg P ha^{-1}.

For this region, the authors did not find in the literature any examples of soil test P being used in diagnostic and recommendation procedures. In Mali, the soil testing laboratory (Laboratoire des Sols, SRCVO, Sotuba) uses Bray-2 and a modified Olsen method to extract plant available P. Total P is extracted by digestion with a mixture of H_2SO_4 and HNO_3. Solution P is measured colorimetrically with a Technicon AutoAnalyzer (Technicon Industrial Systems, 1977).

Moreover, in traditional cropping systems of southern Mali, the appearance of witchweed or striga (*striga spp.*) is an indication of low soil fertility. Land infested with striga is left in fallow for several years. Striga is known to prevail in conditions where soil moisture and fertility (particularly low N and P status) are limiting (INTSORMIL, 1989).

Phosphate Sorption in Sandy Soils of Niger

This study was conducted to determine P sorption characteristics of selected soils as a function of position on the landscape and toposequence sites. Relationships between soil characteristics and P adsorption were also determined.

Materials and Methods

Three g of soil were equilibrated in 30 ml of 0.01 M $CaCl_2$ containing various amounts of P as $Ca(H_2PO_4)_2.H_2O$ for nine (9) days at 24 ^{0}C following procedures described by Fox and Kamprath (1970). Supernatant P was determined colorimetrically by the ascorbic acid method of Watanabe and Olsen (1965).

Adsorbed P was calculated as the difference between P initially added and that remaining in supernatant solution. Adsorption isotherms were obtained by a plot of adsorbed P against P remaining in solution. The amount of sorbed P at the equilibrium P solution concentration of 0.2 µg P ml^{-1} will be referred to as standard P requirement (SPR) (Juo and Fox, 1977). Regression models were used to investigate the correlation between P sorption and selected soil characteristics.

Soil samples from selected pedons of the toposequences of Hamdallaye and Malgourou (Niger) were used. Each toposequence was divided into seven (7) areas of detailed study (ADS)

Table 1. Selected properties of some horizons of Pedon 2, Hamdallaye (Aridic Rhodic Kandiustalfs).

	Horizons			
	Ap1	**Ab**	**Bt2**	**Bt7**
Depth (cm)	0-3	13-24	32-53	182-194
Clay (%)	2.5	5.9	9.7	10.7
Sand (%)	93.9	89.2	86.2	85.0
pH (H_2O)	5.3	4.9	5.0	5.6
ECEC (cmol (+)/kg)	0.5	0.7	0.9	0.8
Base saturation (%)	82	29	22	48
Al. saturation (%)	12	59	67	46

Table 2. Selected properties of some horizons of Pedon 2, Malgourou (Aridic Rhodic Kanhaplustalfs).

	Horizons		
	Ap	**Bt1**	**Btoc3**
Depth (cm)	0-8	17-37	37-59
Clay (%)	9.7	24.0	31.1
Sand (%)	73.7	60.1	53.7
Gravel (%)	1	8	11
pH (H_2O)	5.3	5.3	5.3
ECEC (cmol (+)/kg)	1.3	1.5	1.9
Base saturation (%)	80	65	41
Al. saturation (%)	13	28	52

from the edge of the plateau (ADS1) to the valley floor (ADS7). Selected properties of two of these pedons are given in Tables 1 and 2.

Results and Discussions

The soils at Hamdallaye have extremely low P sorption capacity, particularly in the surface horizons. Values of SPR ranged from 13.5 to 45.6 µg P g^{-1} of surface soil (Fig. 1). These soils also had a low P buffering capacity. However, soils at Malgourou had higher P sorption and buffering capacities. The SPR values for isotherms corresponding to surface horizons ranged from 34.8 to 142 µg P g^{-1} of surface soil (Fig. 2).

These differences might have been due to differences in the two toposequences. At the Hamdallaye toposequence, soils are formed on deep eolian mantle, are sandy, and have been classified as Ustipsamments and Kandiustalfs. At the Malgourou toposequence, soils are generally formed on Continental Terminal residuum, are loamy in texture, shallow, and gravelly at depth. Soils at Malgourou have been classified as Kandiustalfs and Kanhaplustalfs.

Bationo (1986) reported SPRs of less than 15 µg P g^{-1} for a similar soil at Sadoré, near Niamey. The SPR values for Malgourou compare rather well with results reported by Owusu-Bennoah and Acquaye (1989) for soils of Ghana which occur in ecological zones similar to the Malgourou area. These authors reported mean SPRs of 25 µg P g^{-1} for sandy soils (<10 % clay) developed from sandstone and Tertiary sand material of the Savanna zone. They found a mean SPR of 80 µg P g^{-1} for soils containing 10 to 20 percent clay, independent of parent material.

Both sites showed an important increase in P sorption with depth (greater than 2.5-fold as determined by ratios of SPRs).

Factors which are most important to P retention in acid soils are Al, Fe, and clay content (Sample et al., 1980). Clay content, dithionite-citrate extractable Fe_2O_3, and BET-surface area were correlated with samples from 28 representative soil profiles of Wet Africa (Juo and Fox, 1970). For the same soils, organic matter was found to be a major variable in depressing P sorption. Manu et al. (1991) reported that P sorption maxima of selected millet producing soils of West Africa were most highly correlated with organic carbon, clay, and poorly crystalline Al and Fe phases. At Hamdallaye, SPR correlated best with clay content, exchangeable acidity, exchangeable aluminum, Bray-1 P and organic carbon. The best prediction equation for the soils at Hamdallaye included

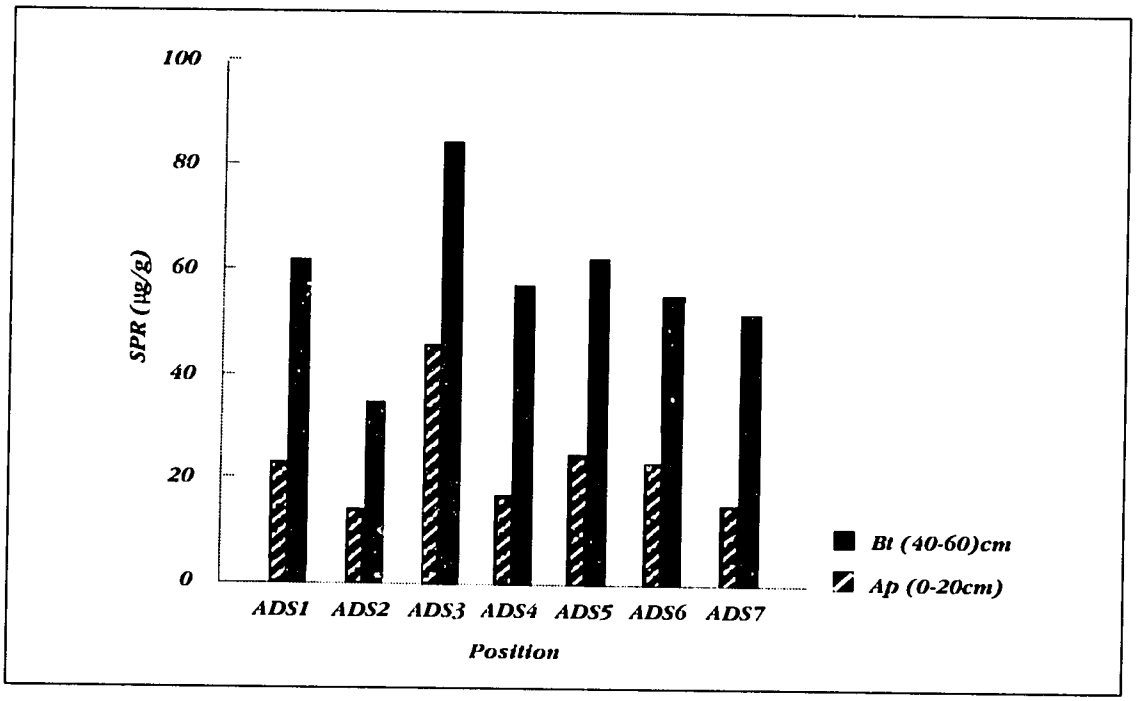

Figure 1. Standard P requirement (SPR) values (in µg g⁻¹) at ADS positions for Hamdallaye.

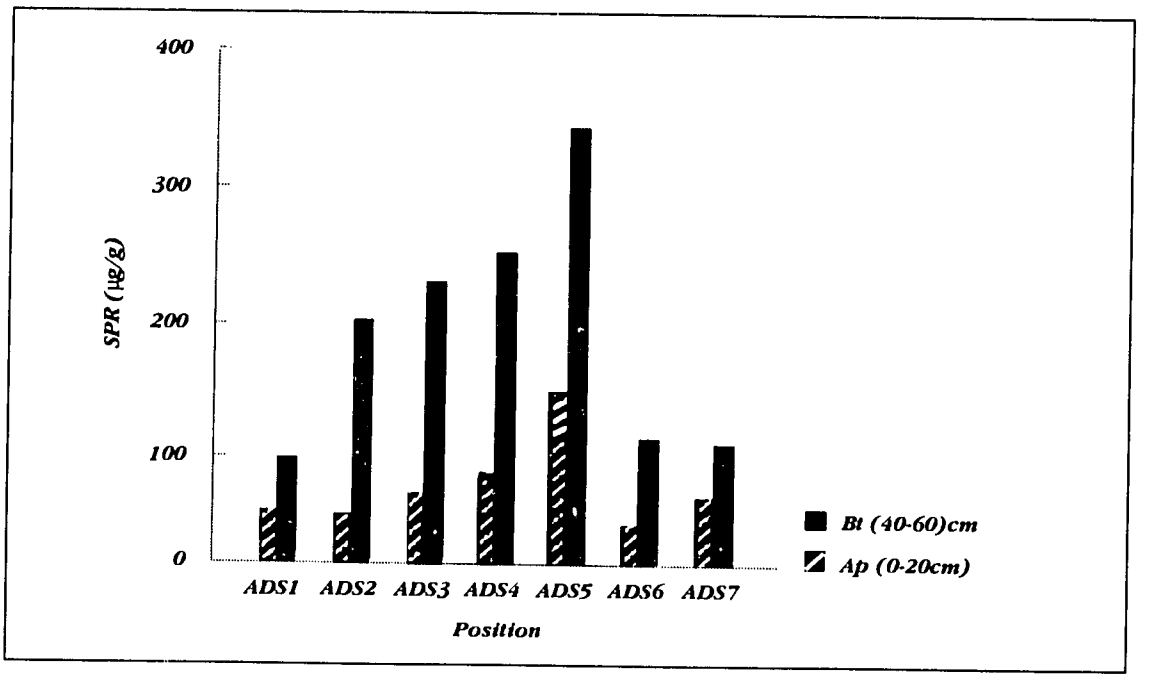

Figure 2. Standard P requirement (SPR) values (in µg g⁻¹) at ADS positions for Malgourou.

percent clay, organic carbon, and exchangeable acidity. This equation is as follows:

$$Y = 33.69 + 2.31X_1 - 190.90X_2 + 36.22X_3; R^2 = 0.948 \quad (1)$$

where Y is P sorbed in $\mu g\ g^{-1}$, X_1 is percent clay, X_2 is percent organic carbon, and X_3 is the exchangeable acidity in cmol kg^{-1}.

The SPRs of soils at Malgourou correlated best with clay content, exchangeable acidity and Al, free Fe, and percent Al saturation. The prediction equation at Malgourou was obtained with clay content, exchangeable aluminum, and Bray-1 P. This equation is as follows:

$$Y = -56.34 + 7.04X_1 + 64.11X_2 + 17.80X_3; R^2 = 0.982 \quad (2)$$

where Y is P sorbed in $\mu g\ g^{-1}$, X_1 is percent clay, X_2 is the exchangeable Al in cmol kg^{-1}, and X_3 is Bray-1 P.

The strong correlation (Figs. 1 and 2) between P sorption and the clay content explain the increases in the amounts of P sorbed with increasing soil depth. In fact, most of the pedons studied had an argillic horizon.

Conclusions

Surface soils at the toposequence of Hamdallaye (Mali) and Malgourou (Niger) had low P sorption and buffering capacities. However, soils at Malgourou sorbed higher amounts of P (a mean of 66 vs. 22.9 $\mu g\ g^{-1}$) because of their higher clay contents. In addition, they had greater P buffering capacities. Phosphorus sorption at both sites increased with depth by a factor of 2.5.

Phosphorus sorption by the soil increased most with clay content, exchangeable acidity, Bray-1 P, and free Fe content. Organic carbon content had a depressive effect on SPRs.

Sorghum Response to Applied P

This was a greenhouse experiment conducted as an initial step upon which to base P rates for a field study to measure response of sorghum to applied P in Grossarenic and Plinthic Paleustalfs of the Cinzana station (Mali).

Materials and Methods

The study was designed as a 2X10 (Lime X Phosphorus) factorial experiment (completely randomized design with 3 experimental units per treatment). An area previously identified for poor early sorghum growth was sampled (15 cm of surface soil) for the study. Selected properties of the soil used (sandy, mixed, hyperthermic Plinthic Paleustalfs) are given in Table 3. The lime factor consisted of a control and the lime requirement (LR). The LR was based on exchangeable Al as suggested by Kamprath (1970). The liming material was Diamou lime, a local material containing approximately 90 percent CaO. Rates of P included the following: 0, 2.5, 5, 10, 15, 20, 40, 60, 80, 100 mg kg^{-1}. All treatments received 100 mg N kg^{-1} (as urea and KNO_3) and 50 mg K kg^{-1} (as KNO_3) so that these nutrients would not be limiting factors on sorghum growth.

The limed soil was subjected, before planting, to three cycles of wetting-drying during which

Table 3. Selected properties of the soil (Plinthic Paleustalfs of the Cinzana station) used for the experiment.

	Horizons			
	Ap	**Bt2c**	**Bv2**	**Bv4**
Depth (cm)	0-24	35-50	77-101	150-180
Clay (%)	5.1	7.3	12.0	28.7
Sand (%)	85.8	82.2	76.2	59.3
pH (H_2O)	5.5	5.1	4.9	4.6
Org. C (%)	0.13	0.14	0.15	0.17
ECEC (cmol (+)/kg)	0.90	1.15	2.13	2.72
Bray-1 P (mg/kg)	5.24			

exchangeable acidity was monitored for neutralization of exchangeable Al. Then P rates were applied (mixing with dry soil) as TSP. Three replications of each treatment were planted using Malisor 84-5, a Malian genotype sensitive to soil acidity.

Sorghum was thinned to three plants per container and grown for 31 days during which the soil moisture content was brought to field capacity by weighing.

Crop data collected included weekly measurement of plant height and dry matter produced. At the end of the experiment, each experimental unit (10 L plastic container) was sampled (soil and plant).

Soil analyses included pH, exchangeable acidity, exchangeable Al, and available P (Bray-1). Soil Ph was determined in water (1:2 soil-water ratio), using a glass electrode and a pH meter. Exchangeable acidity and Al were determined, using the KCl method described by Thomas (1982). Available P (Bray-1) was extracted as outlined by Olsen and Sommers (1982) and measured with a Technicon AutoAnalyzer (Technicon Industrial Systems, 1977).

Plant samples were wet digested (Nelson and Sommers, 1980) and analyzed colorimetrically for N and P (Technicon Industrial Systems, 1977) and by atomic absorption for Ca (Lanyon and Heald, 1982), Al (Barnhisel and Bertsch, 1982), Mn (Gambrell and Patrick, 1982), and Fe (Olson and Ellis, 1982).

Data were analyzed statistically, using PROC GLM (SAS, 1985). In addition, PROC SORT and PROC REG (SAS, 1985) were used to find the regression model that best fit plant and soil response to applied P.

Materials and Methods

Sorghum Growth and Yield

Leaf purpling and stunted growth were seen only in treatment combinations without P (N, NK, and the 0 rate of P combined with lime levels). Also, leaf purpling was more strongly expressed when the mineral supplements N or NK were applied without P. Combining lime with N or NK did not prevent the appearance of the above symptoms. These observations suggest that P is strongly related to the expression of early poor sorghum growth in sandy soils of the Cinzana station.

Direct effects of lime levels and P rates were significant on plant height (Table 4). Plant

Table 4. Selected mean soil and plant data as influenced by the main effect of lime in a Lime x P rates (2x10) factorial experiment conducted under greenhouse conditions.

Treatment	Height at harvest *cm*	Dry matter *g/pot*	Bray-1 P *µ/g*	Shoot P *g/kg*
Check	42.31 b†	4.15	18.68 a	2.51
Liming	45.31 a	4.56	19.36 a	2.74
Interaction‡	NS	S	NS	S
CV (%)	10.71	16.86	11.46	8.0

† *Means followed by the same letter are not significantly different at P = 0.05, using Duncan's new multiple range test.*
‡ *Lime x P rates.*

S,NS: *Significant and non-significant interactions, respectively, at 0.05 level of significance.*

Table 5. Selected mean soil and plant data as influenced by the main effect of P rates in a Lime x P rates (2x10) factorial experiment conducted under greenhouse conditions.

NK + P (mgP/kg)	Height at harvest *cm*	Dry matter *g/pot*	Bray-1 P *µ/g*	Shoot P *g/kg*
0	26.20 d†	0.85	2.99 h	1.75
N + 0	16.43 e	0.44	4.09 h	1.72
NK + 0	17.83 e	0.40	4.13 h	0.81
NK + 2.5	33.27 c	2.29	4.48 h	1.70
NK + 5	45.36 b	4.63	5.23 h	1.80
NK + 10	45.68 b	4.62	7.97 g	2.14
NK + 15	56.50 a	6.20	11.60 f	2.13
NK + 20	57.16 a	6.02	14.72 e	2.29
NK + 40	54.74 a	6.88	24.86 d	3.04
NK + 60	55.17 a	6.43	37.59 c	3.99
NK + 80	58.70 a	7.13	49.07 b	4.71
NK + 100	59.10 a	6.39	61.48 a	5.41
Interaction‡	NS	S	NS	S
CV (%)	10.71	16.86	11.46	8.0

NOTE: *N was applied at a rate of 100 mg kg^{-1} and K at 50 mg kg^{-1}*
† *Means followed by the same letter are not significantly different at P = 0.05, using Duncan's new multiple range test.*
‡ *Lime x P rates.*
S,NS: *Significant and non-significant interactions, respectively, at 0.05 level of significance.*

height significantly increased with increasing P rates up to 15 mg P kg^{-1} (Table 5). Adding more than 15 mg P kg^{-1} did not result in a significant increase in plant height.

Statistical analysis of the data for dry matter yield (DMY) showed that the direct effects of lime levels and P rates as well as their interactions were significant (Tables 4 and 5). Data in Table 5 show that application of the mineral supplements (N and NK) did not produce a DMY significantly higher than that of the control. Increasing P rate beyond 15 mg P kg^{-1} of soil did not significantly increase DMY under either limed or unlimed soil conditions (Fig. 3). Liming significantly enhanced the effect of P only at an applied P rate of 5 mg kg^{-1} (Fig. 3).

It is important to note that a rate as low as 2.5 mg P kg^{-1} of soil not only prevented the symptoms of early poor growth, but also produced both significant sorghum growth and dry matter yield compared with the control (Table 4, Table 5, and Fig. 3). This observation indicates that these soils are very deficient in P, have an extremely low P fixing capacity, and plants respond to a small application of soluble P.

Bray-1 P Extracted

Liming did not affect Bray-1 P (Table 4). A similar effect of lime was reported on plant available P by Martini et al. (1974) and Reeve and Sumner (1970a). No significant increase in

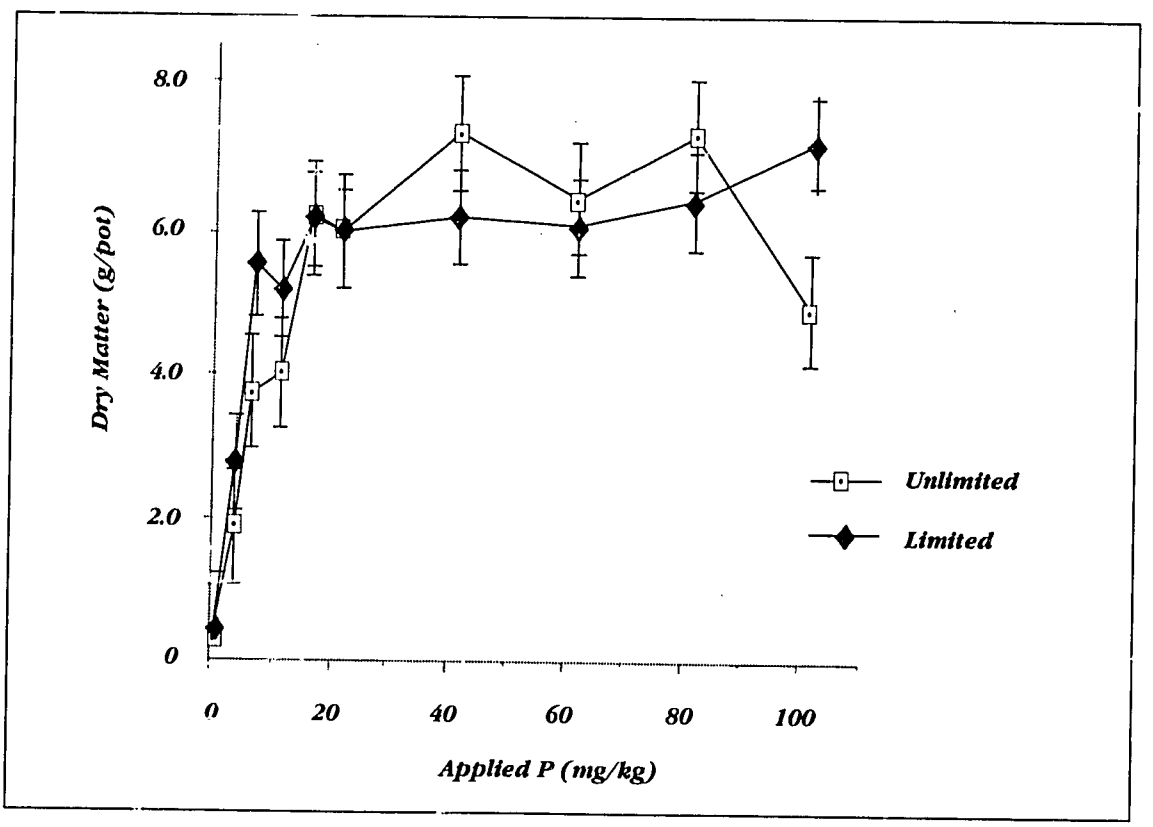

Figure 3. Sorghum dry matter yield as influenced by lime, P rates, and a mineral supplement (N and K).

Bray-1 P was observed as a result of application of 2.5 and 5 mg P kg^{-1} (1a [illegible]). Every increment above the rate of 5 mg P kg^{-1} resulted in a significant increase in Bray- [illegible] At each of these P rates, at least 60 percent of the applied P (as TSP) was extracted with Bray-1 P solution. Optimum sorghum growth and DMY were both obtained with an application of 15 mg P kg^{-1}. Bray-1 P extracted from this treatment was 11.60 mg P kg^{-1}. Critical P requirement for sorghum under greenhouse conditions can therefore be considered to be around 11.60 mg P kg^{-1} Jomini et al. (1991) reported a critical P requirement of 11 mg kg^{-1} for millet. However, a value of mg P kg^{-1} has been determined to be the critical P level required to obtain 90 percent of the maximum millet yield in the sandy soils of Niger (Bationo et al., 1989).

Shoot P Concentration

Data presented in Tables 4 and 5 show the significant impact of lime levels, P rates, and their interactions on shoot P concentration. Shoot P concentration appeared to be generally proportional to the rate of applied P. Phosphorus concentration in the shoot of treatments that received less than 10 mg P kg^{-1} was lower than 2 g kg^{-1}. Hanway and Olson (1980) reported that a plant is considered to be low or very deficient in P if its P concentration is less than 2 or 1.5 g kg^{-1}, respectively. Ajakaiye (1979) found that sorghum grew best when P concentration in the shoot (24 days after planting) ranged from 2.2 to 8.1 g kg^{-1}. The range for millet at the same stage was 4.9 to 5.7 g kg^{-1}.

Conclusions

An application as low as 2.5 mg P kg^{-1} of soil not only prevented symptoms of poor early growth, but produced a significant dry matter increase in the greenhouse. This indicates the low P status and sorption capacity of these soils. A rate of 15 mg P kg^{-1} of soil provided adequate P for optimum sorghum growth and DMY on Plinthic Paleustalfs of the Cinzana station (greenhouse).

About 60 percent of the applied P was extracted under most treatments by the Bray-1 solution. The critical P requirement for sorghum under greenhouse conditions appears to be about 11.60 mg P kg^{-1} of soil.

PDSS Recommendations

Factors such as clay content, organic matter content, exchangeable acidity, Bray-1 P, and free Fe content were best correlated with P sorption of selected soils of the Sahel regions of West Africa. Each of these factors can be critical in the development and testing of models for the determination of P fertilizer necessary to increase soil test P to the critical level.

Jomini et al. (1991) developed an equation to estimate the annual P carryover (soil test P prior to the next crop or next year). This equation is a follows:

$$b(t+1) = 1.95 + 0.45b(t) + 0.14xp(ssp,t) - 0.14y(t) \qquad (3)$$

where b(t+1) is the soil test P (in mg P_2O_5 kg^{-1}) prior to the next crop, 1.95 is the soil initial Bray-1, b(t) is the soil test P prior to the current crop, xp(ssp,t) is the amount of single superphosphate (ssp) applied to the current crop in kg P_2O_5 ha^{-1}, and y(t) is the amount of P removed by the yield of millet grain (yield in units of quintals ha^{-1}).

Amendment with factors such as soil erosion and management would expand the purpose of Jomini's model due to their influence on P behavior and P status of soils. Erosion may remove soil surface materials to expose layers or horizons containing more clay, Fe oxide, exchangeable Al, and percent Al saturation. However, erosion also decreases soil organic matter content. All of these factors increase P sorption in soils. Soil management strategies such as application of manure or crop residues will increase organic matter content and mineralizeable P of surface soils and thus decreasing P sorption capacity. For example, Juo and Fox (1977) estimated that the P requirement of selected bench-mark soils of West Africa would double if the surface soil should be lost by erosion.

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Contact Person

Mamadou D. Doumbia
Soil and Crop Science Department
Texas A&M University
College Station, TX 77843
Telephone: (409) 845-3814
Fax: (409) 845-0456
Electronic Mail: (BITNET) L334RL@TAMVMI..BITNET

A Dynamic Model Of Phosphate Fertilization Under Uncertainty

P. A. Jomini
Purdue University, Department of Agricultural Economics
J. Lowenberg-DeBoer
Institut National de Recherches Agronomiques du Niger (INRAN)
R. R. Deuson
Institut d'Etudes et de Recherches Agronomiques (INERA)
A. Bationo
International Fertilizer Development Center, ICRISAT Sahelian Center

Introduction

This paper presents a method for assessing the economic viability of phosphate fertilization. The method accounts for the following:

1. Carryover effects of phosphorus (P) fertilizers.
2. Different potential sources of P.
3. Constraints that might affect a farmer's decision in applying fertilizer.

We account for the carryover effects of P fertilizer by using a dynamic model of farmer decision making. This requires a carryover function to describe how P carries over from one period to the next. A two-equation system was chosen to describe the way plant-available and non-available P stocks change from one decision period to the next.

Different sources of P provide different levels of P immediately available for plant uptake. The estimation of the carryover function mentioned above provides an indication of the solubility of these different P sources. In this case, the solubilities of partially acidulated phosphate rock (PAPR) from the Tapoa area in Niger and ground phosphate rock (GPR) from Tahoua are compared with that of commercially available simple superphosphate (SSP).

Factors influencing the farmer's decisions to fertilize include crop response to fertilizer applications and competing uses of the resources involved in fertilization. In this model, crop response is represented by a linear response and plateau function. This function was estimated for millet response to P, nitrogen (N), and a measure of available moisture (R). Available moisture is used to define different states of nature which determine the extent of millet response to fertilizer.

Modeling Nutrient-Soil Relationships

Carryover and Solubility of P

Annual carryover equations for all P sources are modeled according to the schematic in Figure 1.

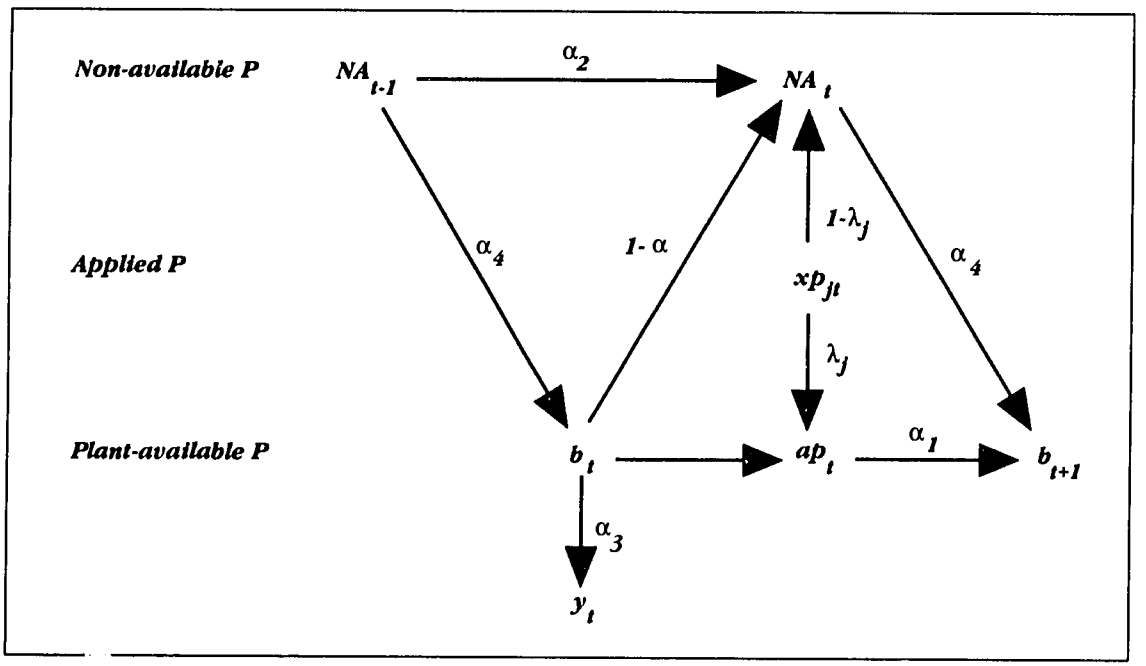

Figure 1. A schematic model of phosphorus flows in the soil.

Since P is found in different forms in the soil, this model takes into account the degree of availability for plant uptake in determining a product's desirability. Because the various P sources analyzed present different degrees of solubility, both plant-available and non-available P stocks are modeled, contrasting with earlier modeling efforts which concentrated only on the plant-available stock (see for example Lanzer and Paris, 1981). The products analyzed in these studies were in general very soluble (SSP or TSP).

By contrast, in the present study, complicated patterns of P flows between immediately available and less available P stocks are important factors. In Figure 1, the two stocks are represented by b_t which corresponds to the plant-available stock as measured by the Bray Pl soil test, and NA_t, the unavailable stock. We abstract in this analysis from the organic portion of P. The flows in and out of each stock are indicated by arrows, and the corresponding proportions are represented by parameters α_i and λ_j.

When a P fertilizer application of xp_{jt} is made, the proportion λ_j is immediately available for plant uptake, and (1- λ_j) is added to the unavailable stock. The plant-available stock of P during the cropping season is the sum of the beginning plant-available stock (b_t) and the available portion of what is applied ($\lambda_j xp_{jt}$), designated as ap_t. The plant-available stock is decreased by yield (α_3). In order to maintain a balance between the plant-available and unavailable stocks (NA_t), P flows between these stocks are modeled. Parameter α_4 represents the amount of P from the unavailable stock that becomes available for plant uptake during the period. Parameter α_1 represents the proportion of the stock available for plant uptake during the cropping season (ap_t) which is made available for plant uptake in the following period.

Parameter α_2 represents the proportion of unavailable P that carries over into the following period's stock of unavailable P. This is affected by additions of P through wind action and P removal through rain-induced erosion.

In light of the above discussion, the two following equations are used to model nutrient behaviour in the soil system:

$$b_{t+1} = \alpha_1(b_t + \sum_{j \in J} \lambda_j xp_{jt}) + \alpha_3 y_t + \alpha_4 NA_t \quad (1)$$

$$NA_t = \alpha_2\ NA_{t-1} + (1 - \alpha_1)\ b_t + \sum_{j \in J} (1 - \lambda_j)\ xp_{jt} \quad (2)$$

where:

b_t is the plant-available soil P content at the beginning of t,
xp_{jt} is the application of fertilizer j during period t,
y_t is millet grain yield during period t,
NA_t is the non-available portion of P in the soil during period t.

This mathematical model of soil P flows is based on a nutrient balance approach in which the stock of nutrients in any period is a function of: 1) the previous stock; and 2) information we have on the intervening flows in and out of the system and between pools of phosphorus. Because information on erosion and the contribution of rainfall to the P stock is not available, all the flows cannot be accounted for. What is reflected by the parameters to be estimated, however, is as follows:

$\alpha_1 = \partial b_{t+1} / \partial b_t$ the rate at which plant-available soil P from period t carries over into period $t+1$,
$\alpha_2 = \partial NA_t / \partial NA_{t-1}$ the rate at which unavailable P carries over into the following period,
$\alpha_3 = \partial b_{t+1} / \partial y\{.\}$ the average rate at which plant-available P is exported through grain yield from the field during period t, used here as a proxy for exports due to the harvest of plant matter for grain, and part of the stalks and leaves used for construction, fodder and other purposes; α_3 is expected to be negative,
$\alpha_4 = \partial b_{t+1} / \partial NA_t$ the rate at which unavailable mineral P is transformed into plant-available P in the following period through the natural weathering of soil particles, and
λ_j the rate at which P source j is immediately made available for plant uptake.

Parameter λ_j is interpreted as the rate at which applied P is immediately made available for plant uptake by assuming that applied P is converted into plant-available P at the same rate as native soil P. The rate at which applied P is immediately available to plants can be estimated by the ratio of the coefficient on each fertilizer application xp_{jt} $(\alpha_1\lambda_j)$ and the coefficient on b_t (α_1).

Nitrogen

In light of the difficulties associated with the measurement of available N and the uncertainties in the processes which supply this nutrient to the crop, the movement of N in the soil is not modeled here. However, the following crucial assumptions are made:

1. The supply of N to the crop is sufficient to promote adequate plant growth and response to P fertilization at lower levels of this nutrient.

2. The supply of N is assumed to limit plant growth when a response to applications of this nutrient is observed under an adequate supply of P.

3. Increased plant growth promoted by fertilization results in increases in plant residues, thus improving the soil's organic matter, and hence total N status.

An Economic Model of Decision Making

Authors modeling farmers' economic behaviour have used the maximization of the sum of discounted cash flows or discounted profits in analyzing the fertilizer problem (e.g., Godden and Helyar, 1980; Gunnarsson, 1982; Kennedy, 1981, 1986 and 1988). In these studies, risk was either assumed not to be important enough to affect decisions or incorporated in the model by adding a risk premium to the rate of time preference, thus increasing the rate at which future earnings are discounted.

Another approach to risk is to aggregate expected income and its variability as perceived by decision makers in a single index called *utility*. In general, the utility function increases in expected income and decreases in whatever measure of variability is used. An extension to this approach is the use of a multi-objective utility function in which various objectives of the decision maker are weighted and aggregated in a single measure (Hazel and Norton, 1986).

In empirical models of farming in Niger, decision makers have in general been assumed to maximize profits (Krause et al., 1987; Adesina, 1985 and 1988). In general, the head of the household was implicitly assumed to be the only decision maker. However, it might be argued that, in this type of economic environment and given the importance of relations between production and consumption decisions, the relevant objectives to be modeled are the entire household's. Hence a household modeling approach such as the models developed by Nakajima (1986) and found in Singh et al. (1986) which integrate production and consumption activities and with multiple objective utility functions seems more appropriate. Such models however usually centre on the important questions of labour and other resources' allocation among household activities. Risk is typically modeled in a crude fashion if at all.

A Utility-based Model of Farmer Decision Making

In this section, we present a utility-based model developed to explicitly account for risk involved in using fertilizer technologies. It is assumed that we are capable of capturing the effects of risk on the farmer's behaviour through a concave and monotonically increasing utility function of consumption. If the farmer is risk averse, his utility function is strictly concave, making marginal gains smaller as the level of his income and/or consumption increases. If the farmer is risk-neutral, the problem reduces to the maximization of the expected flow of discounted net incomes, where the discount rate only accounts for the passage of time. However, in this model, a new dimension is added. Utility is assumed to be a function of consumption. The difference between net income, used earlier, and consumption is savings which increases wealth. This wealth is available in the following period for investment in production activities or consumption. Hence, the utility function evaluates the utility of consumption in each period t, depicted in the following equation:

$$U_t = U\{C_t\} = U\{W_{t-1} + \pi_t - W_t\} \tag{3}$$

where:

U_t is the utility level attained in period t,
$U\{.\}$ is the utility function of consumption,
W_t is wealth at the end of period t,
π_t is the level of net income generated during period t, and
C_t is the consumption level in period t,

Savings S_t are defined as the portion of wealth which is not consumed, or:

$$S_t = \pi_t - C_t = W_t - W_{t-1} \tag{4}$$

The farmer is required to choose in each period an optimal combination of fertilization, savings and consumption. Savings generated during any period will be available in the following period to purchase fertilizer or to consume.

Traditionally, researchers have used the direct maximization of time-adjusted expected utility resulting from an economic activity as the objective of the decision maker. The aggregate utility function is:

$$U_A = \sum_{t=0}^{T-1} d_t \, U_t\{.\} \tag{5}$$

where:

U_A is the aggregate utility for the entire horizon relevant to the decision maker, and

d_t is a factor which adjusts the utility flows occurring in different periods for the passage of time.

Factor d_t accounts for the preference of the decision maker for the present. This preference for the present is a function of time and the risks supported by the decision maker. It is therefore related to an opportunity cost of capital which includes a premium for risk. The opportunity cost of capital can be estimated by the rate of discount used to compare monetary amounts between different periods. A correspondence between utility and monetary discount rates may exist depending on the utility function used. However, the measures traditionally used as private rates of discount apply to monetary amounts. While using a risk premium in the discount rate is convenient, it is not a very clear way of accounting for risk in agricultural production activities. This points to the need for a model which explicitly accounts for risk and time preferences. Such a model is explained in the following section.

A Model With Risk and Time Preferences

The model is based on Jean's (1978) certainty equivalent model of firm decision making over time in a risky environment. Its main characteristic is that it treats risk and time preferences separately and explicitly.

Assume the farmer maximizes the expected value of the utility derived from consumption each time period (t). Then, for each time period, there is a certain consumption level, called henceforth the certain consumption equivalent (CCE), which the farmer is ready to exchange against the uncertain set of outcomes he is faced with. The CCE is defined for each period as:

$$U\{CCE_t\} = E[U\{C_t(s)\}] = \sum_{s=1}^{S} p(s)\, U\{C_t(s)\} \tag{6}$$

where:

$U\{.\}$ is an increasing, concave function of consumption,

CCE_t is the certain consumption equivalent,

$E[.]$ is the expected value operator,

$C_t(s)$ is consumption at time t, under state of nature s,

$p(s)$ is the probability with which state of nature s might occur.

The CCE for period t is therefore rewritten:

$$CCE_t = U^{-1}\{\sum_{s=1}^{S} p(S)U\{C_t(s)\}\} \tag{7}$$

where:
$U^{-1}\{.\}$ is the inverse of the utility function $U\{.\}$, and all other notation is as before.
The CCE_t is expressed in monetary terms and is a single-valued index of the desirability of a distribution of expected outcomes.

Combining Risk and Time Preferences

Instead of directly maximizing the stream of utility derived from consumption during the planning period, the farmer is now assumed to maximize the stream of discounted certain consumption equivalents over the same planning period:

$$\Omega = \sum_{t=0}^{T-1} (1-\varphi)^{-t} CCE_t \tag{8}$$

where:
Ω is the value of the objective function, i.e. the sum of the discounted certain consumption equivalents over the entire planning period, and
φ is a risk-free private rate of discount which reflects the decision maker's rate of time preference.
Jean (1976, p. 112) indicates:

> *The use of the risk-free discount rate in the present value computation can be justified on grounds other than the marginal rate of time preference. The rate should be the appropriate rate for non-risk situations. If the discount rate is regarded as an opportunity cost of not investing in alternate projects, the alternate projects should be those with minimal or zero risk, such as the holding of government bonds.*

This model has been developed using concepts based on the expected utility hypothesis which is a principle that pervades much of the decision theory research (Anderson et al., 1977). It is developed from the premise that the decision maker maximizes utility from income. Jean (1976) indicates that the certainty equivalent is a good summary measure of the tradeoff between expected income and its distribution and (p. 112) "seems to be the most theoretically correct method of handling risk over time." In this conceptual formulation of farmers' objectives, the effects of time and risk preferences are accounted for separately. A dynamic model using this formulation is described in the following section.

A Schematic Representation of Information and Decision Making

Farmers' cropping decisions are based on their knowledge of past events and the expectations they may have about future conditions. The relations between decisions and available information are illustrated in Figure 2. At the beginning of any period t, the farmer has information on the level of his liquid assets (W_t) and the fertility of the soil (b_t). This information on initial conditions (in the dark gray box in Figure 2) for the period at hand is based on past known events. The level of the stocks is conditioned by states of nature $s_{t-1}, s_{t-2}, \ldots s_1$ which prevailed in

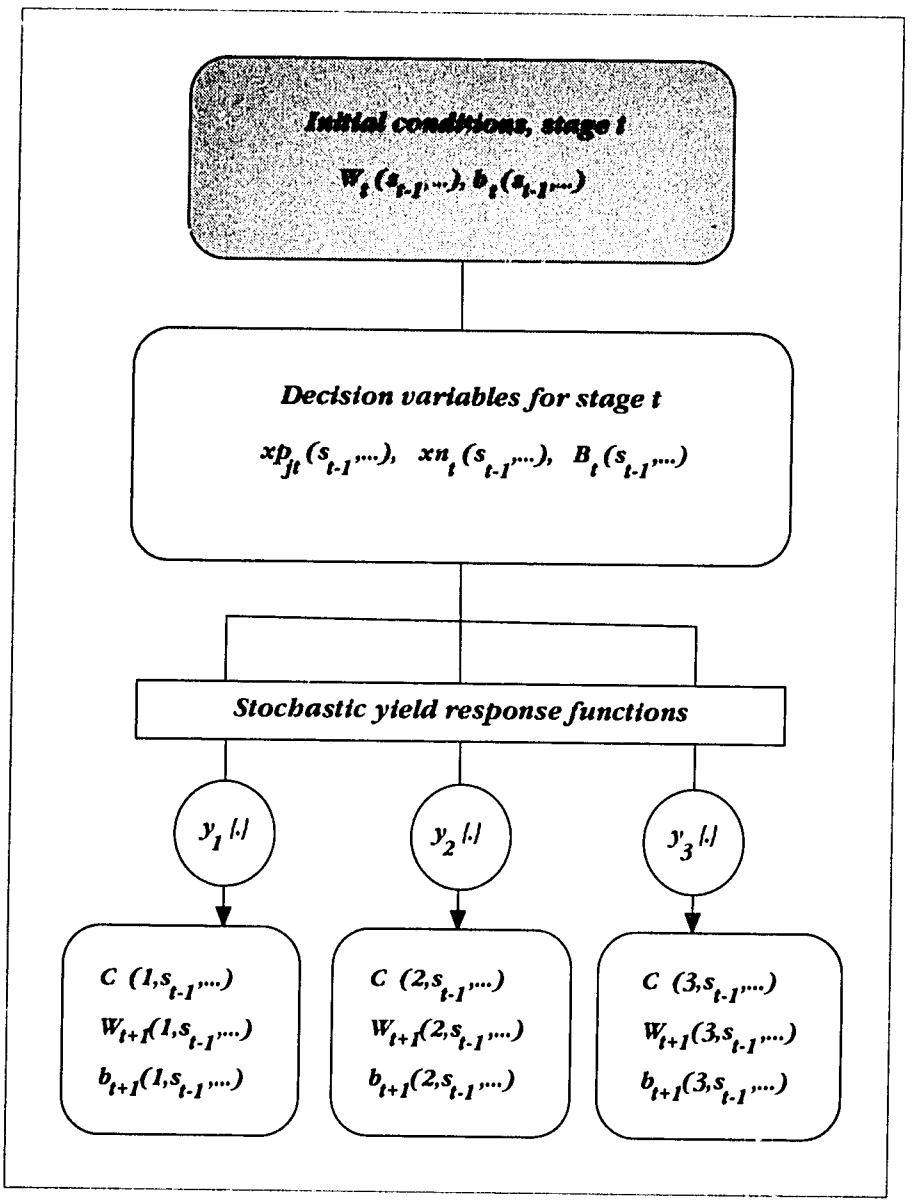

Figure 2. Schematic of the relation between information and decision in the fertilization problem.

the previous stages or time periods. Hence these stock variables are indexed by the stage t and the sequence of previous states of nature $(s_{t-1},...)$ which led to them, assuming appropriate decisions were taken during each one of these previous periods.

On the other hand, at the beginning of stage t, when fertilization decisions are made, the decision maker forms expectations about events he will face in the current period. In our case, the expectations are based on past experience, and concern the distribution of useful rainfall which conditions the distribution of yields, $y_s[.]$. Rainfall affects the outcomes, i.e., the distribution of income and consumption $C_t(s_t,...)$, and ending wealth $W_{t+1}(s_t,...)$ and soil fertility $b_{t+1}(s_t,...)$. For any one state of nature that occurred in t, W_t and b_t constitute part of the initial conditions for stage $t+1$.

These two groups of information, i.e., initial conditions for the period and expectations about conditions ahead, are used to decide on a fertilization strategy for the current period. This determines current decision variables xp_{jt}, xn_t and B_t, listed in the second shaded box in Figure 2. They are the levels of fertilization and borrowing required to follow the desirable fertilization strategy.

Events relevant to the fertilization decision occur in the sequence described in Figure 2. In Niger, at the beginning of the season (May-June), farmers assess the levels of their financial resources and soil fertility. At this time, they also form their expectations about the potential outcomes resulting from the conjunction of their decisions and intervening stochastic events. These expectations can be summarized in the form of the consumption certainty equivalents described above. Based on this information, fertilizer application and borrowing rates are chosen and the strategy executed in the course of the cropping season (June-October). These actions affect the potential outcomes which can be measured at the end of the season (November) and affect the following season's initial conditions and decisions. The actual outcome depends on which state of nature will have prevailed; it determines the amount of resources available for consumption and production activities in the following stage $(t+1)$.

In the following section, a mathematical representation of the framework in which farmers make their fertilization decisions is developed based on the principles described in this and previous sections discussing the concepts of utility of consumption.

A Mathematical Representation of Farmer Decision Making

An assumption is made that the farmer maximizes the stream of discounted certainty equivalents of the consumption achieved from growing millet on his farm over a planning horizon of length T, subject to constraints describing the production technologies at hand and the flows in and out of financial and soil stocks:

$$\max_{B_t, xp_{jt}, xn_t} \Omega = \sum_{t=0}^{T-1} (1-\varphi)^{-t} p(s_{t-1},\ldots) CCE_t(s_{t-1}, s_{t-2},\ldots) + (1-\varphi)^{-T} F_T(s_{T-1}, s_{T-2},\ldots) \tag{9}$$

such that:

$$CCE_t(s_{t-1}, s_{t-2},\ldots) = U^{-1}\left\{\sum_{s=1}^{S} p(s_{t-1},\ldots) U\{C_t(s_t, s_{t-1},\ldots)\}\right\} \tag{10}$$

$$\pi_t(s_t, s_{t-1},\ldots) = P_y y_s\{ap_t(s_{t-1},\ldots, an_t(s_{t-1},\ldots)\} - \sum_{j\in J}(c_j xp_{jt}(s_{t-1},\ldots)) - c_N xn_t(s_{t-1},\ldots) - rB_t(s_{t-1}, s_{t-2},\ldots) \tag{11}$$

$$\sum_{j\in J}(c_j xp_{jt}(s_{t-1},\ldots)) - c_N xn_t(s_{t-1},\ldots) + C_t(s_t, s_{t-1},\ldots) \le W_{t-1}(s_{t-1}, s_{t-2},\ldots) + B_t(s_{t-1}, s_{t-2},\ldots) \tag{12}$$

$$W_{t+1}(s_t, s_{t-1},\ldots) = W_t(s_{t-1}, s_{t-2},\ldots) + \pi_t(s_t, s_{t-1},\ldots) - C_t(s_t, s_{t-1},\ldots) \tag{13}$$

$$b_{t+1}(s_t, s_{t-1}) = \alpha_1 b_t(s_{t-1}, s_{t-2}, \ldots) + \sum_{j \in J} (\alpha_1 \lambda_j xp_{jt}(s_t, s_{t-1}, \ldots))$$
$$+ \alpha_3 y_s\{ap_t(s_{t-1}, \ldots), an_t(s_{t-1}, \ldots)\} + \alpha_4 NA_t(s_{s-t}, \ldots) \tag{14}$$

$$NA_t(s_{t-1}, \ldots) = \alpha_2 NA_{t-1}(s_{t-2}, \ldots) + (1 - \alpha_1) b_t(s_{t-1}, \ldots) + \sum_{j \in J} (1 - \lambda_j) xp_{jt}(s_{t-1}, \ldots) \tag{15}$$

$$ap_t(s_{t-1}, s_{t-2}, \ldots) = b_t(s_{t-1}, s_{t-2}, \ldots) + \sum_{j \in J} (\lambda_j xp_{jt}(s_{t-1}, s_{t-2}, \ldots)) \tag{16}$$

where indices are:

t	for time, from periods 1 to T,
s_t	which stands for a state of nature, s, occurring in period t;

flow variables are:

$CCE_t(s_{t-1}, s_{t-2}, \ldots)$	the certainty equivalent of consumption in period t, after the sequence of states of nature $s_{t-1}, s_{t-2}, \ldots, s_1$ has taken place,
$C_t(s_t, s_{t-1}, \ldots)$	the consumption that would take place in period t under state of nature s_t given that the sequence of states of nature $s_{t-1}, s_{t-2}, \ldots, s_1$ has taken place,
$\pi_t(s_t, s_{t-1}, \ldots)$	net income at time t under state of nature s_t given that the sequence of states of nature $s_{t-1}, s_{t-2}, \ldots, s_1$ has taken place,
$xp_{jt}(s_{t-1}, \ldots)$	P fertilizer application from source j in period t given the sequence of states of nature $s_{t-1}, s_{t-2}, \ldots, s_1$
$xn_t(s_{t-1}, \ldots,)$	N fertilizer application in period t given that the sequence of states of nature $s_{t-1}, s_{t-2}, \ldots, s_1$ has taken place,
$B_t(s_{t-1}, \ldots)$	the amount of money borrowed during period t to finance fertilizer purchases and consumption during the period, assuming the sequence of states of nature $s_{t-1}, s_{t-2}, \ldots, s_1$ has taken place;

stock variables are:

$b_t(s_{t-1}, \ldots)$	the level of plant-available P in the soil at the beginning of period t, before fertilization takes place, and assuming states of nature $s_{t-1}, s_{t-2}, \ldots, s_1$ have occurred,
$NA_t(s_{t-1}, \ldots)$	the level of non-available P in the soil after fertilization has taken place in period t, assuming states of nature $s_{t-1}, s_{t-2}, \ldots, s_1$ have occurred,
$ap_t(s_{t-1}, \ldots)$	the level of plant-available P after fertilization for period t has occurred, given that the sequence of states of nature $s_{t-1}, s_{t-2}, \ldots, s_1$ has taken place,
$an_t(s_{t-1}, \ldots)$	the level of plant-available N after fertilization for period t has occurred, given that the sequence of states of nature $s_{t-1}, s_{t-2}, \ldots, s_1$ has taken place,
$W_t(s_{t-1}, \ldots)$	the wealth at the beginning of period t following the sequence of states of nature $s_{t-1}, s_{t-2}, \ldots, s_1$ in previous periods, and
$F_T(s_{T-1}, s_{T-2}, \ldots)$	the value of final stocks of soil P and wealth at the end of the farmer's planning horizon, assuming states of nature $s_{T-1}, s_{T-2}, \ldots, s_1$ occurred;

functions are:

$U\{.\}$	the utility function by which the farmer evaluates the consumption permitted by his production and investment activities,
$y_s\{.\}$	the yield function corresponding to state of nature s;

and parameters are:

φ	the annual rate of discount the farmer uses to compare monetary flows between different periods,
P_y	the price of millet grain,

c_j the cost of a unit of P_2O_5 supplied by P source j,
c_N the cost of a unit of N supplied by urea,
λ_j and α_i the carryover parameters discussed earlier,
$p(s_t)$ the probability of state of nature s in period t,
$p(s_{t-1}, s_{t-2}, \ldots) = p(s_{t-1})p(s_{t-2})\ldots p(s_t)$ the joint probability of states of nature s_{t-1} occurring in period $t-1$, s_{t-2} occurring in period $t-2$, etc.

In the objective function (9), the farmer is assumed to maximize the sum of: 1) the expected sum of discounted certainty equivalents of consumption above the minimum necessary to reproduce labour over a planning horizon of length T; and 2) the final value of the stocks left at the end of the planning horizon. The certainty equivalent for each stage T given a sequence of states of nature in the preceding stages is defined in Equation 10.

Total income is calculated in Equation 11 for each year, based on the state of nature which occurs in the period and the previous states of nature. This total income is the difference between the value of the crop and monetary outlays during the season. Outlays include the cost of fertilizer and interest costs on the loan that may be needed to purchase fertilizer and food during the period.

Expected prices are expressed in real terms and are assumed constant over time. The influence of expected changes in input prices on the fertilization decision when carryover matters was investigated by Jomini and Lowenberg-DeBoer (1987). These authors showed that with expectations of increasing input prices, soil fertility mining may be an economically optimal management strategy. Walker and Jodha (1986) indicate that for households operating under rainfed conditions near subsistence level (therefore consuming a large part of farm output), price risk is of relatively little importance compared to the overriding importance of risks associated with yield variability. Therefore only yield variability is modeled here, and prices are not associated with a probability distribution.

A liquidity constraint (Equation 12) is included for each period and state of nature. This requires that wealth at the beginning of the period and borrowing during the period cover at least monetary production expenses and consumption for the current stage.

Wealth at the beginning of the following period $(t-1)$ is the sum of wealth at the end of periods 1 through $t-1$ and current income, less consumption in period t. Wealth in this sense is composed of the liquid means of storing value mentioned earlier, and includes stored grain and monetary instruments.

The evolution of soil fertility across stages is described in Equations 14 and 15. They are based on the deterministic equations 1 and 2 discussed earlier, but depend on the states of nature that occurred in previous periods. The amount of P available for plant uptake after fertilization is calculated in Equation 16.

The farmer is assumed to know the initial fertility of the soil and his wealth. This is expressed in the following initial conditions:

$$b_0 = \underline{b}_0 \tag{17}$$

$$W_0 = \underline{W}_0 \tag{18}$$

At the end of the planning horizon (stage T), residual wealth and soil fenility are evaluated as:

$$F_T(s_{T-1}, s_{T-2}, \ldots) = W_T(s_{T-1}, s_{T-2}, \ldots) + \min_{j \in J}(c_j \lambda_j^{-1}) b_T \tag{19}$$

where ending soil fertility, b_t, is evaluated by the cost of increasing soil P by 1 unit using the cheapest source of P available.

The farmer is assumed to maximize the discounted sum of 'excess consumption certainty equivalent' under 3 possible states of nature, over 3 years. Choices available to the farmer include:

1. Consuming at least a minimum level of consumption ($\underline{c}$) related to the size of the household he is responsible for.
2. Saving part of currently available wealth for future consumption or fertilization in the following period.
3. Financing consumption or fertilization through equity or borrowing.
4. Applying P fertilizer in the form of SSP, PAPR or PRT sequentially or simultaneously
5. Applying fertilizer now or when sufficient cash is available.

This results in a model composed of 396 equations and 383 variables spread over 27 possible time paths. Stochastic dynamics increase model size rapidly, although this model is after all rather simple, and a very partial representation of the decision problems farmers face in Niger.

Specific Biological Functions and Parameters

Yield Production Function

Before the above model can be applied, the biological relations must be specified more precisely. The generic production function used in Equation 11 is a linear response and plateau function estimated by Jomini et al. (1991). It is characterized by 3 plateaus which depend on 3 states of nature. These states of nature in turn depend on moisture availability during the cropping season. For each state of nature s, the function is written:

$$y^s = \min\left(0.97 + 0.61ap_t, 7.75 + 0.06an_t, M^s\right) \tag{20}$$

where M^s is the plateau maximum corresponding to state of nature s, and all other notation is as before. Table 1 provides the plateau maximum and probability of occurrence attached to each state of nature.

Carryover of P

Parameters for the system of equations used to specify the carryover of P are from Jomini et al. (1992) where the authors estimate P carryover and availability for SSP, PAPR and GPR. The estimates for Equations 1 and 2 are found in Table 2.

Table 1. Plateau maximum and probability attached to each state of nature.

State of nature	Plateau *(kg/ha)*	Probability *(%)*
Bad	540	35
Low	775	45
Sufficient	961	20

Source: Jomini et al. (1991)

Dynamic Farm Model Results

Parameters for four different scenarios are shown in Table 3. All of the scenarios depicted are based on millet farming in Niger. In the first scenario, a low discount rate, some degree of risk aversion ($\rho = 4.0$), and a 'high' initial wealth (twice the resources needed to meet the minimum food requirement) are assumed. In Scenario 2, initial wealth is lowered to ascertain the effect of competition between consumption and fertilization activities for financial resources. In Scenario 3, the farmer is assumed to be a strict profit maximizer ($\rho = 0$), and to have sufficient financial resources in the first period. This will show the impact of the behavioural assumptions made

Table 2. Carryover equation parameters.

	Parameter	Estimate
Annual rates of P carryover (%)	α_1	0.39353
	α_2	1.01017
	α_4	0.04490
Immediate solubility (%)	λ_{SSP}	0.87051
	λ_{PAPR}	0.42638
	λ_{PRT}	0.25733
Yield effects on soil P (ppm kg^{-1})	α_3	-0.14678

Source: Jomini et al. (1991)

NOTE. Parameters apply to the following equations:

$$(1)\ b_{t+1} = \alpha_1 (b_t + \sum_{j \in J} \lambda_j xp_{jt}) + \alpha_3 y_t + \alpha_4 NA_t$$

$$(2)\ NA_t = \alpha_2\ NA_{t-1} + (1 - \alpha_1)\ b_t + \sum_{j \in J} (1 - \lambda_j)\ xp_{jt}$$

Table 3. Parameters for different scenarios considered in the dynamic analysis.

Parameters	Scenarios			
	1	2	3	4
Prices				
output [FCFA/kg]	50	130	130	50
SSP [FCFA/kg $P2O_5$]	278	278	278	∞
PAPR [FCFA/kg P_2O_5][a]	222	222	222	222
GPR [FCFA/kg P_2O_5][b]	129	129	129	129
Urea [FCFA/kg n]	125	125	125	125
Discount rate [%]	7.5	7.5	7.5	7.5
Risk aversion	4.0	4.0	0.0	4.0
Initial				
wealth [FCFA]	107,500	146,738	279,500	107,500
fertility [ppm]	3.0	3.0	3.0	3.0

a *Based on engineering estimates, the cost of P_2O_5 in PAPR is assumed to be 80 percent of the cost of P_2O_5 in SSP.*

b *Based on engineering estimates, the cost of P_2O_5 in GPR is assumed to be 46 percent of the cost of P_2O_5 in SSP.*

concerning risk. In Scenario 4, SSP is assumed not to be available in order to assess the private costs to farmers of a policy making the import of SSP prohibitive.

Results for the scenarios described in Table 3 are found in Tables 4 and 5. Standard deviations across all states of nature are provided next to each variable.

Scenario 1: Current Price Levels and Non-limiting Financial Resources

Starting with low fertility (3 ppm available P), the desirable soil fertility is still 11.11 ppm, and no N should be applied. This is achieved by applying 9.3 kg P_2O_5/ha in the form of SSP (52 kg SSP/ha) in the first year to achieve the desirable fertility level. In following years, less fertilizer is needed to maintain the desirable fertility level. The annual cost of maintenance fertilization is less than 2000 FCFA[1]/ha (US$6.87/ha). The expected yield is 693 kg/ha millet grain, with a maximum attainable yield of 775 kg/ha. Yield is limited by the relatively low profitability of applying N and additional P at the assumed input-output price structure. Total farm cereal production is expected to be about 2000 kg millet grain, and income generated by this activity is expected to be in the order of 100 000 FCFA/year (about US$333/year). Expected income is variable, with a coefficient of variation (CV) of about 17 per cent.

[1] FCFA: Franc CFA; in 1987, 300 FCFA = 1US$

Assuming a five person household, the level of expected farm income from growing cereal corresponds to an annual per capita income of about 20,000 FCFA (or US$66). Gross domestic product (GDP) for the period 1981–1985 was reported by Ancey et al. (1987) as 638 x 10^9 FCFA. This corresponds to a per capita annual income of 106,000 FCFA (US$350). Assuming per capita GDP is an adequate estimate of the production on a farm of the type modeled here (3 ha, 5 people), cereal production would then account for about 20 per cent of per capita production. We suspect however that annual per capita income on this type of farm is below the national average because this average includes mining and commercial activities which are expected to be more profitable than farming.

In the first period, a relatively high consumption level is achieved as starting wealth is high. In the long term, cereal production provides sufficient income/production to sustain a level of

Table 4. Summary of fertilization strategies for the dynamic model under Scenarios 1 and 2.

Scenarios[a] & Variables	Period 1		Period 2		Period 3	
	mean	*s.d.*	*mean*	*s.d*	*mean*	*s.d*
Scenario 1:						
Carryover P [ppm]	3.00	0	5.14	1.6	5.30	1.6
Avail. P [ppm]	11.11	0	11.11	0	11.11	0
Appl. P [kg P_2O_5/ha]	9.32	0	6.87	1.9	6.68	1.9
Expected						
yield [kg/ha]	693	112	693	112	693	112
production [kg]	2008	324	2008	324	2008	324
income [FCFA]	92934	16220	94906	16220	95056	16220
consump [FCFA]	100013	0	94718	15999	90964	15841
wealth [FCFA]	100421	16220	100609	15963	104700	10574
Scenario 2:						
Carryover P [ppm]	3.00	0	5.14	1.6	6.47	2.3
Avail. P [ppm]	11.11	0	14.16	0	11.11	0
Appl. P [kg P_2O_5/ha]	9.32	0	10.38	1.9	5.34	2.6
Appl. N [kg N/ha]	0	0	31	0	0	0
Expected						
yield [kg/ha]	693	112	730	156	693	112
production [kg]	2008	324	2116	451	2008	324
income [FCFA]	253407	42171	255662	58629	256807	42171
consump [FCFA]	139750	0	240978	41848	258186	57288
wealth [FCFA]	260395	42171	275079	58099	273700	25679

[a] *Scenario parameters are found in Table 3.*
Scenario 1: base input and output prices, unconstraining beginning financial resources and positive risk aversion.
Scenario 2: higher output price, lower starting financial resources, positive risk aversion.

consumption about 70 percent above the minimum consumption requirement. In the worst case, in the third period, if weather is consistently bad, consumption 20 percent above the minimum requirement is achieved as fertilization and consumption activities compete for the same financial resources.

Scenario 2: Limiting Financial Resources and Better Output Price

The increased output price (to 130 FCFA/kg grain or US$0.44/kg grain) provides an adequate incentive for increased fertilization and production. In this scenario, stiff competition between consumption and fertilization activities for cash resources in the initial period does not allow farmers to fertilize heavily and limits consumption to a low level in the first period. A small loan of 500 FCFA (US$1.67) is needed in this period to allow limited fertilization and minimum consump-

Table 5. Summary of fertilization strategies for the dynamic model under Scenarios 3 and 4.

Scenarios[a] & Variables	Period 1		Period 2		Period 3	
	mean	*s.d.*	*mean*	*s.d*	*mean*	*s.d*
Scenario 3:						
Carryover P [ppm]	3.00	0	6.30	2.3	6.51	2.3
Avail. P [ppm]	14.16	0	14.16	0	14.16	0
Appl. P [kg P_2O_5/ha]	12.83	0	9.03	2.6	8.80	2.6
Appl. N [kg N/ha]	31	0	31	0	31	0
Expected						
yield [kg/ha]	730	156	730	156	730	156
production [kg]	2116	451	2116	451	2116	451
income [FCFA]	253690	58628	256741	58629	256931	58629
consump [FCFA]	258047	0	256741	58418	256931	58418
wealth [FCFA]	275143	58628	275143	58628	275143	58628
Scenario 4:						
Carryover P [ppm]	3.00	0	6.12	1.6	6.89	1.7
Avail. P [ppm]	11.11	0	11.11	0	11.11	0
Appl. P [kg P_2O_5/ha][b]	31.19	0	19.20	6.3	16.21	6.3
Expected						
yield [kg/ha]	693	112	693	112	693	112
production [kg]	2008	324	2008	324	2008	324
income [FCFA]	88663	16220	93184	16221	94310	16221
consump [FCFA]	95742	0	92995	15909	90271	15726
wealth [FCFA]	100421	16220	100610	15962	104650	10646

[a] *Scenario parameters are found in Table 3.*
Scenario 3: higher output price, unconstraining financial resources and profit maximization.
Scenario 4: base prices but SSP is unavailable, unconstraining financial resources, positive risk aversion.
[b] *In the form of GPR.*

tion in the first year. This is the only scenario in which borrowing is used to attain both consumption and fertility targets.

Target fertility in the first period is 11 ppm as in Scenario 1. But in the second period, target soil fertility is 14 ppm for P and 31 kg N/ha, and consumption almost doubles. Soil fertility steadily increases and wealth stabilizes around 275,000 FCFA/year (US$917/year). A higher output price therefore fosters a significant increase in fertilizer use and in consumption, even when little equity is available initially.

This case illustrates the inadequacy of the current valuation of ending soil P when low discounting is used. The current valuation of residual fertility is based on the cost of fertilization when actually a measure of the productive potential of P in the soil is needed. With this high output price and a fixed input price, the ending soil P content is undervalued, which results in a lowered target soil fertility. A remedy to this modeling problem might be to increase the number of stages modeled. However, this does not seem an efficient way of dealing with the problem due to the size of the model at hand. One might use the average shadow value of ending soil fertility (808 FCFA/ppm or US$2.67/ppm). However, because this is an average value, it does not provide sufficient incentive to maintain high soil fertility. No solution at this time seems satisfactory in finding an appropriate value for ending soil fertility in the stochastic problem.

Scenario 3: High Initial Wealth and Output Price, Profit Maximization

For the profit maximizer ($\rho = 0$), risk is not taken into account in the decision to fertilize. The objective function is reduced to expected profit maximization. Under the assumptions of Scenario 3, a high soil fertility is maintained in order to obtain relatively high expected yields. Expected income and consumption are also higher than in previous scenarios. Expected per capita consumption in the first year is equivalent to 397 kg grain, substantially higher than the assumed subsistence level (215 kg grain/capita). Variability in consumption and income has increased over that of previous solutions with lower returns. These results are to be expected when decisions made by decision makers with lower aversion to risk are examined.

Scenario 4: SSP Is Not Available to Farmers

When SSP is not available to farmers, the assumed price structure favors the use of GPR at the rate of 31 kg P_2O_5/ha in the first period. The target fertility and average yield are the same as if SSP were available. The unavailability of the more soluble source of P decreases slightly expected income and consumption from the levels expected under Scenario 1 (by 5 percent and 4 percent, respectively, in the first year).

Conclusions

A dynamic model of farmer decision making under uncertainty was developed to investigate the relative merits of alternative sources of P in the management of soil fertility in Niger. Three products — SSP, PAPR and GPR — were compared with respect to their ability to profitably increase millet production. Low fertilization rates (50-60 kg SSP/ha were shown to increase low fertility soils' P concentration to 11 ppm, a level sufficient to bring potential millet grain yield to 775 kg/ha and expected yield to 695 kg/ha. Due to its higher degree of solubility, SSP was the preferred product under the current price structure.

Experiments using the four scenarios lead to the following comments on the model's charac-

teristics. The recommended soil fertility is valid for a wide range of input and output price combinations. Two characteristics of the model contribute to this stability:

1. The assumption that millet response is appropriately modeled by a function that does not allow for nutrient substitution and whose derivatives are discontinuous.

2. The assumption that the impact of different states of nature (weather) on yield can be captured with just three states of nature.

P carryover between cropping seasons is significant. While the dynamic model takes this into account, the value of P at the end of the decision period influences decisions in earlier periods. Ending P is valued in terms of a replacement cost instead of its potential for production. This results in a relatively low value attributed to the ending P stock. This low value influences decisions in preceding periods. Increasing the number of periods in the model would reduce the effect of the end-period valuation of P. However, the stochastic nature of the model makes it large and difficult to extend for more than a few periods (3 periods were modeled in this paper).

One way of circumventing this problem may be to run the model once, then use the level of state variables at the end of the first period as initial conditions for a set of second runs based on the outcome of each state of nature in the first period. However, if the ending period valuation affects P decisions in the first period, this will not help. An alternative way of valuing P is to use the production function to evaluate the production potential of residual P.

Two relevant issues, however, should be borne in mind:

1. With high discount rates, farmers are less sensitive to costs and benefits that may occur in the future.

2. The purpose of the dynamic model is to provide a recommendation for the first period; it does not provide a multiple period cropping plan; it can however be used with different initial conditions reflecting farmers' differing situations both geographically and in time.

These mitigate the need to search for a better treatment of end-period P.

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Contact Person:

Patrick A. Jomini
Industry Commission
P.O. Box 80
Belconnen ACT 2616
Australia
Telephone: 61-6-264-3172
Fax: 61-6-253-1660

Soil Phosphorus Kinetics And Crop Response

A. B. Onken
Texas A&M University, Research and Extension Center

Introduction

Applying correct amounts of fertilizer is one of the primary keys to optimizing profits from its use. To determine the appropriate fertilizer rate, growers must be able to assess the nutrient supplying power of the soil in relationship to crop yield and fertilizer rate. This relationship needs to be quantitative, continuous, and in a form suitable for economic analyses in order to be most effective. Current diagnostic techniques used to assess phosphorus (P) supplying power of soil are less reliable than desired and are frequently based upon a noncontinuous high, medium, and low classification. Thus, a constant effort exists to develop new or modify old techniques. In plant nutrition, rates at which processes take place in soil are known to be important. It follows, therefore, that kinetic studies of P in soils might be useful in describing reactions and in determining plant availability. Even though a small body of research data is developing for the kinetics of P processes in soil, some controversy exists relative to model development, techniques for measurement, and applicability of data. The purpose of this presentation is two-fold. First, to briefly review previous P kinetic research, particularly as it pertains to crop response; and second, to discuss some areas where kinetic data might be useful.

Previous P Kinetic Research

Several kinetic models have been used to describe P reactions in soil. Among those most often used are: 1) multiple simultaneous first order reactions (Amer et al., 1955; Evans and Jurinak, 1976; Elkhatib and Hern, 1988); 2) two-constant rate equations (Kuo and Lotse, 1974; Olsen, 1975; Onken and Matheson, 1982); 3) the Elovich equation (Chien et al., 1980; Chien and Clayton, 1980; Onken and Matheson, 1982); and 4) the parabolic-diffusion equation (Cooke, 1966; Evans and Jurinak, 1976). Additionally, an empirical model for desorption of P in water has been proposed that contains expressions for water/soil ratio and the initial amount of desorbable soil P (Sharpley et al., 1981).

A number of studies has been conducted in which kinetic equations have been compared for describing soil P dissolution. Kuo and Lotse (1974) concluded that a two-constant rate equation fit both adsorption and desorption P data for two lake sediments. Eight kinetic models were compared by Chien et al. (1980) for dissolution of water soluble P from three sources of rock phosphate in three soils and concluded the data best fit an Elovich equation. Pursuing the use of the Elovich equation further, Chien and Clayton (1980) fitted P release data that had been originally interpreted as involving three simultaneous first-order reactions (Amer et al., 1955) and P sorption data originally interpreted as involving three mechanisms (Ryden et al., 1977) to Elovich equations illustrating the possible use of Elovich equations to describe kinetics of both P sorption and dissolution from soils. Eight kinetic models were compared by Onken and Matheson (1982) for

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describing dissolution of P from four soils taken from six test locations. They found that no single model best described P dissolution from all soils, but that the two-constant rate, Elovich, and differential-rate equations were most often the best. Four kinetic models were compared by Elkhatib and Hern (1988) for desorption of P from 10 acid soils, and they concluded that a first-order rate equation best described P-desorption rates. Given the wide range of chemical and physical characteristics of the soils and diversity of experimental techniques utilized, it is not unexpected that several kinetic models have been found to be useful in describing P reactions in soil .

A limited amount of research has been conducted to determine the effects of soil properties and experimental conditions on reaction kinetics of P with soil. Constants of the Elovich, two-constant rate, and differential-rate equations have been shown to be affected by soil/solution ratio (Onken and Matheson, 1982; Sharpley, et al., 1981). Temperature effects on kinetic constants of P reactions in soil have been shown to follow Arrhenius-type relationships (Kuo and Lotse, 1974; Onken and Matheson,1982; Griffin and Jurinak, 1973). Chien et al., (1980) concluded that temperature had no effect on P dissolution from rock phosphate because the release of P from rock phosphate and subsequent sorption by the soil both followed an Arrhenius-type relationship.

Correlation of various soil chemical and physical characteristics to kinetic equation regression coefficients was attempted by Enfield et al. (1976) without success. In contrast, Sharpley (1983) found extractable Al for acid soils and calcium carbonate equivalent for calcareous soils correlated well with constants of the Elovich equation. Sharpley (1983) proposed an empirical kinetic model and found that ratios of Fe or clay to organic C and calcium carbonate or clay to organic C for

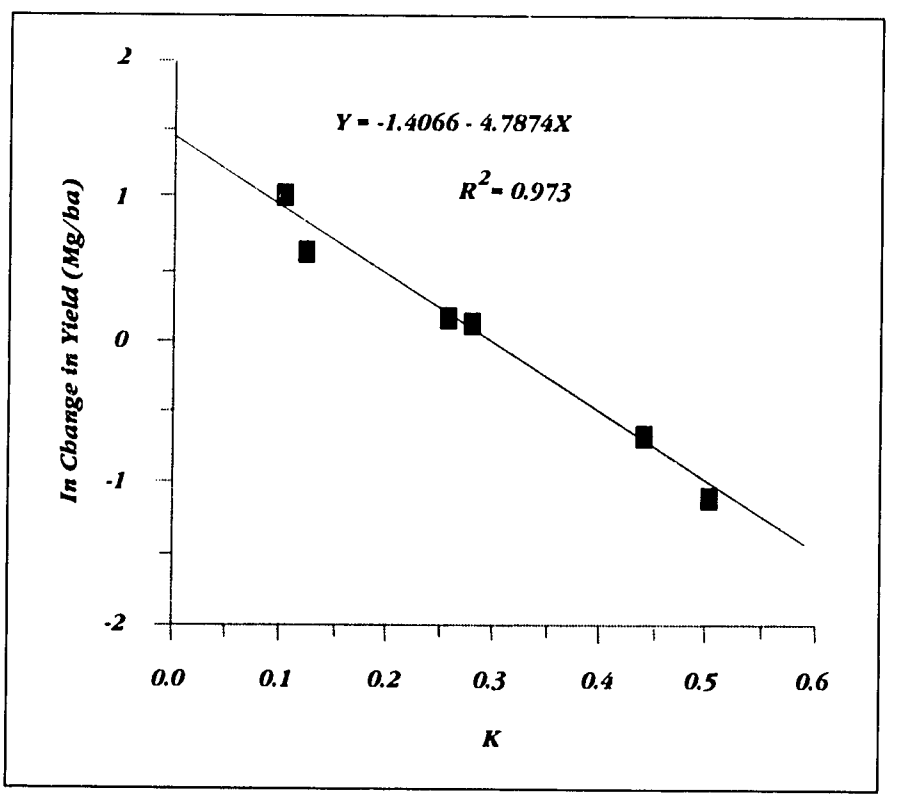

Figure 1. Relationship between grain sorghum yield response to applied P and the rate constant, K, for the two-constant rate equation.

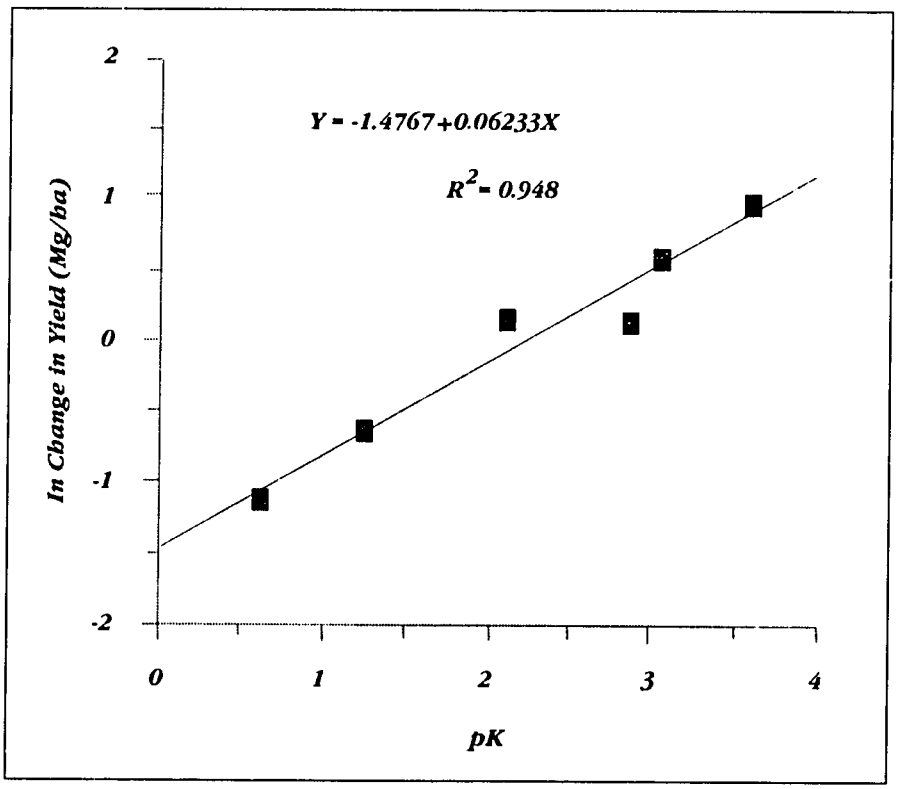

Figure 2. Relationship between grain sorghum yield response to applied P and the rate constant, K, for the differential-rate equation.

acid and calcareous soil, respectively, correlated with model constants. Ratios of Al to clay and ferric oxide to organic C have been found to correlate well with first-order equation constants (Elkhatib and Hern, 1988). It has been suggested that soil properties might be used to estimate constants for appropriate kinetic models to predict P dissolution from soil (Elkhatib and Hern, 1988; Sharpley, 1983).

Knowledge of P reaction kinetics in soil, particularly as they relate to crop response, has been projected as being potentially useful (Chien et al., 1980; Cooke, 1966; Olsen, 1975; Onken and Matheson, 1982; Sharpley, 1983; Sikora et al., 1990). A significant correlation was found by Cooke (1966) between the dissolution-rate constant of soil P to an anion-exchange resin for a parabolic-diffusion equation and P uptake by rye grass in a greenhouse experiment. Also in a greenhouse experiment, Olsen (1975) obtained a significant correlation between P uptake by millet and the dissolution-rate constant from a derived rate equation for P extracted by EDTA from a wide range of soils. Significant correlations between dissolution-rate constants for EDTA extractable soil P and grain yield response of field grown grain sorghum to applied P on several soils were found by Onken and Matheson (1982) utilizing the differential-rate and two-constant rate equations. Also found was a significant relationship for grain yield response and the value of beta from the Elovich equation. Cooke (1966) concluded that P uptake by plants was influenced more by the dissolution rate of soil P than the equilibrium P concentration in soil solution. Investigating water insoluble fractions of mono-ammonium phosphate, Sikora et al. (1990) found the beta constant of the Elovich equation to be a better indicator of P availability to sorghum-sudan grass than the pseudo first-order rate constant, the AOAC available P method, AOAC water soluble P, or equilibrium P concentration. Olsen (1975), however, concluded that as a measure of P availability to a

crop, a single extraction for a specified time period was as effective as determining the dissolution-rate constant.

Results and Discussion

We conducted a series of studies to determine the potential usefulness of kinetic measurements on soil as a diagnostic technique for predicting crop response to applications of P fertilizer.

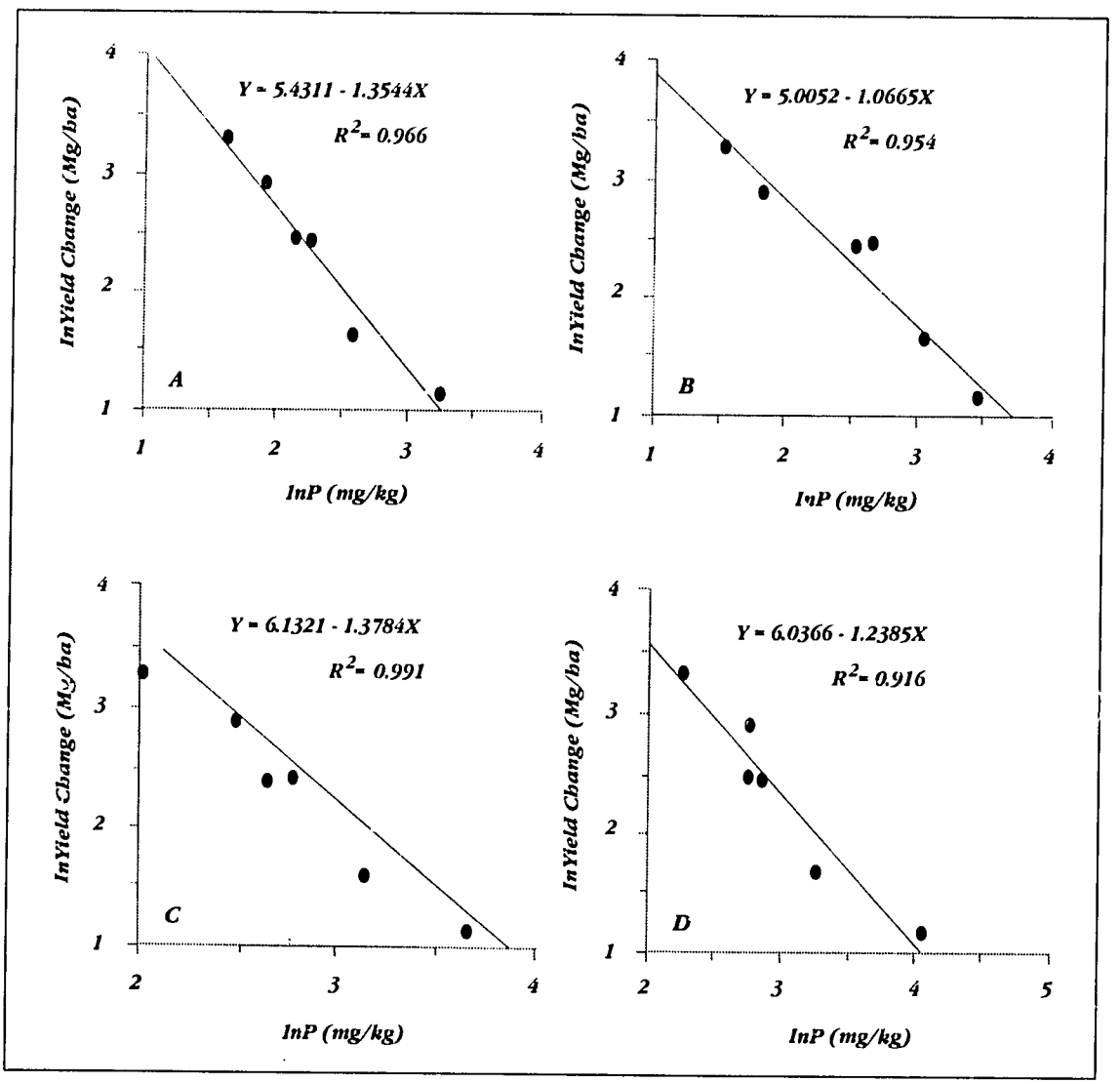

Figure 3. Relationship between change in grain sorghum yield due to P application and P extracted by EDTA solution for four extraction times. A = 30 min.; B = 60 min.; C = 160 min.; D = 360 min.

A saturated solution of EDTA in water was used as the extractant since it had previously been shown to relate crop response to applied P when used as a single extract for a specified time period (Onken et al., 1980). Positive relationships were obtained between grain yield response of sorghum to applied P and kinetic equation constants (Figs. 1 and 2); these results have been previously reported (Onken and Matheson, 1982). This discussion will compare information obtained from single soil extracts to that obtained from kinetic equation constants for the purpose of predicting crop responses to applied P for both short- and long-term planning horizons. Relationships between the change in grain yield due to P application and soil P extracted during four time intervals are given in Figure 3. Coefficients of determination (R^2) ranged from 0.916 to 0.971. The ln-ln relationship was the best found of several that were tried, including linear, second-order polynomials, and semi-log. The relationship between yield change and the dissolution rate constant from the two-constant and differential-rate equations had R^2 values of 0.97 and 0.95 (Figs. 1 and 2). Thus, the usefulness of kinetic data and single soil extracts for predicting crop response to P fertilizer application was similar. From these results the question arises as to whether or not kinetic data could yield sufficient additional information to warrant the extra effort required in its being obtained.

Another area in which kinetic data might prove useful is reaction of applied P. We have conducted a very preliminary study by obtaining kinetic data for P dissolution from two soils taken from grain sorghum field plots to which P rates of 0 and 40 kg/ha had been applied for two years. The soil samples analyzed were taken approximately 24 and 12 months after the initial and second P fertilizer application, respectively. A significant grain yield response was obtained both years due to P application on the Olton clay loam, but not on the Sherm silty clay loam. Grain yields were in the range of 7 to 9 Mg/ha, both years. Dissolution data for the two soils are shown in Figure 4. A greater increase in extractable P due to P application was obtained from the Sherm silty clay loam than from the Olton clay loam, particularly after 100 minutes of extraction time. The dissolution curves in Figure 4 indicate the reaction products of fertilizer P applied to the Sherm silty clay loam were more soluble than those of the Olton clay loam. This can be more clearly seen with a plot of the difference in extractable P between the two soils for each treatment (Fig. 5). The difference in extractable P between the two soils was greater with, than without, two years of P application. Also, increasing time of extraction resulted in increasing the difference in extractable P between the two soils due to P application. Thus, the soil with the most soluble P compounds at the start of the experiment had the most soluble reaction compounds after P application. This indicates that long-term P reaction products may be related to original P compounds. If so, this could have major implications relative to application amounts and rates of reaction to formation of plant unavailable forms. Dissolution of P with time fit a two-constant rate equation better than an Elovich equation for both soils and treatments (Figs. 6 and 7).

Regression equations for the data in Figures 6 and 7 yield additional information (Table 1). Dissolution rate constants, k_A, from the two-constant rate equations were much greater for the Sherm silty clay loam than the Olton clay loam for each treatment. The two years of P applications to the Olton clay loam resulted in a similar k_A value as for the Sherm silty clay loam without P application. The values of k_A also exhibited a much greater percentage increase due to P application for both soils than was found for any single extraction time. In contrast, the ß values for the Elovich equation did not exhibit large changes due to P application, nor did the ß value for P treated Olton clay loam approach that of untreated Sherm silty clay loam. Thus, the values of k_A were a more sensitive measure of change in P status than the other parameters measured. These results indicate the possibility that kinetic data might provide useful information relative to early- and long-term reaction products of applied P and rates at which reactions to unavailable

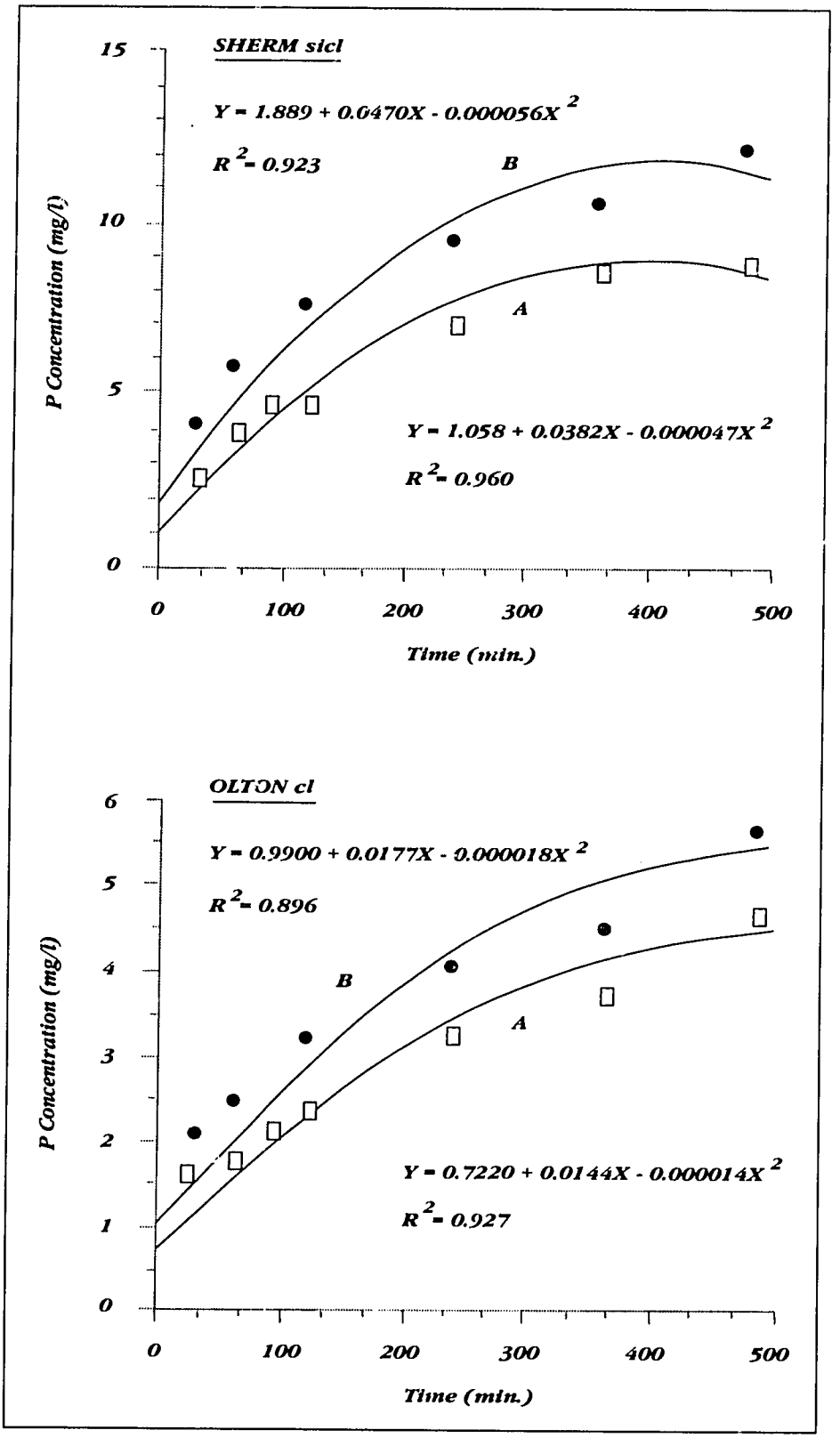

Figure 4. Concentration of P in EDTA solution as a function of extraction time. A = No applied P; B = 40 kg P/ha, two years.

forms are taking place that would not be obtained from single extracts.

Furnishing producers with economic analyses, along with their soil test results, in order to provide additional information on which to base a decision for optimizing profits from fertilizer application, has become more feasible than in the past due to increased computerization in soil testing laboratories. Both short-term and long-term economic analyses are required when carry-over effects from previous fertilizer applications occur, as would be the case with P (Stoecker and Onken, 1989). Short-term fertilizer profits are maximized by applying the amount of fertilizer which would equate additional crop yield due to applied fertilizer to the per kilogram price of fertilizer divided by the appropriately adjusted price of the crop. Marginal productivity for applied fertilizer can be calculated from the first derivative of a response function relating crop yield, soil test level, and applied fertilizer. This information can be used to make fertilizer-rate decisions based upon expected fertilizer costs and crop prices.

Calculations for optimizing long-term profits require a carry-over function when fertilizer applied in a previous year would influence yields in a subsequent year and the marginal rate of substitution of residual soil P and applied P is not equal to one. In many soils this is a probable occurrence. It is, therefore, important to obtain the best response and carry-over functions possible.

Barrow (1980) has suggested that it might be more useful to measure rate of P desorption rather than trying to separate adsorbed and firmly held P in evaluating residual P. Thus, decreases in rates of desorption would be related to decreasing effects of previously applied P on plant

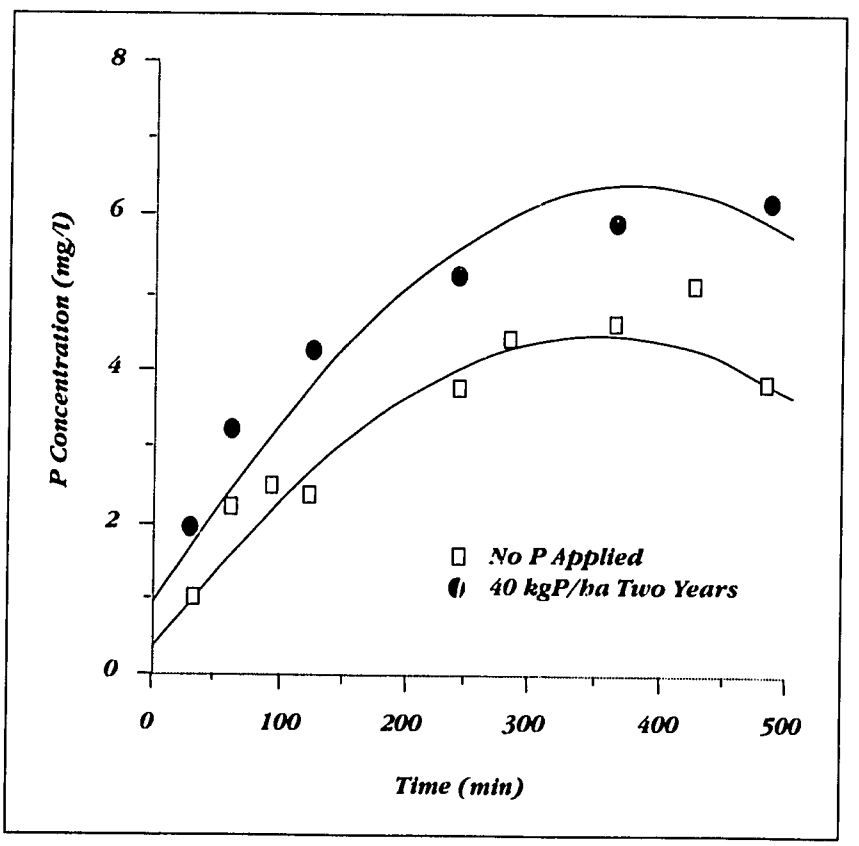

Figure 5. Difference in P concentration in EDTA extract between Sherm silty clay loam and Olton clay loam as affected by P treatment and time of extraction.

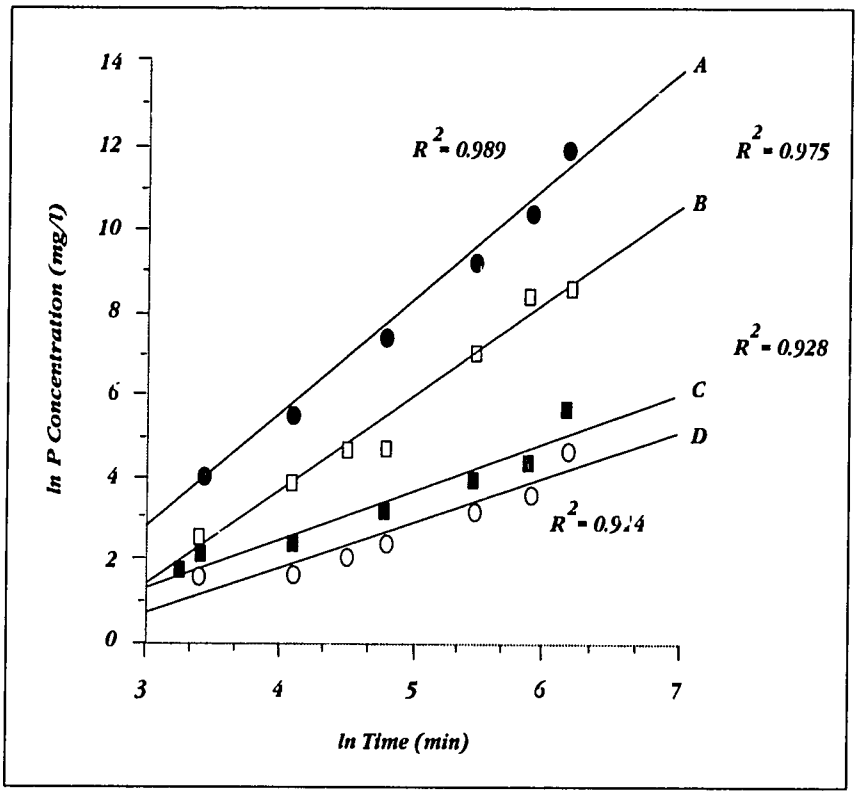

Figure 6. Elovich plot of P dissolution data. A = Sherm silty clay loam, 40 kg P/ha, two years; B = Sherm silty clay loam, no P applied; C = Olton clay loam, 40 kg P/ha, two years; D = Olton clay loam, no P applied.

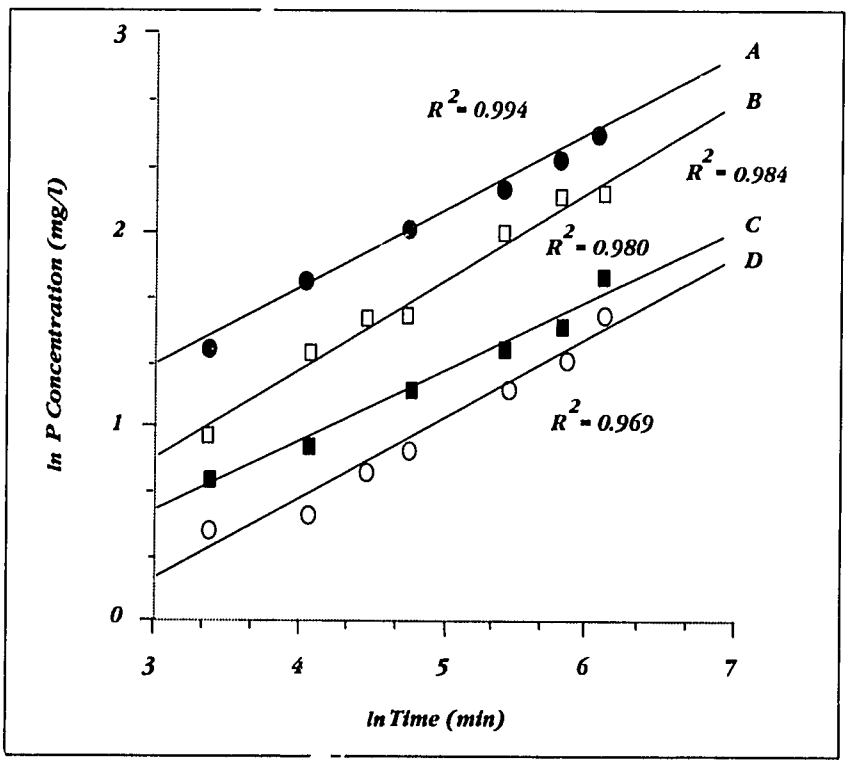

Figure 7. Two-constant rate equation plot of P dissolution data. A = Sherm silty clay loam, 40 kg P/ha applied each of two years; B = Sherm silty clay loam, no P applied; C = Olton clay loam, 40 kg P/ha applied each of two years; D = Olton clay loam, no P applied.

Table 1. Coefficients of determination and constants for two kinetic equations and the amounts of extractable soil P at two extraction times for two soils with and without two years of P application.

Soil	P-applied/yr	Two-constant rate equation		Elovich equation		Extractable soil P mg/kg	
	kg/ha	R^2	k_A	R^2	β	*60 min*	*480 min*
Sherm silty clay loam	0	0.984	0.61	0.975	0.43	58.5	125.0
Sherm silty clay loam	40	0.994	1.19	0.989	0.36	85.0	173.5
Olton clay loam	0	0.969	0.37	0.914	0.92	26.0	67.5
Olton clay loam	40	0.980	0.62	0.928	0.84	36.5	81.5

growth. In a thirty-year study, McCollum (1991) found that annual applications of P removed in a crop would maintain soil test P (Mehlich-1) in the range to produce maximum yields. However, these same applications would not maintain a high soil test level because the reaction rate of P to nonextractable forms was a greater factor than crop removal. Reaction of P to nonextractable forms was best described by first-order kinetic equations. Rate constants varied with the level of soil test P. Soils with high levels of extractable P had higher rate constants than soils with low levels of extractable P. This means that higher initial soil test levels will take longer to decline to critical levels, but not necessarily in proportion to lower initial soil test levels. For example,

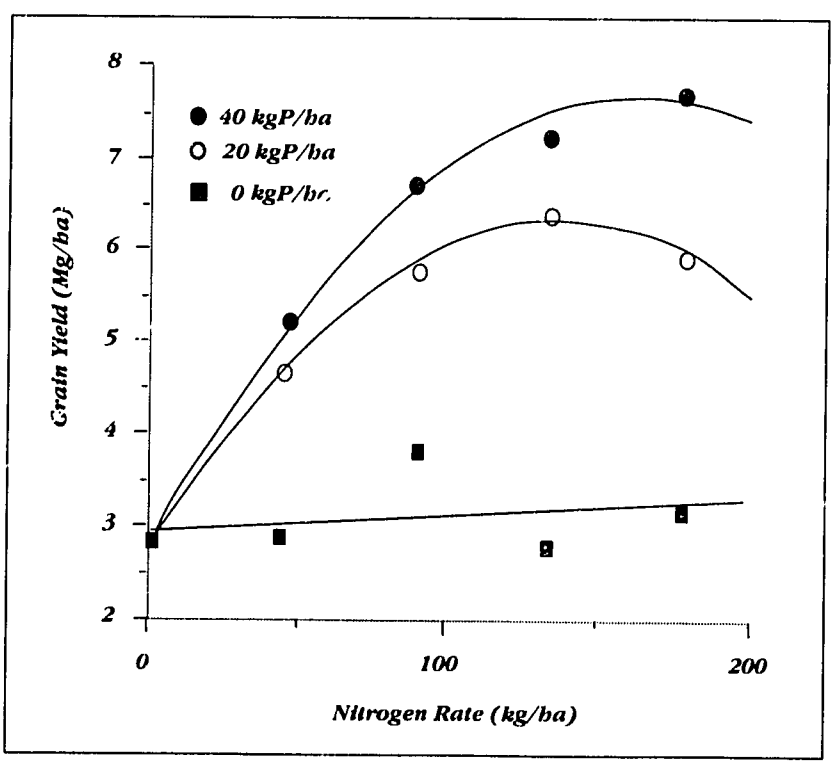

Figure 8. Yield of grain sorghum as affected by rates of N and P fertilizer.

doubling the initial soil test level might result in a 50 percent increase in the time required to reach the critical soil test level. Clearly, evaluation of residual fertilizer effects requires a time dependent response function. This research strongly indicates that current kinetic theory can be useful in developing the required relationships.

Kinetic analysis to evaluate the effects of various soil and environmental factors on P reactions in soil as they relate to crop response may be important. Barrow (1974) used a kinetic approach to describe the decrease in effectiveness of phosphate fertilizer for plant growth due to time and temperature. Relationships such as these may be required in order to fully develop satisfactory carry-over functions.

Ultimately we will want to develop economic analyses of soil test results for N and P interactions such as shown in Figure 8. These will require that yield response and carry-over equations be developed as a function of nutrient interactions in addition to previously discussed factors. The use of dissolution kinetics may be useful in describing the effects of N and P applied simultaneously on reaction rates and residual value of P.

Although the research effort directed at the kinetics of P reactions in soil has not been extensive, and even less intense in relationship to crop responses, it has shown strong potential for increasing our ability to quantify various important relationships and factors influencing those reactions and responses.

Summary

Optimizing profits from fertilizer use requires application of appropriate amounts. Production functions relating crop yield, soil tests, and fertilizer amounts and carry-over value that can be subjected to economic analysis have proven useful for this purpose. Phosphorus dissolution kinetics has been investigated to determine its potential for assessing soil nutrient supplying power and applied P fertilizer reactions. Single soil extract P and dissolution-rate constants were both found to have positive relationships with grain yield changes and plant uptake of P due to P application. Dissolution-rate constants were more sensitive to changes in soil P status than single soil extracts. Results indicate that kinetic data might provide useful information relative to short- and long-term reaction rates and products not obtainable from single extracts. Evaluation of residual fertilizer effects requires a time-dependent response function. Indications are that current kinetic theory can be useful in developing the required relationships.

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Contact Person:

Arthur Onken
Texas A&M University
Research and Extension Center
Route 3, Box 219
Lubbock, TX 79401
Telephone: 806-746-6101
Fax: 806-746-6528
Electronic Mail: (BITNET) maizao@tamum1.bitnet

Indexing Phosphorus Availability For Soil Productivity And Water Quality

A.N. Sharpley
USDA-ARS, National Agricultural Water Quality Laboratory

Introduction

An increased awareness of nonpoint source pollution via agricultural chemical transport in runoff has stimulated an urgency in obtaining information on the impact of agricultural management on surface water quality. Eutrophication of surface water leads to problems with its use for fisheries, recreation, industry, or drinking, due to the increased growth of undesirable algae and aquatic weeds. Although nitrogen (N), carbon (C), and phosphorus (P) are associated with accelerated eutrophication, most attention has focused on P, due to the difficulty in controlling the exchange of N and C between the atmosphere and a water body, and fixation of atmospheric N by some blue-green algae. Thus, P is often the limiting element and its control is of prime importance in reducing the accelerated eutrophication of surface water.

With an increase in disturbance of pristine land, there is a general increase in the loss of P in runoff. Inputs from point sources are easier to identify and control than nonpoint sources. As a result, nonpoint sources now account for a larger share of all discharges than a decade ago (USDA, 1992). Consequently, a major focus of nonpoint source pollution abatement programs will be to minimize the loss of agricultural P in runoff through implementation of alternative or improved management practices. This will require research on the long-term management of soil P availability, in relation to soil productivity and water quality.

Due to the lengthy and labor intensive nature of field studies quantifying the dynamics of soil P availability and losses in runoff, decision support systems, which include simulation models, are important tools to assess the relative ability of different management practices to minimize P transfer and its environmental impact. There are many models availal le which simulate soil P cycling and transport in runoff. However, a major limitation to their use is often the lack of input data to run them, as many models require detailed information on soil physical, chemical, and biological properties as well as on crop and tillage operations. Some of these limitations may be overcome by development of soil data bases. In addition, linkage of soil productivity and water quality models may be necessary to evaluate the long-term effects of agricultural management on water quality. A lack of adequate field data, however, limits rigorous testing of a model's ability to simulate a lake's response to changes in agricultural management and weather conditions.

Clearly, the use of many models by field personnel, such as farm advisors, extension agents, and consultants, will be restricted by data and computer requirements. Thus, an indexing procedure is needed to identify agricultural soils and management practices that might impact the biological productivity of receiving water bodies.

This paper discusses the main factors influencing soil productivity and water quality associated with P and their use in development of a P indexing procedure to assess the potential impact of management on P loss from agricultural land and quality of receiving waters.

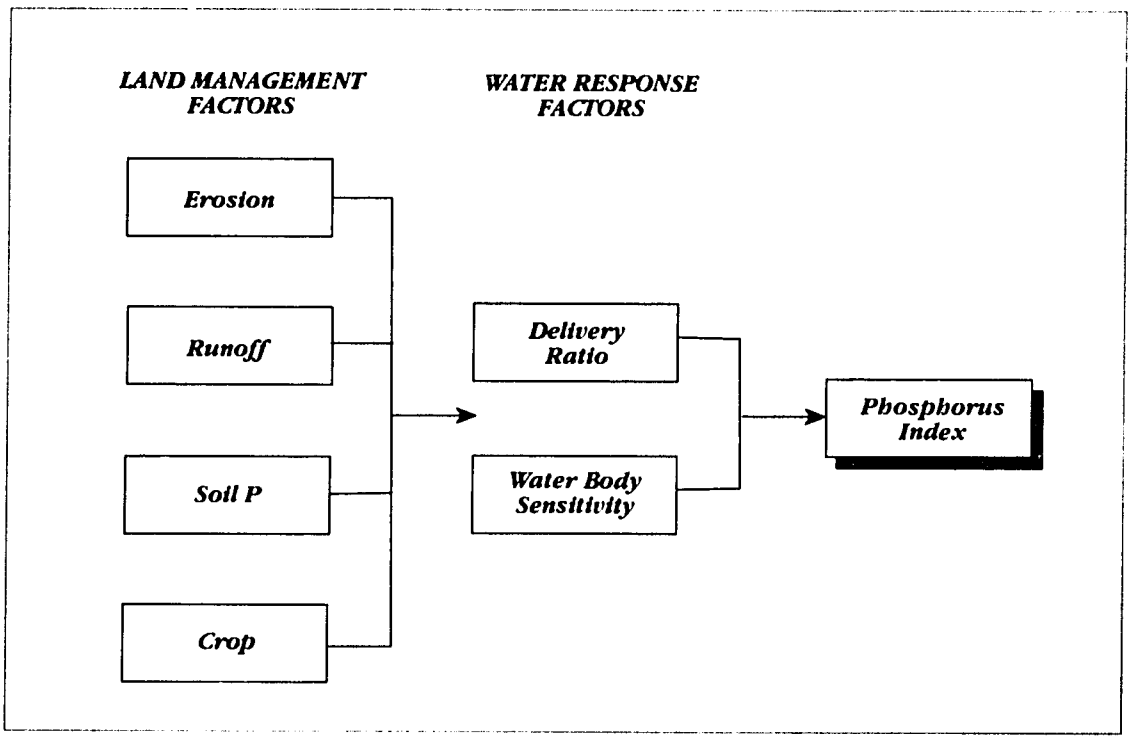

Figure 1. Components of a soil and water P availability index.

Indexing Approach

The basic principle of water quality indices is to synthesize data by means of a simple quality vector or algorithm. Hence, the index will be a simplified expression of a complex combination of several factors or parameters that make information more easily and rapidly interpretable than a list of numerical values. Such an index would be helpful for field personnel with limited resources working with land owners to identify sensitive areas and suggest management options to reduce the risk of water quality problems associated with P.

For initial development of such an index, critical factors influencing soil P availability, transport in runoff, and susceptibility of receiving water bodies to P inputs, have been identified in Figure 1. These are: runoff potential; erosion potential; soil P reactivity; crop type and yield goals; water delivery ratio; and water body sensitivity.

In general, surface runoff is the main mechanism of P transport from agricultural land, except for some organic or coarse textured soils where subsurface flow may contain high concentrations of P. The transport of P in runoff can occur in soluble (SP) and particulate (PP) forms. Particulate P encompasses all solid phase forms, which includes P sorbed by soil particles and organic matter eroded during runoff, and constitutes the major portion of P transported from cultivated land (75-90 percent). Runoff from grass or forest land carries little sediment, and is, therefore, generally dominated by the soluble form. While SP is immediately available for biological uptake, PP can provide a long-term source of P for aquatic plant growth (Carignan and Kalff, 1980). To a large

extent, the loss of SP and PP in runoff will be determined by soil and crop factors. These two factors govern both the amounts of P lost in runoff and relative magnitude of erosion and runoff for a given management system.

The effect of both land management and water response factors on P transport to a lake are conceptualized in Figure 2. The role of each of these factors is discussed below.

Runoff and Erosion

Soluble P

The transport of SP in runoff is initiated by the desorption, dissolution, and extraction of P from soil and plant material (Fig. 2). These processes occur as a portion of rainfall interacts with a thin layer of surface soil before leaving the field as runoff. Simulated rainfall studies have shown this layer to range from 1 to 5 mm in depth (Sharpley, 1985b). Consequently, the accumulation of

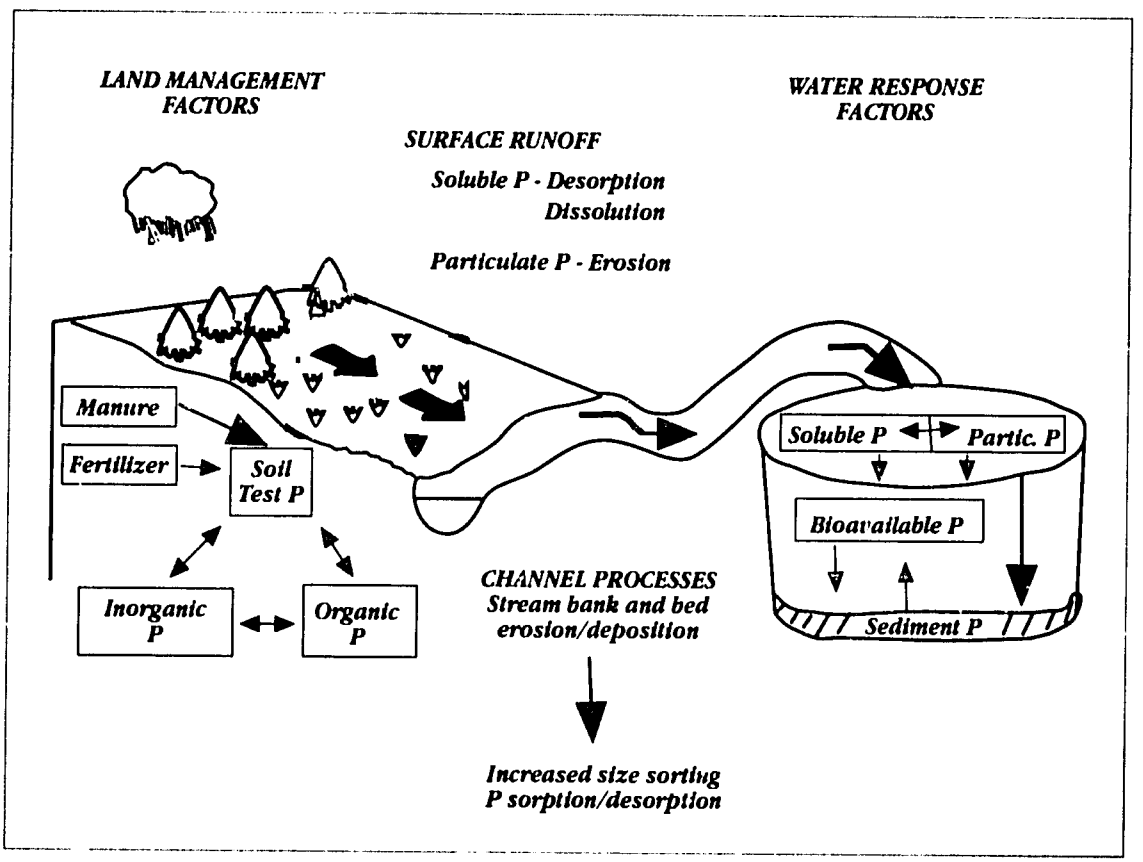

Figure 2. Factors involved in P transport from agricultural land.

P at the soil surface, as with continuous broadcast applications of fertilizer P or manure, will increase the risk of P loss in runoff.

The remaining rainfall percolates through the soil profile where sorption of P by P-deficient subsoils generally results in low concentrations of soluble P in subsurface flow. Exceptions may occur in organic or peaty soils, where organic matter may accelerate the downward movement of P together with organic acids and Fe and Al (Duxbury and Peverly, 1978; Miller, 1979). Similarly, P is more susceptible to movement through sandy soils with low P sorption capacities (Ozanne et al., 1961) and in soils which have become waterlogged, where a decrease in Fe (III) content occurs (Khalid et al., 1977).

Particulate P

Sources of PP in streams include eroding surface soil, streambanks, and channel beds (Fig. 2). The primary source of sediment in watersheds with a permanent vegetative cover, such as forest or pasture, is from streambank erosion. This sediment will have characteristics similar to the subsoils or parent material of the area, which are often P deficient.

During detachment and transport of sediment, the finer-sized fractions of source material are preferentially eroded. Thus, the reactivity and P content of suspended sediment is greater than source soil on a mass basis. This has led to the determination of enrichment ratios (ER) for P, calculated as the ratio of the concentration of P in the sediment (eroded soil) to that in the source soil (Fig. 3). Enrichment ratio values of 1.3 and 3.3 for total and available P, respectively, were

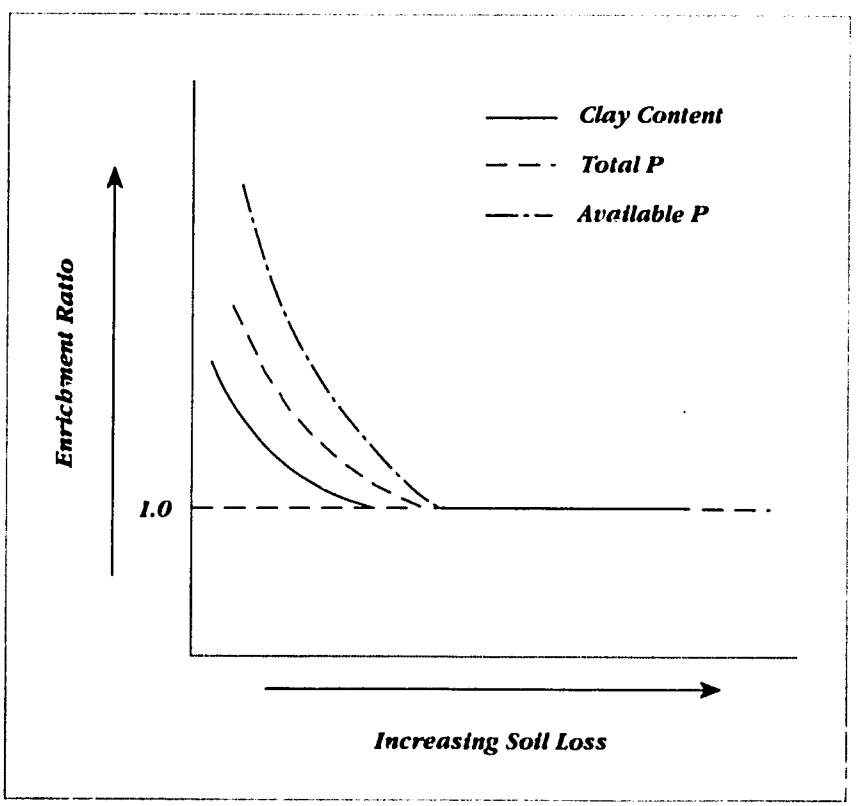

Figure 3. The enrichment of clay, total P, and available P with soil loss.

observed by Rogers (1941). More recently, Sharpley (1985c) observed that the enrichment of Bray-I (2.45) was greater than for other forms of P (total, inorganic, and organic) (1.48) for six (6) soils using simulated rainfall. Phosphorus desorption-sorption characteristics, buffer capacity (1.49), sorption index (1.56), and equilibrium P concentration (EPC) (1.80) are also enriched in runoff sediment compared to source soil.

Bioavailable P

In the past, most studies have measured only SP and total P (TP) transport in runoff. However, estimation of bioavailable P (BAP) transport in runoff is needed to more accurately estimate the impact of agricultural management practices on the biological productivity of surface waters (Hegemann et al., 1983; Sonzogni et al., 1982). Bioavailable P represents P that is potentially available for algal uptake and is comprised of SP plus bioavailable PP (BPP). Although BPP can be quantified by algal culture tests (USEPA, 1971), these assays generally involve long-term incubations (100 days) and, thus, do not lend themselves to routine analysis. Hence, more rapid chemical extraction procedures have been used to measure the BPP content of eroded soil material and include NaOH (Dorich et al., 1985), NH_4F (Porcella et al., 1970), and ion exchange resins (Hanna, 1989).

Use of these methods has shown a wide range in percent bioavailability of P in suspended and deposited lake sediments (Sharpley and Menzel, 1987). However, these extractions require collection of a large volume of runoff to provide an adequate amount of sediment for analysis and are, thus, not applicable to the routine measurement of BPP transport in runoff. There is still a need for methodology that will facilitate P estimation. One such method may be the use of iron oxide-impregnated filter paper strips, which have been developed and successfully applied to the estimation of plant available P in a wide range of soils and cropping situations (Menon et al., 1989a, b; Sharpley, 1991). The strips are made by soaking filter paper in a 10 percent $FeCl_3$ solution, conversion to $Fe(OH)_2$ by ammonia vapor, and cutting the paper into 10 x 2 cm strips. One strip is shaken with soil (1 g soil in 40 mL 0.01 *M* $CaCl_2$) for 16 hours and P removed from the strip by 40 mL 0.1 *M* H_2SO_4.

It is proposed that one strip be shaken with 50 mL of unfiltered runoff with the amount of P removed from the strip representing potentially bioavailable P (subsequently referred to as strip BAP). The strip BAP content of runoff sediment from several agricultural watersheds in the Southern Plains is related to the growth of P-starved *Anabena*, *Euglena*, and *Selenastrum Capricornutum* incubated for 29 days with runoff sediment as the sole source of P (Fig. 4).

It is suggested that the strips act as a P-sink and thereby more closely simulate P removal from sediment-water systems by algae. In as much, strip BAP may have a stronger theoretical justification for its use over other chemical extractants. In addition, prepared paper strips may be sent to a field location of limited resources and strip BAP measured using only a 100 to 500 mL bottle in which a strip and unfiltered runoff sample is shaken overnight. The strip may then be dried and returned to an analytical laboratory for P removal and measurement. This would also avoid potential problems with P transformations during sample storage and shipping. Future strip development with the use of prepackaged color reagents, may allow P determination in the field by comparison with a color chart.

Clearly, parameters relating to runoff potential and soil erosion will be primary components of the index. An estimate of runoff potential and soil erosion may be obtained from soil survey and site information, such as SCS runoff curve number; soil texture, permeability, and cover; slope length and gradient; crop management; rainfall; and erosion control practices. As a first approximation, this information is used in conjunction with equations predicting soil erosion such as the

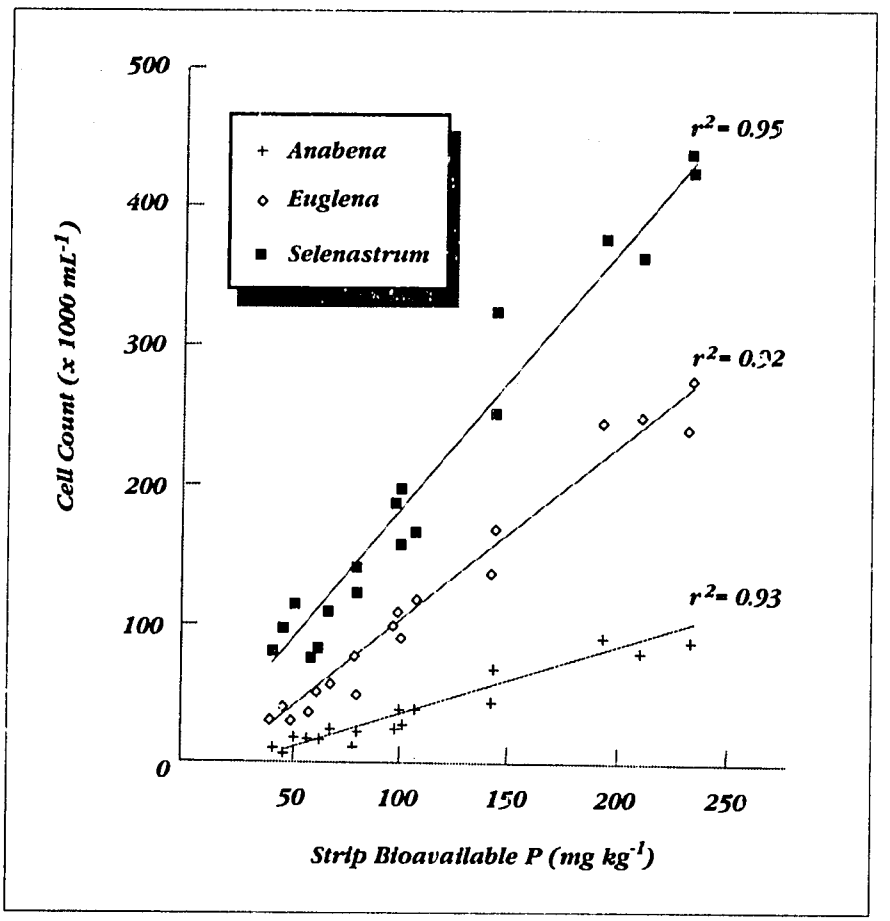

Figure 4. Relationship between the bioavailable P content of runoff sediment extracted by an iron-oxide impregnated paper strip, and growth of P-starved algae during a 29-day incubation period.

Universal Soil Loss Equation (USLE, Wischmeier and Smith, 1965), Modified USLE (MUSLE, Williams, 1975), Rangeland USLE (RUSLE, Renard et al., 1991), or Water Erosion Potential Predictor (WEPP, Laflen et al., 1991).

Soil P Availability

Immobilization of soil P in inorganic and organic forms unavailable for crop uptake necessitates P amendments as fertilizer, animal manure, or crop residue material to achieve desired crop yield goals. Thus, P application has become an integral and essential part of crop production systems. The proper management of applied P may reduce P enrichment of agricultural runoff via increased crop uptake and vegetative cover. On the other hand, a history of continuous P applications via fertilizer and manure may result in excessive accumulations of soil test P above crop requirements (King et al. 1990; McCollum, 1991). For example, Pierzynski et al. (1990) attributed soil test P (Bray I) levels in excess of 200 and 600 mg kg^{-1} in several Midwestern U.S. soils to addition of commercial fertilizer and sludge, respectively. Sharpley et al. (1991) examined several Oklahoma soils receiving long-term applications of poultry and swine manure and found

soil test-P (Bray I) levels of up to 279 mg kg^{-1}.

The rate and extent of soil test P increase with P application is a function of certain physical and chemical soil properties (Lopez-Hernandez and Burnham, 1974). For example, Sharpley et al. (1984; 1989) demonstrated that the portion of fertilizer P remaining as available P (resin P) 6 months after application, decreased as clay, organic C, Fe, Al, and $CaCO_3$ content increased for over 200 widely differing soils (Table 1). With an increase in degree of soil weathering, represented by soil taxonomic and other related properties, a general decrease in availability of applied fertilizer P was evident. Clearly, the dynamics of fertilizer P availability will differ between soils, which will be of importance to the degree of P enrichment of surface runoff.

Unfortunately, after high soil test P levels have been attained, considerable time is generally required for significant depletion, as demonstrated by the studies of Fixen and Ludwick (1982) and Kamprath (1967). As the accumulation of soil test P near the soil surface is directly related to an increase in the concentration and loss of P in runoff (Oloya and Logan, 1980; Sharpley et al., 1981), reliable soil test procedures will be an essential factor in identification of potential water quality problems. Even in high P-fixing soils, such as the Brazilian Oxisols studied by Yost et al. (1981), erosion of fixed P may be an important source of bioavailable P in a river or lake system.

Soil Test P

Soil test procedures to estimate plant available P commonly use a variety of chemical extraction methods, which are closely related to plant growth and uptake of P under certain climatic and soil conditions (Fixen and Grove, 1990). Alternative procedures using quantity (concentration of sorbed P) and intensity (solution P concentration) factors (Kuo, 1990; Moody et al., 1988), as well as the use of resin accumulators (Yang et al., 1991) or Fe oxide-impregnated paper strips as a sink for plant available P (Menon et al., 1989a, b), have been proposed. Anion exchange resins

Table 1. Percent fertilizer P available (as resin P) 6 months after application (data adapted from Sharpley et al., 1984; 1989).

Related properties	Number of soils	Availability	
		Mean	*Range*
		%	
Calcareous			
$CaCO_3$	56	45	11-72
Slightly weathered			
Base saturation Available P pH	80	47	7-74
Moderately weathered			
Clay Available P Organic C	27	32	6-51
Highly weathered			
Clay ExExtractable Fe	40	27	14-54

more closely simulated soil P removal by plant roots and their action is generally independent of soil type. However, their widespread use in routine soil testing has been limited by slow and cumbersome methodology. Although exchange resins in membrane and spherical forms have been used in biochemical and medical research for some time, they have only recently received attention as a potential tool in soil testing (Saggar et al., 1990; Schoenau and Haung, 1991).

The amount of P extracted by Fe oxide-impregnated paper strips (strip P), was more closely related to both dry matter yield and uptake of maize than Bray-I P for four soils ranging in pH from 4.5 to 8.2 (Menon et al., 1989a, b,). Sharpley (1991) reported that the impregnated strips primarily removed physically-bound P (anion exchange resin P) from 203 soils on which the use of the test is recommended (Sharpley, 1991). Thus, it is possible that the paper strip may extract amounts of P closely related to plant availability for soils ranging widely in physical and chemical properties.

The close correlation between strip P and soil test P does not in itself justify adoption of the procedure to quantify P uptake. It does emphasize, however, the potentially wide applicability of strips to estimate plant available soil P and suggests further evaluation of the methods is warranted. For example, the strips have potential use as a nondestructive method to measure in-situ soil P availability, as P extracted by strips embedded in soil columns, was closely related to Bray-I P for acid and Olsen P for alkaline and calcareous soils (Menon et al., 1990). In addition, dry matter yield and P uptake by maize from soils treated with rock P (RP) and partially acidulated RPs, was more closely correlated with strip P (r^2 = 0.83 and 0.88, respectively) than Bray-I P (r^2 = 0.53 and 0.45, respectively) (Menon et al., 1989a). Acid extractants like Bray-I reagent can overestimate P from such soils by dissolving more P than what would be available for plant use, whereas Olsen could underestimate P (Chien, 1978; Mackay et al., 1984). Consequently, strip P was more effective than other soil P tests in evaluating P availability from different RP's applied to soil.

Organic P

Even though inorganic P has generally been considered the major source of plant available P in soils, the depletion in soil organic P content with continuous cropping (Adeptu and Corey,

Table 2. Average amount of soil organic P mineralized annually for several climatic regions. Data from Sharpley (1985a) and Stewart and Sharpley (1987).

Region	Fertilizer P applied	Organic P mineralized	Percent mineralized †
	——kg P ha^{-1} yr^{-1}——		% yr^{-1}
Southern Plains	0	23	11
	25	17	8
Temperate	0	11	2
	34	6	1
Tropics	0	157	15
	40	67	18

†*Percent of total organic P mineralized annually.*

1977; Sharpley and Smith, 1983), the incorporation of fertilizer P into soil organic P (McLaughlin et al., 1988), and the lack of crop response to fertilizer P due to organic P mineralization (Doerge and Gardner, 1978) emphasize the need to consider organic P in the management of soil P availability. In some situations, mineralizable organic P may be an important source of P to crops and subsequently runoff (Table 2). In tropical soils, more frequent soil wetting and drying cycles and greater amounts of soil organic P increase potential mineralization of organic P compared to temperate region soils (Table 2). The fact that maximum organic P mineralization rate, crop uptake of P, and runoff potential frequently occur at approximately the same time of year (i.e., spring) emphasizes the need to quantify the contribution of organic P to P cycling.

Several studies have shown that soil P supply, represented by crop yields, were more closely estimated by including extractable organic P (Adeptu and Corey, 1976; Bowman and Cole, 1978). Bowman and Cole (1978) used a modification of the Olsen P test, which measured the total amount of P (inorganic plus organic) extracted by the reagent. Caution must be exercised, however, in relating amounts of organic P extracted to crop response in the field, due to the fact that the conditions of P extraction may not duplicate conditions for organic P mineralization in the field and sorption of mineralized organic P could affect its availability. Even so, soil test methods that estimate or give credit for this mineralizable organic P pool may avoid potentially excessive fertilizer P applications.

Because of the importance of soil P in determining both SP and PP loss in runoff and its dynamic nature in surface soil, an estimate of its content will be required for the index. Soil test P may be used. However, an estimate of the bioavailable P content of surface soil (strip P) may be more appropriate for indexing the potential impact of P transfer on accelerated eutrophication. Because of the ease of bioavailable soil P determination and a lack of general correlation with soil test P (Sharpley and Smith, 1992; Wolf et al., 1985), its measurement should not be substituted by soil test P.

Crop Factors

Crop type and yield will influence the degree of vegetative soil cover and amount of P removed from the soil system, if the crop is harvested. In addition to influencing soil erosion, crop type cover can affect the amount and relative bioavailability of P transported. For example, the leaching of P from plant material in different stages of growth and decay, may account for seasonal fluctuations and differences from watershed to watershed in P loss in runoff (Burwell et al., 1975). Increased SP losses in runoff from alfalfa plots (33 gha^{-1}) compared to forested (4 g ha^{-1}), corn (11 g ha^{-1}) and oat plots (16 g ha^{-1}), during several simulated rainfall events (7.4 to 12.2 cm^{-1}) over a 2-year period, were attributed to larger amounts of P leached from alfalfa (Wendt and Corey, 1980). On a larger scale, Muir et al. (1973) found a significant correlation between SP concentration in major streams of Nebraska and legume growth statewide. They suggested that SP concentrations in the Platte River, Nebraska, may reflect P leached from alfalfa residues, carried in runoff during the growing season.

Soil P utilization also varies from crop to crop (Fig. 5). Thus, it may be possible to select a scavenger crop that has a higher affinity or requirement for P and thereby reduce soil nutrient stratification. Alfalfa for example, has reduced subsoil nitrate accumulations (Mathers et al., 1975). May the same be true for surface soil accumulations of P using this or other crops? It is possible that by utilizing residual soil P, careful crop selection may reduce the amount of nutrients potentially available to be transferred to surface waters. Thus, potential P transfer from soil to runoff as estimated by the index will be a function of crop type.

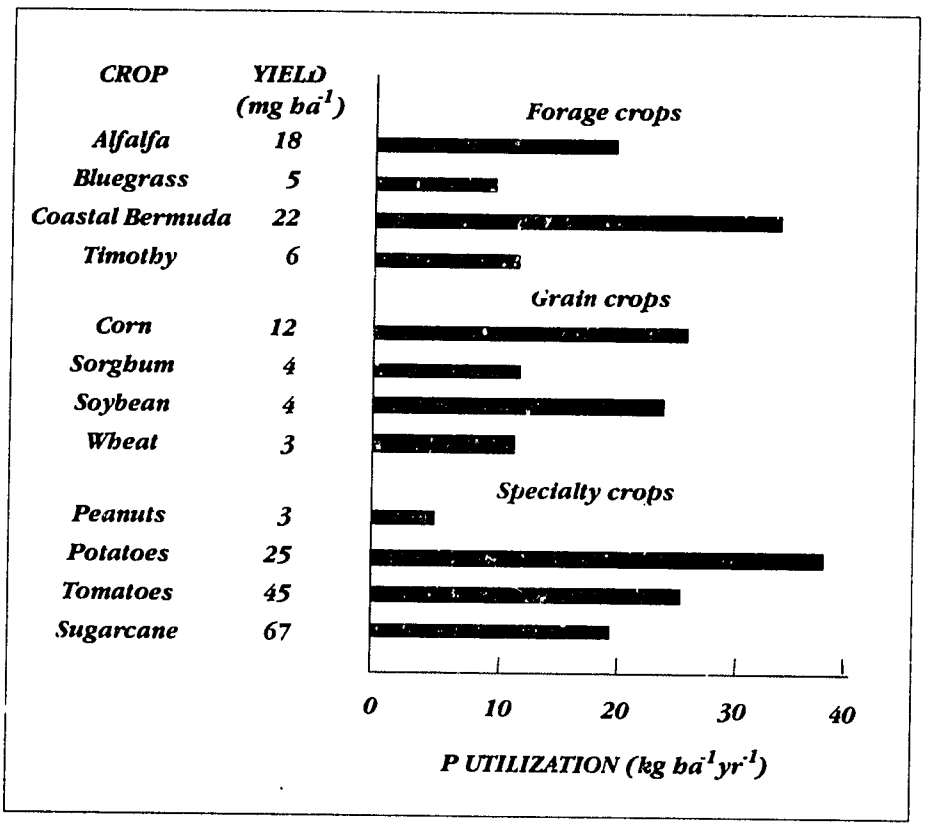

Figure 5. Approximate annual P utilization by several crops (Fertilizer Handbook, 1982).

Changes in P Bioavailability During Transport

Transformations between SP and PP can occur during transport in stream flow (Fig. 6). These transformations are accentuated by the selective transport of fine materials, which have a greater capacity to sorb or desorb P. In addition, SP may be removed by stream macrophytes (McColl, 1974; Vincent and Downes, 1980) and PP deposited or eroded from the stream bed with a change in stream flow velocity.

The relationship between the form of P transported in runoff and P sorption capacity is demonstrated by data from several unfertilized watersheds in the Southern Plains (Fig. 7). Soluble P concentration decreased with an increase in suspended sediment concentration (Fig. 7a). The inverse linear relationship between SP and logarithm sediment concentration was similar for different watersheds on the same major soil type at each location. However, relationship slope increased with an increase in P sorption capacity of the dominant soil type at each location (Fig. 7b). In other words, SP concentration can be modified to a greater extent during transport in runoff by suspended sediment from source soil having a higher sorption capacity.

The direction and extent of P exchange between soluble and particulate forms will depend on the SP and PP concentration of stream flow, equilibrium P concentration (EPC_0) of the sediments contacted, and rate of stream flow. The EPC_0 is defined as the soluble P concentration that is supported by a solid sample at which no net sorption or desorption takes place (Taylor and Kunishi, 1971). If the SP concentration of runoff or stream flow falls below the EPC_0 of the suspended or streambank material contacted, P will be desorbed. However, if the SP concentra-

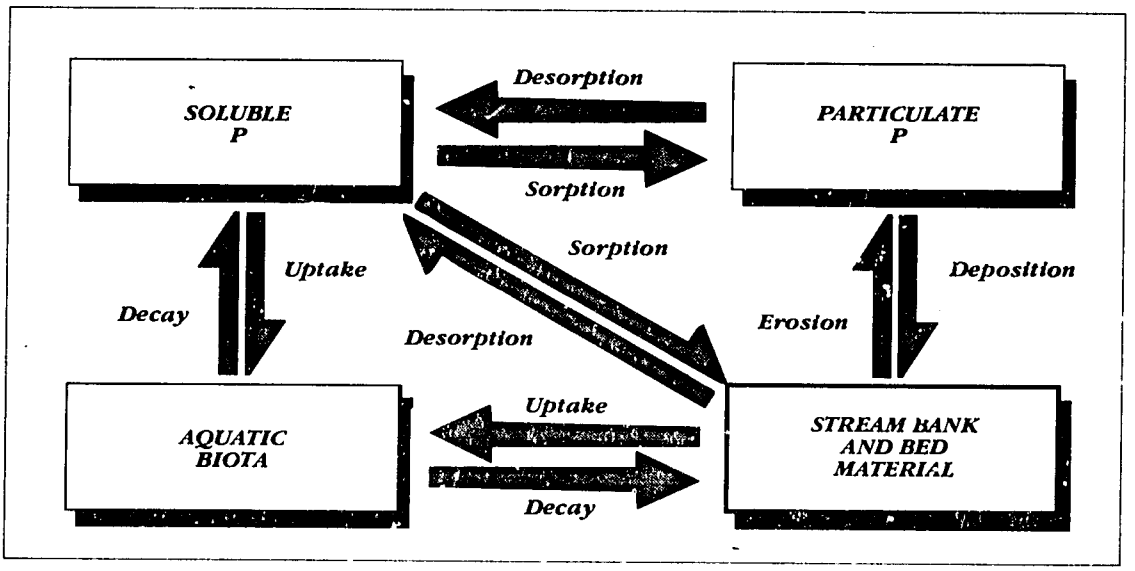

Figure 6. Phosphorus transformations during transport to a water body.

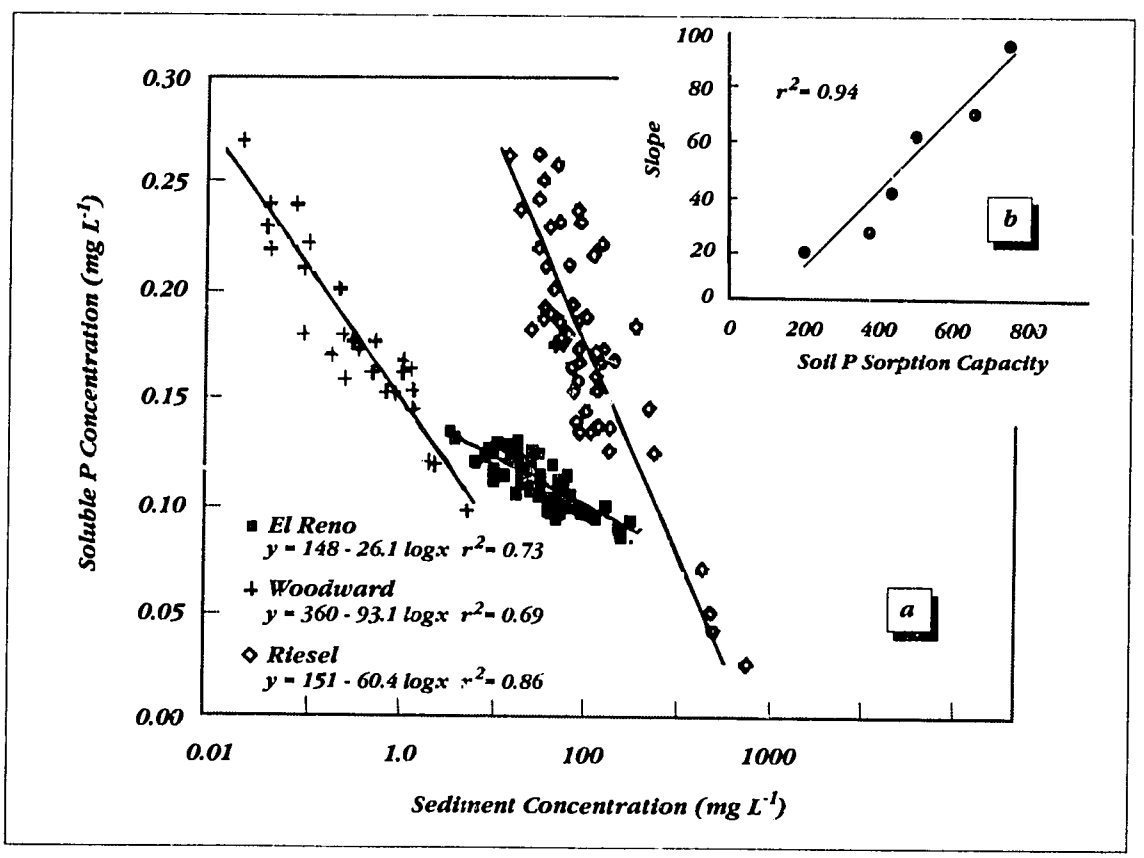

Figure 7. Relationship between (a) sediment and soluble P concentration of runoff from the unfertilized native grass watersheds in Oklahoma and Texas and (b) between slope of the sediment-soluble P regression and P sorption capacity of the dominant soil at each watershed location.

tion increases above the EPC_0, P may be sorbed by the suspended or streambank material contacted. For example, soluble P concentrations of 0.10 to 0.13 mg L^{-1} of runoff from fertilized fields were reduced to 0.009 mg L^{-1} by sorption during movement downstream (Kunishi et al., 1972). Thus, changes in P bioavailability occurring between the point where it leaves a field to where it enters a water body, must be considered in indexing the potential impact of land management on water quality.

Water Body Sensitivity

For any water body, the depth of photic zone, degree of surface mixing, development of reducing conditions at the water-sediment interface, and water residence time of will influence it's sensitivity to P inputs. If properties of the water body are such that particulate material and associated P rapidly settle from the water column (i.e., a deep, stratified lake of long water residence time), then control of SP rather than PP inputs, may be of greater short-term benefit in reducing biological productivity.

Once sediment settles to the bottom of a lake, however, P bioavailability may be increased by development of reducing conditions at the sediment-water interface (Nurnberg et al., 1986; Patrick and Khalid, 1974). For example, in a study of the P dynamics of two shallow hypereutrophic lakes in Indiana, Theis and McCabe (1978) found that the SP concentration of lake water was reduced by sorption during oxic periods and increased by release of sediment P during anoxic periods. This release of P from sediment can supply BAP for several years after its deposition (Jacoby et al., 1982; Larsen et al., 1981). Consequently, BAP estimates should be used in conjunction with information on the physiochemical properties of the receiving lake. The trophic response or sensitivity of a given water body to P input may be approximated by an empirical equation, such as those developed by Jones and Lee (1982) and Vollenweider and Kerekes (1980).

Conclusions

This paper describes the main land management and water response factors that should be considered in developing an index to assess the risk of agricultural P loss in runoff to degrade water quality. This decision support system is being developed by a national team of scientists (Phosphorus Indexing Core Team - PICT[1]) led by the USDA-SCS, National Water Quality Technology Development Staff. The system is intended for use as a tool for field personnel to easily identify agricultural areas or practices that have the greatest potential to accelerate eutrophication. The PICT group is developing the means to rank each index factor in terms of vulnerability for P loss. Combining all factors into a matrix will then provide an overall assessment of site vulnerability for surface water P enrichment. Taking this a step further, the matrix will identify management options available to land users that may allow them flexibility in developing control strategies.

Agronomic and economic studies have shown that measures to control nonpoint source pollution are much more effective if concentrated on specific source areas rather than on a general basis over large areas. Consequently, index procedures that will specify source areas vulnerable to P loss in runoff, will aid implementation of nonpoint source abatement programs.

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[1] The PICT group consists of: J. Lemunyon, D. Goss, G. Gilbert, J. Kimble, T. Sobecki, USDA-SCS; A. Sharpley, USDA-ARS; F. Thicke, USDA-ES; T. Daniel, Univ. Arkansas; T. Logan, Ohio State Univ.; M. Nearing, Univ. Georgia; A. Pierzynski, Kansas State Univ.; T. Sims, Univ. Delaware; and R. Stevens, Washington State Univ.

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Contact Person:

Andrew N. Sharpley
USDA-ARS
National Agricultural Water Quality Laboratory
P.O. Box 1430
Durant, OK 74702-1430, USA
Telephone: 405-924-5066
Fax: 405-924-5307

Phosphorus Diagnosis And Recommendations In Volcanic Ash Soils

J. Espinosa
Potash and Phosphate Institute, Latin American Office

Introduction

Soils derived from volcanic ash (Andisols) cover an appreciable area of Central and South America. The Andisols' clay fraction is dominated by allophane and imogolite (amorphous, short range ordered minerals) which come from the weathering of pyroclastic material produced from recent volcanic depositions. Research conducted in the last decade has demonstrated that humus aluminum complexes also play a significant role in Andisol chemical behavior.

One of the most important characteristic of Andisols is their high capacity to immobilize (fix) phosphorus (P) on the surface of the amorphous minerals and humus-Al complexes. This is the principal chemical constraint of Andisols. It seems that the P fixing capacity varies with the type of clay mineral affecting the residual value of phosphate applications. This in turn complicates the diagnosis of P availability. In some cases, calibration studies have failed to determine the relationship between soil tests and fertilizer recommendations for certain crops.

Phosphorus Fixation in Andisols

Initially P fixation in Andisols was considered to occur only on the active surface of allophane and imogolite. However the importance of humus-Al complexes in the process has attracted attention (Wada, 1980; Sadzawka and Carrasco, 1985; Nanzyo, 1987).

The P fixation mechanisms include chemiabsorption, displacement of structural Si and precipitation (Sadzawka and Carrasco, 1985). On the other hand, soil humus in Andisols readily forms metal complexes with transition metals like Al. Furthermore, hydroxyl groups attached to the complexed Al enter into ligand exchange reactions with $HPO_4^=$ and $H_2PO_4^-$ (Wada, 1980; Sollins, 1991).

The formation of allophane and imogolite is restricted by the accumulation of humus and the subsequent formation of humus-Al complexes. The strong complexation of Al with humus limits the possibility of coprecipitation of Al and Si released from the weathering of volcanic ash. These processes have been documented in Andisols from Japan and Colombia (Inoue and Higashi, 1988; Benavides and Gonzalez, 1988).

Accumulation of organic matter is higher in volcanic soils located at higher altitudes (> 2000 m above sea level). Indirect evidence obtained in Andisols of Ecuador and Colombia leads to the conclusion that P fixation is strongly related to the carbon content of the soil (humus-Al complexes). This would indirectly indicate the pattern of clay mineral formation in the soil and the intensity of P fixation. It seems that allophanic soils tend to fix less phosphate.

Data from a greenhouse exploratory experiment which was designed to study the relation between total carbon and phosphate fixation is presented in Table 1. Sorghum was planted in

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Table 1. Effect of P rates on the subsequent P retention of two Ecuadorian Andisols with different carbon content.

P_2O_5 rates	Total carbon		P fixed after first harvest	
	Dystrandept	Eutrandept	Dystrandept	Eutrandept
—*kg/ha*—	----------%----------		----------%----------	
0	5.0	1.2	42	14
150	5.3	1.1	40	11
300	4.9	1.1	40	8
450	5.1	1.1	42	8

Source: Espinosa et al., 1987.

pots containing soil treated with different rates of phosphate. After harvest, P retention was characterized in the treated soils using the technique described by Fassbender (1969). Data from this experiment suggests that in fact there is a strong relation between total carbon and P fixation. Another observation is that P retention is not reduced with the high rates of P applied to the Dystrandept which has a higher content of total carbon. It was expected that high rates of P would satisfy or at least reduce the fixation capacity of the soil.

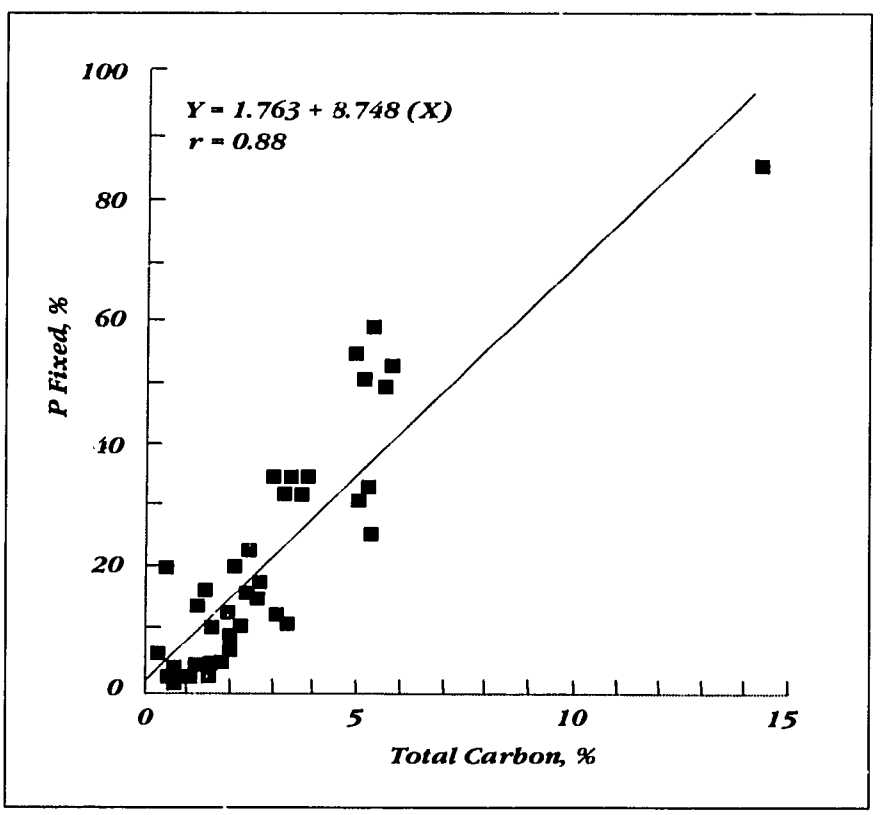

Figure 1. Correlation between total carbon and P fixation in Andisols.

From the practical point of view, it seems that in Andisols, total carbon content would be a good parameter to predict P fixing potential of soil. Figure 1 presents the correlation between P fixed and total carbon content of 42 Andisols from Ecuador. It will be necessary to conduct field experiments to confirm that this relationship holds and how it relates to P diagnosis and recommendations.

Phosphorus Residual Effect and P Soil Test in Andisols

It has been reported from several parts of the world that calibration studies on Andisols to relate soil extractable P with crop yield and fertilizer requirements are not always successful. Table 2 presents data from a greenhouse experiment conducted with a Hawaiian Andisol which, according to soils test, had an adequate supplement of P. However, yield data indicate that P content in the soil was not sufficient to support growth of the two indicator plants, brachiaria, and lettuce.

Similar results have been reported in field experiments with Andisols from the highlands of Ecuador (INIAP, 1991). Potatoes were grown in the same plots for three consecutive growing cycles. Results presented in Table 3 indicate that the yields obtained in the check plot are low even though the P content, extracted with $NaHCO_3$, was high (28 ppm). The critical level for these soils is supposed to be 12 ppm. There was an appreciable yield response to increasing P rates in all cycles indicating that the residual effect in this soil is low; but the soil test did not reflect this fact. The plots which received an application of 300 and 450 kg P_2O_5/ha in the first and second cycle increased the P test of the soil to 38 and 59 ppm, respectively. However, potato yield in the third cycle, without P application, was low again. The same trend is observed with low and high P application rates. It is suspected that the same trends would be observed if other soil extractants were used.

Data presented in Table 4 suggests that even at very high rates of phosphate application, the fixing capacity of the soil is not satisfied, and the residual benefit is low. To obtain an adequate potato yield, P application is needed every cycle.

The Dystrandept soil used in the above experiment is a typical soil in the potato area of he

Table 2. Response to the application of P to an Eutrandept soil from Hawaii.

Brachiaria		Lettuce	
P Rate	**Rel. Yield**	**P Rate**	**Rel. Yield**
µg/g	%	µg/g	%
0	4	0	26
50	76	240	59
150	100	520	79
		850	96

Extracted soil P (ppm): Bray 1 = 61; Bray 2 = 175; Olsen = 35
Adapted from: Fox, 1980.

Table 3. Residual P effect on potato yield and its relation to soil test in a Dystrandept soil from Ecuador.

Cycle 1		Cycle 2		Cycle 3		Extracted P†
P_2O_5	Yield	P_2O_5	Yield	P_2O_5	Yield	
kg/ha	*t/ha*	*kg/ha*	*t/ha*	*kg/ha*	*t/ha*	*ppm*
0		0	6.04	0	6.37	28
0	3.09	0	5.90	300	32.39	41
0		300	39.34	300	31.19	46
150		0	9.90	0	8.33	28
150	18.46	150	32.65	0	11.32	32
150		150	35.44	150	30.45	40
300		0	17.92	0	7.90	27
300	27.60	300	36.54	0	12.44	38
300		300	39.86	300	32.63	64
450		0	18.84	0	13.21	34
450	27.74	450	42.55	0	24.09	59
450	450	45.12	450	28.28	89	

†*P extracted with $NaHCO_3$.*

highlands of Ecuador. Its total carbon content is 5.3 percent, and it is expected that humus-Al complexes are the dominating material in the clay fraction. It is difficult to distinguish allophane or imogolite from humus-Al complexes and until recently soils containing these materials were grouped together in the suborder Andept in the Inceptisol order. The new Andisols order was created and it groups all soils derived from volcanic materials (ICOMAND, 1986; Arnold, 1988). This new grouping within soil taxonomy allows the separation of soils with humus-Al complexes from allophanic soils. This fact could lead to a better characterization of P fixation in Andisols.

Long term experiments have demonstrated that P critical levels considered adequate in a soil change for different crops in rotation on the same soil (Smyth and Cravo, 1990). Similar observations have been reported in Dystrandepts of the highlands of Ecuador and Colombia. As dis-

Table 4. Potato yield in the third cycle related to previous phosphate applications.

Cycle 1	Cycle 2	Cycle 3	Total P_2O_5 applied	Yield
kg P_2O_5/ha				*t/ha*
0	0	300	300	32.39
150	150	0	300	11.32
300	0	0	300	7.90
150	150	150	450	30.45
450	0	0	450	13.21
0	300	300	600	31.20
300	300	0	600	13.43
300	300	300	900	32.63
450	450	0	900	24.08

cussed above, the residual effect of P applications on potatoes is low in these soils, but the opposite is true with a pasture mixture on the same soil. Table 5 illustrates the lack of response to P application when the soil tests high in P (35 ppm extracted with $NaHCO_3$) and the good residual effect. This would suggest that there is a different P critical level for different crops species in the same Andisol. More research is needed in this area.

Violent volcanic activity in the past sent the ash into the atmosphere where it traveled long distances before falling to the surface. This is the reason why there are volcanic ash derived soils at considerable distances from the point of origin. Some of these soils have then developed in an environment of high moisture and temperature located at low altitudes. It is suspected that the amount of allophane and imogolite is higher, but the soil color is dark and they were classified as Dystrandepts like the highland soils. In this case, soil tests predict reasonably well the response to P addition. An example is presented in Table 6 (INIAP, 1990).

Conclusion

The P fixation potential of Andisols appears to be related to the presence of different materials in the clay fraction as a result of different weathering conditions of volcanic ash.

Soils dominated by humus-Al complexes seem to have higher P fixing potential, which is apparently difficult to satisfy.

Soil tests do not adequately predict P status for certain crops. It is necessary to find other parameters which could help to make a better prediction of P requirements in Andisols.

It seems that different crops have different P critical levels in the same Andisol.

Table 5. Effect of P application and residual P on dry matter yield of a pasture mixture in a Dystrandept soil of the highlands of Ecuador.

P_2O_5 Rate *kg/ha*	First Harvest	Fourth Harvest
	t/ha	
0	3.6	3.4
100	3.8	3.7
200	3.3	4.3

P applied one time before seeding.

Table 6. Corn response to P application in a Dystrandept soil from Pichilingue, Ecuador.

P_2O_5 Rate *kg/ha*	Yield *t/ha*
0	7.5
40	8.4
80	8.3
120	8.1

Extracted soil P ($NaHCO_3$) = 12 ppm.

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Contact Person:

Jose Espinosa
Instituto de la Potasa y el Fosforo (INPOFOS)
Los Shyris 2260 y el Telegrafo
Quito, Ecuador
Telephone: 593-2-449-255
Fax: 593-2-449-255

Phosphorus Deficiency Diagnosis And P Soil Test Calibration In Pakistan

K.S. Memon
Sindh Agriculture University, Tandojam, Pakistan, Department of Soil Science
A. Rashid
National Agricultural Research Center, Islamabad, Pakistan, Land Resources Section
H.K. Puno
Sindh Agriculture University, Tandojam, Pakistan, Department of Soil Science

Abstract

Soils of Pakistan are generally alkaline and calcareous. Soil testing, plant analysis and crop response experiments have adequately established P deficiency (<10 mg/kg Olsen P) in the majority (~90 percent) of soils and application of P fertilizers is considered essential for crop production. Current P application rates average approximately one-third of what is recommended for optimal crop production. With these fertilization practices and the adoption of intensive cropping systems, the cultivation of high yielding varieties and the increased use of nitrogenous fertilizers, P deficiency status is not likely to improve in the near future.

Phosphorus fertilizer experiments conducted during the past three decades continue to provide the basis for generalized P fertilizer recommendations for various crops. Research on P soil test-crop response correlation and calibration has gained considerable momentum during the past six years. Many studies have reported the comparative value and usefulness of the Olsen, ABDTPA and Mehlich3 methods in diagnosing P deficiencies. The ABDTPA method appears to be a more likely candidate for adoption as the routine soil test, because it belongs to the same family of soil P extractants as the currently used Olsen method and it has been widely tested under local conditions for analysis of P as well as micronutrients. Critical values of available P, determined by these methods, have largely added to the existing information regarding critical limits. Further research is, however, needed to confirm these results and possibly refine the critical limits according to various soil types. In view of the widely divergent experimental methods and data analysis procedures used by various workers and the reported range in critical levels, it is proposed that a unified approach and methodology for the determination of P soil test critical limits and for P soil test calibration work be adopted. Factors like clay content, lime content, and possibly clay mineralogy should be taken into account while interpreting data from P soil test calibration studies. However, the information about critical limits can not be translated into P fertilizer recommendations unless simultaneous studies are conducted to determine the units of P fertilizer required to raise the value of soil test P by one unit. This would require the integration of P sorption properties of soils into a soil testing program.

Introduction

Most soils of Pakistan are characterized by alkaline pH, calcareousness to varying degrees, low organic matter, total nitrogen and available phosphorus, and generally adequate levels of potassium. Soil texture varies from sandy to clayey with most agricultural soils falling under the

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category of medium to heavy loams and clays. Soil mineralogy is dominated by micas followed by variable quantities of minerals like montmorillonite, kaolinite, vermiculite, chlorite, etc.

Soil fertility surveys indicate that phosphorus, after nitrogen, is the most deficient nutrient in Pakistan soils (Memon, 1986). Deficiency of P and the need for fertilizer P application was first realized in the late 1950s when a small quantity of P fertilizer was imported to determine its value in crop production. Following its introduction, extensive field experiments were conducted on crops of local importance to determine the extent of P deficiency and the quantity of P fertilizer needed to correct these deficiencies. Considerable progress has been made over the past 30 years. Research into P fertilizer requirements of crops has mainly focused on P fertilizer experiments in the field and in the greenhouse. Soil test crop response studies have been done to evaluate various P soil test methods and to determine critical levels of P. The outcome of this research has been generalized fertilizer recommendations and preliminary knowledge about critical levels of P for various crops. Fertilizer recommendations, however, need to be tailored to specific soil and crop situations on a scientifically sound basis. In particular, information is required about the quantity of fertilizer P needed to increase the soil test level to the one desired for optimal or targeted crop yield.

The task is a challenging one in view of the diverse nature of soil and agro-climatic conditions, the changing patterns of soil and crop management, the adoption of intensive cropping systems, the introduction of high yielding crop varieties and the increased use of nitrogen fertilizers. The matter assumes added importance due to low utilization of fertilizer P by the crop to which it is applied and subsequent accumulation of P residues in soils to varying degrees. Evaluation of P deficiency status and its correction through P fertilization, therefore, continues to be the major thrust in P fertilizer research. This paper addresses some aspects of P research that deal with P deficiency diagnosis and the current status of P soil test calibration in Pakistan.

Phosphorus Deficiency Diagnosis

Nutrient deficiencies can be determined by various methods, which include: 1) deficiency symptoms; 2) crop response to application of the nutrient under study; 3) soil testing; and 4) plant analysis. In Pakistan, early work on the determination of P deficiency status in soils was based on crop response to the application of P fertilizers. It was through numerous agronomic field experiments under different soil-crop combinations that the need for P fertilization was initially established. Later, soil testing for available P was routinely adopted and used in conjunction with crop response data. The purpose behind this approach was to determine soil P levels of deficiency and sufficiency and formulate fertilizer recommendations accordingly. Further work on P led to the inclusion of plant analysis as an aid to deficiency diagnosis and determination of P fertilizer efficiency.

While plant analysis data are available from many field experiments, they have not been used as a singular tool for the diagnosis of P deficiency. In most cases, they have served to confirm the results obtained through soil analysis. It is only recently that soil and plant analyses are being used simultaneously to identify soils that are deficient in P and other elements. Some recent studies have laid emphasis on the determination of critical levels of P in plants (Rashid, 1990).

Soil P Status

Olsen's method of soil P extraction with 0.5M $NaHCO_3$ (Olsen et al., 1954) is followed as a routine soil test method by all the soil testing and research laboratories throughout the country.

This is primarily because this method was developed specifically for alkaline and calcareous soils. Using this method, a number of workers have attempted to assess the available P status of Pakistan soils. The data from some of these works have been summarized in Table 1. It is clearly evident that most soils contain <10 mg/kg P even after three decades of P fertilization practices. By most standards, a soil containing <10 mg/kg Olsen P is considered to be deficient. Deficiency of P is, therefore, widespread in the majority (90%) of soils, and the application of P fertilizers is considered essential for crop production. In practice, however, farmers do not always apply P fertilizers. Their decision about fertilizer application depends upon many factors which include, interalia, the kind of crop grown and the produce expected. It is usual for farmers to skip P application to crops like cotton and rice, but wheat, maize and sugarcane are generally fertilized. Current P application rates average approximately one-third of what is actually recommended for optimal crop production. With continuing under-fertilization practices and intensive cropping systems and cultivation of high yielding varieties, the situation is not likely to improve in the near future. This is particularly evident from the data for Punjab soils (Table 1) where a proportion of the soils containing >10 mg/kg Olsen P has remained <10% even after a period of 13 years (from 1973 to 1986). Exceptions are those where some value crops such as banana, sugarcane, vegetables are heavily fertilized with P. According to one survey (Memon, 1985), average Olsen P content of banana fields was 43 mg/kg. From the foregoing discussion, it is apparent that soil testing for P has adequately established that most soils are deficient in P and require P fertilizer application for optimal crop production. However, there is a need to interpret the soil test data better, through well planned P soil test calibration studies.

Plant Analysis as a Diagnostic Tool

In general, P deficiency diagnosis is done through soil testing and crop response to P. Plant analysis for P, although done in many cases, is not emphasized as a diagnostic tool for determining P deficiency. Recent studies, however, indicate renewed interest in plant analysis as a diagnostic tool as well as a means for determining critical limits for various crops. As a diagnostic tool, established critical or standard values, or sufficiency ranges, are used. A comparison is made between laboratory analysis and one or more of these known values or ranges in order to assess the plant's nutritional status. Most importantly, plant analysis findings are used to determine if soil fertility level and applied fertilizers are sufficient to meet the crop requirement.

In a recent soil fertility survey of the districts, Jhelum and Chakwal, Rashid and Qayyum (1990) analyzed soil samples and associated sorghum plants to determine the P fertility status of these soils. Out of 140 locations in Jhelum, 70 percent of soils were highly deficient (<3 mg/kg ABDTPA P) and 26 percent were marginally deficient (4-7 mg/kg ABDTPA P) in P (Table 2). Sixty-one percent of the associated sorghum plants (collected from soil sampling sites) were also deficient in P. In Chakwal, a total of 115 locations were sampled. The extent of P deficiency was: soils – highly deficient, 74%; marginally deficient, 23%; sorghum plants - 77%. Correlation coefficients (r) between surface soil P and P concentration of sorghum plants (<30 cm tall) were: Jhelum, 0.46 (P<0.01) and Chakwal, 0.58 (P<0.01).

Plant analysis is also being used to determine critical levels of P for various crops under local conditions. For wheat grown at Tandojam, Memon and Fox (1983) reported a critical level of 0.25 percent P in recently mature leaf at tillering. The values reported by Rashid (1990) were 0.28 percent for whole shoots (<30 cm tall), 0.3 percent for leaves at flower initiation and 0.22 percent in grain (Table 3). He also reported critical P levels for some other crops (Table 3) using the relationships between P contents and relative grain yields and graphing it by boundary line technique (Webb, 1972).

Table 1. Olsen P status of soils of Pakistan.

Region/Area	No. of Samples	Category I P content mg/kg	Category I % Samples	Category II P content mg/kg	Category II % Samples	Category III P content mg/kg	Category III % Samples	Reference
Punjab (13 districts)	1110	< 3	61	3-12	34	>12	5	Bhatti, 1973
Punjab	6207	< 5	68	5-10	24	>10	8	Malik et al., 1973
Baluchistan *	130	<10	50	10-20	31	>20	19	Shaikh and Bangash, 1974
Rawalpindi/Islamabad	240	<10	52	10-20	38	>20	10	Qayyum, 1984
Punjab	136161	<10	93	–	–	>10	7	Malik et al., 1984
Sindh (Hyderabad)	125**	<10	50	10-20	22	>20	28	Memon, 1986
Punjab	16841	< 5	63	5-10	22	>10	5	NFDC, 1986

* *Olsen P content is expressed as P_2O_5.*

** *50 % of the soil samples were secured from highly fertilized fields under banana and sugarcane.*

Table 2. Phosphorus contents (ABDTPA, mg/kg) of soil samples and associated sorghum plants (whole shoots < 12" tall) in Jhelum and Chakwal districts (Rashid and Qayyum, 1990).

District	No. of Samples	Soil/Plant	Range	Low	Medium	High
		Soil		< 3*	4-7*	> 7*
Jhelum	140	0-15 cm	0.31-10.80	98, 70%+	36, 26%	6, 4%
	140	15-45 cm	0.04-8.30	134, 96%	4, 3 %	2, 1%
Chakwal	115	0-15 cm	0.38-8.87	85, 74%	27, 23%	3, 3%
	115	15-45 cm	0.34-7.01	105, 91%	9, 8%	1, 1%
		Plant		< 0.25%**	0.25-0.6%**	> 0.6%**
Jhelum	140	Sorghum	0.09-0.55%	86, 61%	54, 39%	–
Chakwal	115	Sorghum	0.08-0.45%	88, 77%	27, 23%	–

* *Critical levels of ABDTPA extractable P (Soltanpour, 1985).*

** *Critical level of P in sorghum whole plants (Reuter and Robinson, 1986).*

\+ *Number of samples, % samples under the category.*

Table 3. Critical P concentration in diagnostic plant parts of some Rabi (winter) and Kharif (summer) crops in greenhouse studies (Rashid, 1990).

Species	Critical P concentration (%)		
	Whole shoots[1]	Leaves[2]	Grains
Kharif (summer) crops			
Maize	0.23	0.26	0.28
Sunflower	0.29	0.31	0.20
Mungbean	0.30	0.33	0.34
Mash	0.38	0.28	0.35
Rabi (winter) crops			
Mustard	0.27	0.28	0.72
Wheat	0.28	0.30	0.22
Chickpea	0.26	0.39	0.37
Lentil	0.28	0.33	0.26

1 *Whole shoots <30 cm tall.*
2 *Most recently mature leaves at flower initiation/heading stage.*

Soil Test Crop Response Correlation and Calibration

The suitability of soil tests for predicting P status of a soil can be evaluated by a correlation of P with plant growth parameters such as yield, relative yield, P uptake and P concentration. Olsen's $NaHCO_3$ method has been studied more widely than other extracting solutions. In fact, this test has proved to be quite suitable for alkaline calcareous soils of Pakistan. Despite its routine use in the country, however, the soil test calibration has not been adequately attempted. In order to determine P fertilizer recommendations for various crops, it is necessary to know the soil test value of P, the level of P soil test desired for optimum crop yields (critical level) and the quantity of fertilizer P needed to raise the soil test level to the desired value. The information about critical levels and the associated fertilizer requirements can be obtained from soil test calibration studies.

A brief account of work done on soil tests for available P, soil P test-crop response and critical levels of available P is given below.

Soil Testing for Phosphorus

Many soil test methods have been used in conjunction with plant growth and P uptake to evaluate the availability of various forms of soil P. Determination of available P usually employs extracting solutions which dissolve and remove specific forms of soil P from the solid phase through various reactions. Due to the alkaline and calcareous nature of Pakistan soils, Olsen's method of soil P extraction with 0.5M $NaHCO_3$ continues to be a routine soil P testing method. Among the methods developed later, the ABDTPA (Soltanpour and Schwab, 1977) and Mehlich3 (Mehlich, 1984) methods have received research attention; primarily because these methods can be used for simultaneous extraction of many elements and also because they stand a good chance of being adopted as the routine laboratory methods for determining available P in the alkaline calcareous soils of Pakistan.

In order to compare suitability of various P soil tests, Rashid et al. (1988) evaluated three methods, i.e., Olsen, ABDTPA and Mehlich3, for determining the P fertility of calcareous alkaline

Table 4. Soil P content of Missa soil (silty, mixed, hyperthermic) after incubation with fertilizer P for 56 days (Rashid et al., 1988).

P_2O_5 applied (P) *mg/kg*	Olsen *mg/kg*	ABDTPA *mg/kg*	Mehlich3 *mg/dm³*
0 (0)	3.4	1.9	7.5
10 (4.37)	4.8	2.5	7.8
20 (8.73)	5.7	3.7	10.1
40 (17.47)	8.6	4.8	15.2
80 (34.93)	9.9	7.1	16.6

Coefficient of correlation (r)

Olsen v/s ABDTPA	0.97**
Olsen v/s Mehlich3	0.99**
ABDTPA v/s Mehlich3	0.95*

* *P < 0.05 for 'r' values.*
** *P < 0.01 for 'r' values.*

soils of Pakistan to support cereals, legumes and oilseeds. The soil (Missa series, silty, mixed, hyperthermic) was incubated with graded amounts of P at 25±1° C. Phosphorus extracted by $NaHCO_3$ and ABDTPA methods decreased for up to 42 days of incubation and thereafter remained stable for up to 56 days. The relationship between P soil test values determined by the three methods was highly significant (Table 4) and also showed that extractable P contents by the three soil tests, 56 days after incubation, were closely related with grain and dry matter yield and P uptake in wheat, barley, chickpea, lentil and mustard ($r \geq 0.87$, Table 5). Strong correlations between various soil tests for P ($r \geq 0.95$, Table 4) indicated that ABDTPA and Mehlich3 tests were as effective for evaluating P fertility of soils as the Olsen test. Therefore, they suggested the use of universal soil tests, i.e., ABDTPA and Mehlich3, for routine laboratory analysis as these were easier, cheaper and less time consuming than the currently used $NaHCO_3$ test.

In another study, Rashid and Hussain (1990) grew maize in a pot experiment on 31 bench-mark soils, comprising approximately 65-70 percent of the total agricultural land of Pakistan. Soil testing data showed that the correlations between P contents determined by Olsen, modified Olsen, ABDTPA and Mehlich3 methods were highly significant ($r=0.66$ to 0.95, $P<0.01$). All the tests successfully separated P deficient and non-deficient soils.

In a pot study involving 12 rice soils, Zia et al. (1992) similarly evaluated four P soil test methods (i.e., Olsen, modified Olsen, ABDTPA and Mehlich3). They reported that the relationship between the four methods was highly significant ($r>0.94$, $P<0.01$). The results of another study (Zia et al., 1991) also confirmed the value of the ABDTPA test in evaluating P fertility of rice soils.

In a long term study involving three cropping systems and six rates of P application, Puno (1991) monitored the changes in soil P status as a result of P fertilization and cropping on a seasonal basis. Soil test values (Olsen and ABDTPA) obtained at the end of seven cropping seasons are given in Table 6. The data revealed a highly significant correlation ($r=0.95$) between Olsen and ABDTPA methods. The data further showed that the soil test values were higher under wheat-soybean system than under wheat-fallow or wheat-corn systems. It is believed that soybean, a legume crop, helps in releasing the adsorbed P due to preferential uptake of Ca (Fox and Kankar, 1964).

Using the same plots, Bhand (1991) determined soil P status by four methods at the end of 12

Table 5. Correlation coefficients of extractable P in soil (after incubation) and plant growth and nutrition parameters (Rashid et al, 1988)

Plant parameter	Correlation coefficient (r)*		
	Olsen	ABDTPA	Mehlich3
Wheat			
Grain yield	0.99	0.98	0.99
Dry matter yield	0.95	0.99	0.94
P uptake	0.97	0.99	0.96
Barley			
Dry matter yield	0.97	0.99	0.94
P uptake	0.97	0.99	0.94
Chickpea			
Grain yield	0.92	0.94	0.87
Dry matter yield	0.99	0.98	0.98
P uptake	0.93	0.99	0.91
Lentil			
Grain yield	0.99	0.98	0.97
Mustard			
Grain yield	0.99	0.99	0.98
Dry matter yield	0.99	0.99	0.98
P uptake	0.99	0.99	0.98

* *$P < 0.05$ for 'r' values up to 0.95.*

Table 6. Olsen and ABDTPA P contents (mg/kg) of Sultanpur soil (0-15 cm) after fertilization and cropping for seven cropping seasons under three cropping systems (Puno, 1991)*.

P rate kg P_2O_5/ha/season	Olsen P (mg/kg)		
	Wheat-corn	Wheat-fallow	Wheat-soybean
0	3.35	4.91	3.79
30	4.68	5.02	5.02
60	4.86	5.02	6.24
90	5.58	6.91	7.03
120	6.58	7.25	8.92
150	13.77	10.32	14.50
Mean	6.47	6.57	7.58

P rate kg P_2O_5/ha/season	ABDTPA P (mg/kg)		
	Wheat-corn	Wheat-fallow	Wheat-soybean
0	1.73	2.10	1.80
30	2.40	2.18	2.63
60	3.45	2.93	3.53
90	3.68	3.98	5.48
120	4.95	5.10	6.60
150	8.40	7.13	7.95
Mean	4.10	3.90	4.67

* *Original soil P content before cropping was: Olsen - 2.79 mg/kg; ABDTPA - 1.8 mg/kg.*

cropping seasons (Table 7). In addition to the Olsen, ABDTPA and Mehlich3 methods, he used new soil test (Menon et al., 1989) designated as the iron hydroxide-impregnated filter paper (Pi) soil test. The authors claim that the new soil test P method avoids the limitations encountered with the extracting solutions and works with soils in which P extracted with water is too low and simulates the anion exchange resin method while minimizing the analytical difficulty associated with the resin use. They used Pi strips as a sink for P in a suspension of soil and calcium chloride. They also claim that the Pi test is equally suitable for both acid and alkaline soils. Bhand (1991) reported that there was a highly significant correlation between any two of the above four methods under study. However, the r value was highest (r = 0.99) for the relationship between the Olsen and ABDTPA methods. This was followed by r = 0.88 for Mehlich3 v/s Olsen and r = 0.82 for Mehlich3 v/s ABDTPA. The lowest 'r' values of 0.70 to 0.76 were obtained when the Pi method was compared with the other three methods. Comparing the quantities of P extracted by these methods, he added that Olsen extracted nearly twice as much P as ABDTPA, one-third as much as Mehlich3 and more than half as much as the Pi method. The data reported by Puno (1991) showed that ABDTPA extracted 61 percent of the P extracted by the Olsen method.

The results obtained by Sharpley (1991) for 203 soils showed that the amounts of P extracted by paper strips were closely related (r=0.89 to 0.93, P<0.001) with soil test P (Olsen, Bray I and Mehlich3). Obviously, further work is needed on calcareous alkaline soils of Pakistan to determine the value of paper strips in assessing P fertility of soils.

Table 7. Soil P status (mg/kg) as determined by four methods in relation to history of cropping and P fertilization (Bhand, 1991).

Previously applied P* *kg P_2O_5/ha/season*	Olsen	ABDTPA	Mehlich-3	Pi
Wheat-Maize (WM) Cropping System				
0	4.10	1.70	12.00	6.00
30	4.20	2.00	16.60	12.80
60	7.10	3.50	22.60	15.20
90	8.40	4.30	29.80	15.80
120	11.10	5.50	37.20	21.00
150	10.10	4.80	28.50	14.20
WM mean	7.50	3.60	24.50	14.20
Wheat-Fallow (WF) Cropping System				
0	5.40	2.70	11.60	9.40
30	7.10	3.70	15.40	14.20
60	7.90	4.30	18.60	16.10
90	10.10	5.60	25.50	17.70
120	11.60	6.50	28.40	20.60
150	14.30	8.20	34.70	15.20
WF mean	9.40	5.20	22.40	15.50
Overall mean	8.50	4.40	23.50	14.80

* *Phosphorus was applied to each crop during each of the 11 cropping seasons from Rabi 1983-84 to Rabi 1988-89. Soil P status refers to the samples obtained after cropping for 12 seasons.*

Soil P Test Correlation/Calibration

Phosphorus fertilizer research in Pakistan includes extensive field trials on research stations and in farmers' fields. Thousands of field experiments have been conducted during the past three decades, and these have generated voluminous data which have not yet been adequately utilized to realize fully the objectives of such an extensive effort. While they provided a basis for the formulation of generalized fertilizer recommendations for various crops from time to time, further experimentation proved to be of little further guidance. In fact, most fertilizer trials were not designed to develop soil test calibration data. Quite often, experimental designs followed for field research did not provide for the separation of the effect of one element from the other.

Difficulties were encountered when the National Fertilizer Development Center (NFDC) of Pakistan tried to compile fertilizer response data from various soil fertility research institutes of the country. Confounding of treatment effects of N, P and K , limited replication and insufficient number of treatments for defining a full response curve and lack of required soil data were some of the problems which deserved immediate attention. Realizing such problems, NFDC laid major emphasis on a review of previous work by organizing a number of workshops and seminars and by the adoption of appropriate experimental designs to address the issue of soil test crop response and calibration in an effective manner. Simultaneous efforts by the Pakistan Agricultural Research Council through project orientation and research direction led to the identification of gaps in P fertilizer research.

It was during this period that local and foreign consultants were invited to review soil fertility research programs, identify research gaps and make recommendations for future research. Thus the work done on soil test correlation in Pakistan was recently reviewed by Wahhab (1985), Soper (1985), Portch (1985) and Fox (1989). All these reports point out that research on soil test crop response correlation in Pakistan had fallen short of expectations. They suggested that the first step should be to study the relationship between the soil nutrient (extracted with different methods) and the uptake of that nutrient by plants in different soils. The second step would be to calibrate crop response with the soil nutrient, and the third step would be the formulation of fertilizer recommendations (Wahhab, 1985). In 1990, a symposium was organized by NFDC on the *Role of P in Crop Production*. The outcome of all these efforts has been a better understanding of P fertilizer research issues and approaches and the accelerated efforts of researchers into P soil test correlation and calibration.

A number of studies have been conducted during the past six years or so with the major objective being to relate soil test values determined by different methods with crop response and the establishment of critical levels of P for various crops. These studies will be briefly covered under the following section.

Critical Values for Soil Test Phosphorus

Soil P test-correlation studies should ultimately lead to the development of critical values for the soil test method under study. Notable early works include a greenhouse study by Chaudhry and Memon (1969) using wheat as a test crop. They reported that Olsen P correlated well with dry matter yield and P uptake. Based on their results, they categorized Olsen P test values as under:

Chaudhry and Memon (1969)

< 15	mg P_2O_5/kg	Low (positive response)
15-25	mg P_2O_5/kg	Medium(probable response)
25-32	mg P_2O_5/kg	Medium high
> 32	mg P_2O_5/kg	High (no response).

Table 8. Establishment of critical levels of available P in Pakistan.

Crop	P Soil test	Critical level *mg/kg*	How established	Reference
Wheat	Olsen	8.5	Field experiments on 12 locations, used Bray's nutrient mobility concept, the value is for 97% yield	Malik and Hanif, 1975
	Olsen	8.5	Pot experiment on 20 benchmark soils, used Cate-Nelson scatter diagrams and ANOVA method of Nelson and Anderson (1977)	Nisar, 1988
	Olsen	15	Field experiment for 3 years on Hafizabad loam soil	Bhatti et al., 1988
	Olsen	16	Field experiments, on 23 locations, used Mitscherlich's percent sufficiency concept and Bray's nutrient mobility concept, critical level is for 95% yield.	Rehman, 1990
	Olsen ABDTPA Mehlich3	16 9 24*	Field experiments on 7 locations under dryland conditions, used modified Mitscherlich - Bray equation, values are for 95% yield	Rashid et al, 1991
Maize	Olsen ABDTPA Mehlich 3 Modified Olsen	8.3 5.4 57* 35*	Pot experiment on 31 Benchmark soils, used Cate-Nelson scatter diagrams	Rashid and Hussain, 1990
	Olsen ABDTPA	11.5 10.3	Pot experiment on 15 soils, used Cate-Nelson scatter diagrams	Khattak and Iqbal, 1990
Rice	Olsen	15	Field experiments, on multiple locations, used Mitcherlich's percent sufficiency and Bray's nutrient mobility concepts, critical level is for 95% yield	Rehman, 1990
Apple	Olsen	10.7	Field experiments at 11 locations, used modified Mitscherlich-Bray equations to determine critical level for 95% fruit yield	Rehman and Ghani, 1990

* *mg/dm*^{3}

Limited data available in the country on soil test correlation were reviewed by Wahhab (1985). He suggested adoption of the following scale of Olsen P for P deficiency diagnosis and P fertilizer recommendations:

< 5	mg P/kg	Positive response to P expected
5-10	mg P/kg	Positive response to P likely
> 10	mg P/kg	Response to P is not likely (depends on crop).

The above scale corresponds very closely with that originally proposed by Olsen et al. (1954). Based on the experience of various workers inside and outside the country, Memon (1986) suggested that a soil level of 12-15 mg P/kg may be considered as the cutoff point beyond which crop response to added P may be less likely for the majority of crops. He added that there is a need to establish deficiency and adequacy levels of soil test P in the country on the basis of well-planned and well-managed soil test-correlation and calibration experiments.

The critical limits adopted by soil testing laboratories in Punjab were: <5 mg/kg – poor; 5-10 mg/kg – satisfactory; and >10 mg/kg – adequate (Nisar et al., 1988). While the above scale continues to serve as a tentative guideline, works reported after 1985 have added significantly to existing knowledge about critical soil P levels by the Olsen, ABDTPA and Mehlich3 methods. A summary of critical limits reported by various workers is given in Table 8. Both field and pot experiments were used to establish critical levels. In some studies (Rehman, 1990, Rehman and Ghani, 1990, Rashid et al., 1991), modified Mitscherlich-Bray equations were used to obtain soil test values associated with near maximum (95%) yield of the crops under study. While in others (Nisar, 1988, Khattak and Iqbal, 1990, Rashid and Hussain, 1990), the Cate-Nelson approach (Cate and Nelson, 1965) was used to distinguish between P responsive and non-responsive soils and to determine critical limits above which response to P may not be likely. The values obtained by the latter approach were generally similar to those obtained by using the ANOVA approach (Khattak and Iqbal, 1990), outlined by Nelson and Anderson (1977).

A notably different approach was used by Bhatti et al. (1988). He established five levels of Olsen P (3, 5, 10, 15, and 20 mg/kg) in the field on the basis of P sorption properties of the soil. On each soil P level established, they superimposed five levels of applied P (0, 5, 10, 15 and 20 mg/kg) in the same way. The study was carried out for three years, using wheat as a test crop. Each summer, maize fodder was grown to deplete the soil P level to the original P level or lower. The three-year data (Table 9) showed that the yields were positively correlated with increasing P levels in the soil. However, yield response was not statistically significant beyond the 15 mg/kg P level. Therefore, they concluded that 15 mg/kg Olsen P should be taken as the critical level. They

Table 9. Grain yield of wheat (av. of 3 year data, t/ha) as affected by applied P at various original levels of soil P (Bhatti et al., 1988).

Applied P	**—Original P levels (Olsen, mg/kg)—**				
(mg/kg)	3	5	10	15	20
	Wheat Grain Yield (t/ha)				
0	2.2	2.9	3.2	3.7	3.7
5	2.9	3.2	3.4	3.8	3.7
10	3.2	3.6	3.7	3.9	3.8
15	3.6	3.5	3.7	3.8	3.8
20	3.8	3.7	3.7	3.8	3.9

did not attempt to perform a regression analysis of the data to determine the soil P level associated with a 95 percent maximum yield.

The data in Table 8 show that the critical values range from 8.5 to 16 mg/kg Olsen P in the case of wheat and 8.3 to 11.5 mg/kg Olsen P in the case of maize. Rashid (1990) reported additional data on critical levels tentatively determined for some other crops. For Olsen P, the values were: chickpea – 14.0 to 18.5 mg/kg; lentil – 18.8 mg/kg; mustard – 19.0 mg/kg; mash (black gram) – 8.5 mg/kg; mungbean – 9.2 to 31 mg/kg. Obviously, the values vary considerably, even for the same crop. It may be noted that the information on critical levels is based on widely different approaches in experimental methods and data analyses. In some cases, the critical limit is based on a study conducted on one soil only, while, in others, multiple locations have been used with wide variation in soil properties, such as soil texture, clay and lime contents, and in management conditions, such as irrigated v/s rainfed. Perhaps these variations could be reduced by adopting a uniform approach and an experimental methodology.

In an effort to determine the relationship between soil properties and crop response to P fertilizer, NFDC conducted field trials on wheat from 1981-82 to 1983-84 in collaboration with the Agricultural Research Institute, Tarnab (Nisar et al., 1988). The data from 62 trials showed that soil properties, lime, P Olsen and clay contents were important for the calibration model. They added, however, that the results were not conclusive because of the variation in crop varieties and in irrigation and other management practices.

Recently, Bhand (1991) studied wheat response to residual and applied P in a pot experiment. The data regarding P uptake in wheat grown on 12 previously fertilized soils were plotted against residual soil P determined by four methods (Olsen, ABDTPA, Mehlich3 and Pi). The relationship was described by quadratic equations which are given in Figures 1 to 4. On the basis of these data alone, it would appear that the critical limit of Olsen P is around 12 mg/kg. When grown in the

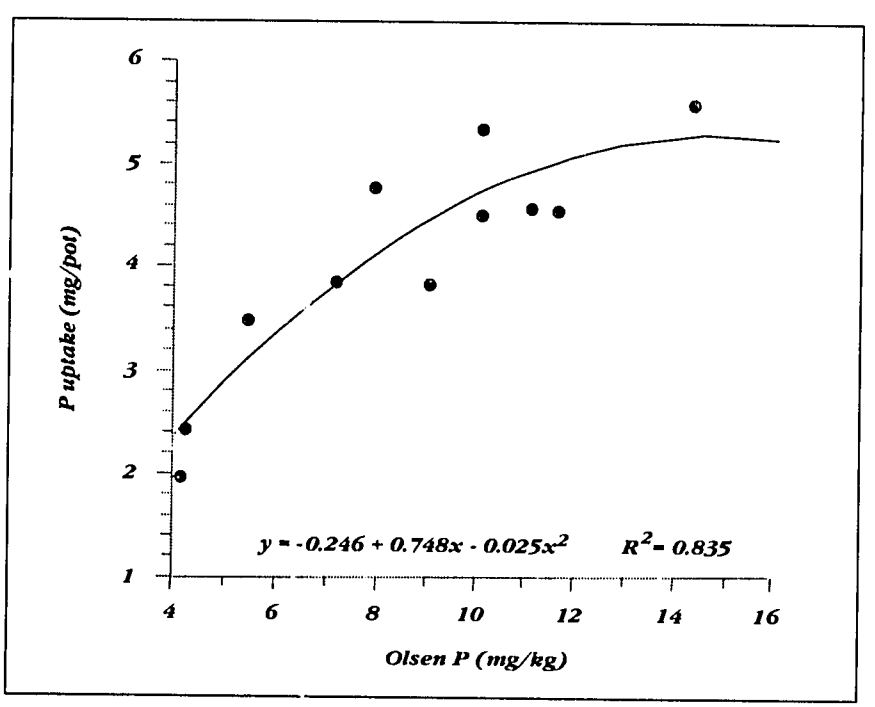

Figure 1. Phosphorus uptake in wheat in relation to Olsen P content of soil with previous history of P fertilization.

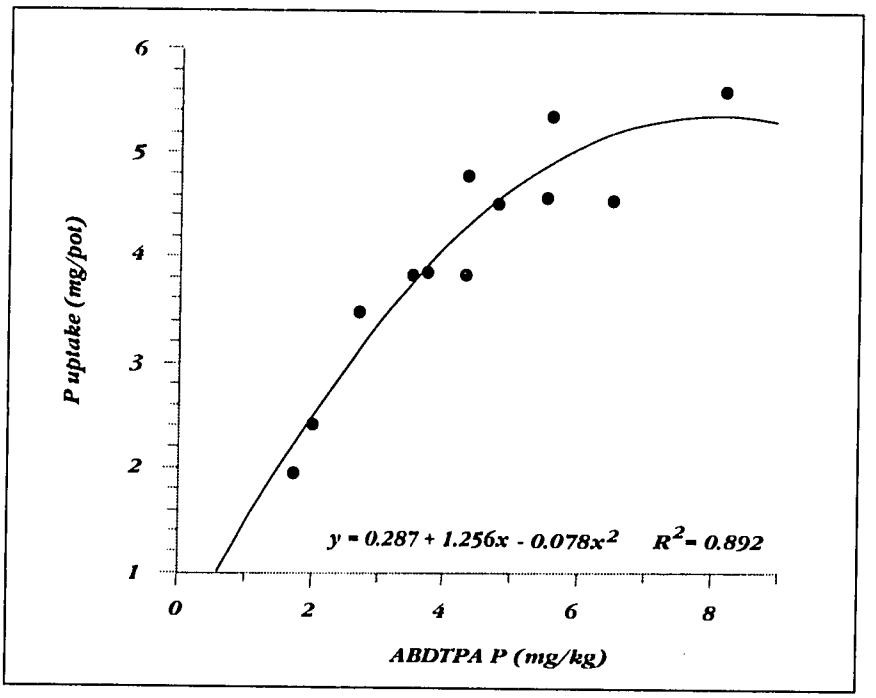

Figure 2. Phosphorus uptake in wheat in relation to ABDTPA P content of soil with previous history of P fertilization.

presence of freshly applied P, however, wheat growth and P uptake showed a significant increase ($P<0.01$) at each level of residual P (Figs. 5 and 6). Evidently, wheat responded better to freshly

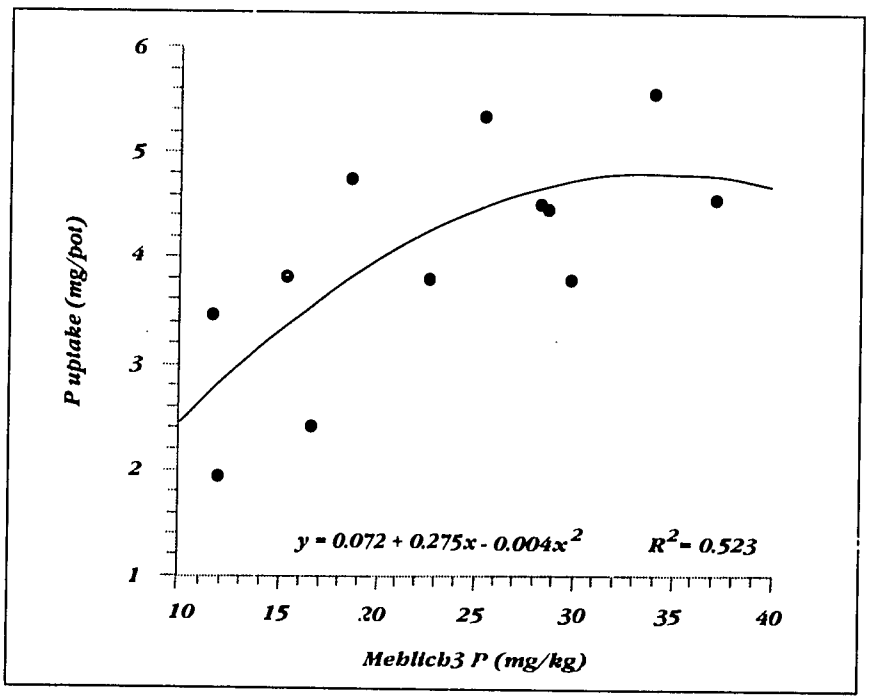

Figure 3. Phosphorus uptake in wheat in relation to Meblich3 P content of soil with previous history of P fertilization.

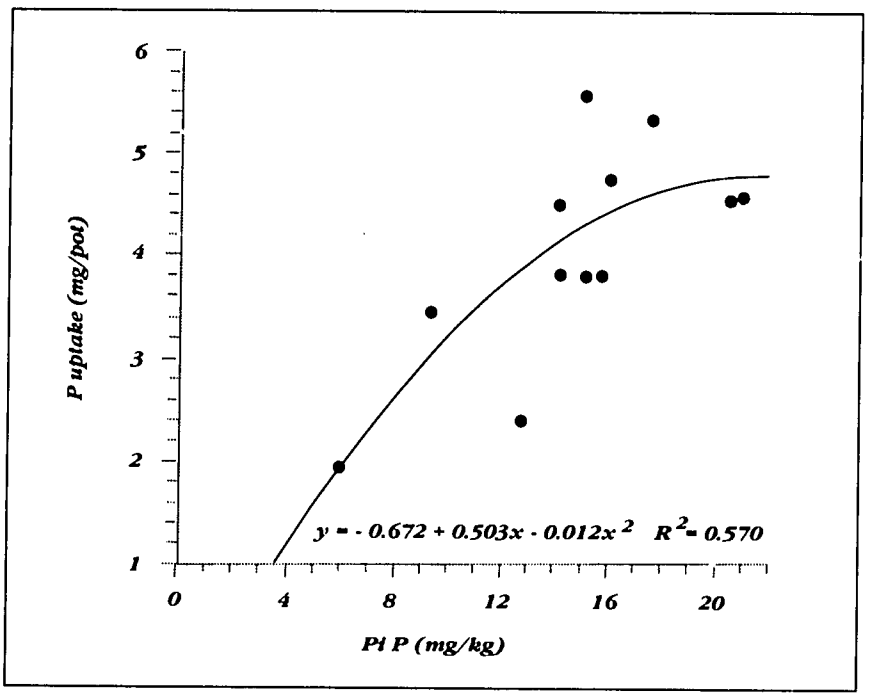

Figure 4. Phosphorus uptake in wheat in relation to Pi P content of soil with previous history of P fertilization.

applied P, such that the residual effects of P were not so pronounced. It is therefore important to know the level of soil P achieved after an addition of P fertilizer.

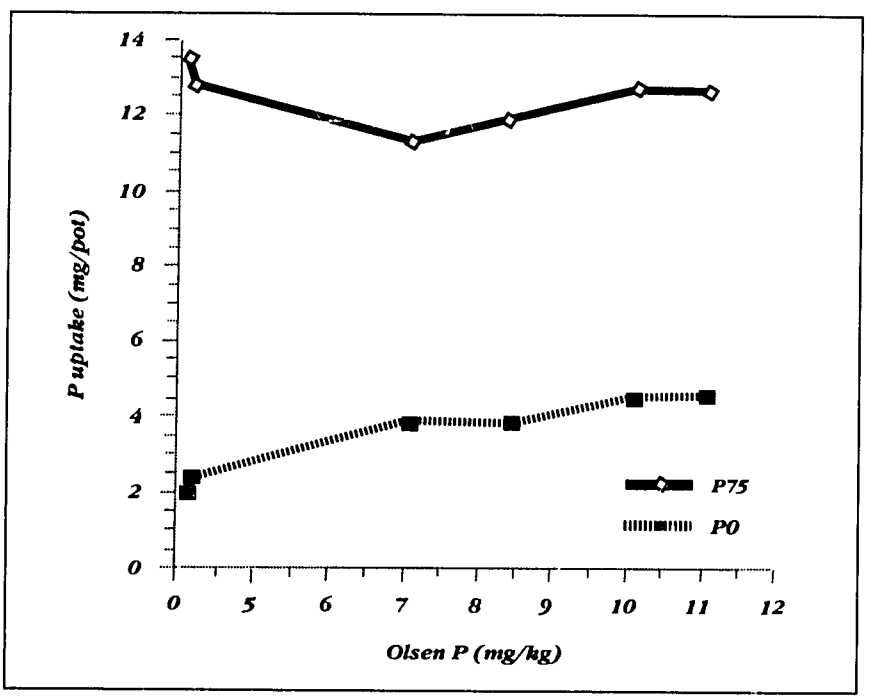

Figure 5. Phosphorus uptake in wheat (grown on soil from wheat-maize plots) in relation to residual and applied P.

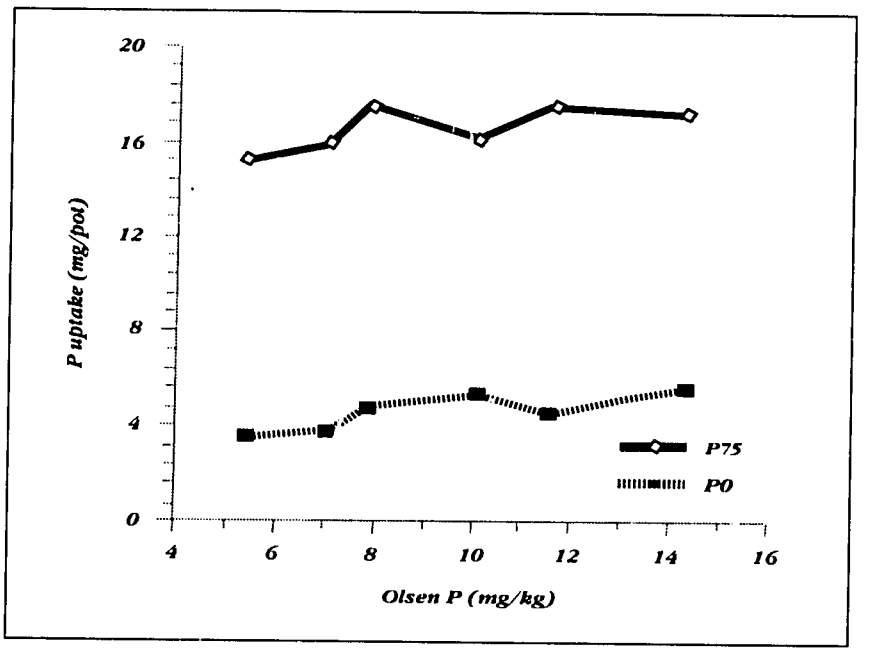

Figure 6. Phosphorus uptake in wheat (grown on soil from wheat-fallow plots) in relation to residual and applied P.

Phosphorus Fertilizer Requirements

Phosphorus fertilizer recommendations, as currently practiced in Pakistan, are generalized and lack a sound enough basis to be site specific. In a recent effort, Nisar et al. (1991) compiled data from 42 field experiments conducted on wheat during a three year period from 1987-88 to 1989-90. They used quadratic equations to describe the relationship between applied P rates and grain yields for each experiment. The economic optimum rate of P_2O_5 at MRR=1 (MRR: marginal rate of return) was calculated for each experiment by using the following relationship:

$$\text{Economic nutrient rate (kg } P_2O_5\text{/ha)} = [(MRR+1)Fp/Cp-b]/2c$$

where Fp is the price of P_2O_5 in Rs/kg; Cp is the crop price in Rs/kg; b, c are the coefficients from the yield equation; and MRR is the marginal rate of return. Thus, at MRR = 0, the economic optimum rate estimate is (Fp/Cp-b)/2c.

The economic optimum rates ranged from 0 to 197 kg P_2O_5/ha for all the sites. The relationship between economic optimum rates at MRR = 1 and soil test values was not as strong (r = 0.33). Reaching tentative conclusions from these data, considering the data from other works and the management level of the farmers, they proposed the following guidelines for making fertilizer recommendations for cereal crops (wheat, rice and maize).

Category	**Olsen P (mg/kg)**	**P_2O_5 Recommended (kg/ha)**			
		Full technology adoption		Partial technology adoption	
		Irrigated	*Rainfed*	*Irrigated*	*Rainfed*
Very low	<5	90-120	75	75	60
Low	5-10	75	50	60	40
Medium	10-15	60	40	40	20
High	15-20	40	20	20	–
Very high	>20	20	–	–	–

Formulating sound P fertilizer recommendations for specific soil-crop situations requires the knowledge of three aspects: 1) a P soil test value; 2) a critical level of P associated with optimum or desired yield of a given crop; and 3) a tested methodology for determining the quantity of P fertilizer needed to raise soil P level to the desired critical level. Phosphorus research in Pakistan has mainly focused on the first two aspects. The third one, dealing with soil properties, such as texture, clay and lime contents, and clay mineralogy, has an important bearing upon the P sorption characteristics of soils. Units of fertilizer P required to raise the P soil test level by one unit depend upon the P sorption or buffering capacity of soils.

Soil testing, as practiced in Pakistan, does not directly provide information on the P sorption characteristics of soils. Such information can be obtained by equilibrating graded amounts of P with a soil and then extracting P with a routine soil test method. The relationship between P applied and P extracted describes the P buffering capacity of that soil.

Phosphate Sorption Curves and Their Utility

Fox and Kamprath (1970) constructed phosphate sorption isotherms to describe the relationship between levels of P in solution established after fertilization in laboratory and the quantities of P sorbed at the end of equilibration. This approach has an advantage over conventional methods of soil testing in that it integrates P intensity, capacity and quantity aspects of the soil, all of which play important roles in controlling the P-flux to roots of growing plants. Moreover, fertilizer requirements can be estimated directly from P sorption curves.

Using the P sorption approach, P requirements of several crops have been determined under a variety of soil and climatic conditions (Fox, 1979, 1981; Vanderzaag et al., 1979; Memon, 1982; Memon and Fox, 1983; Roy and DeDatta, 1985; Memon et al., 1991). For wheat grown at seven locations in Pakistan, India, Tanzania and USA, Memon and Fox (1983) reported that P sorption curves were useful in determining P requirements from a composite yield response curve. They reported a P in solution value of 0.025 mg/L for 95 percent of the maximum yield obtained at these locations. Phosphorus fertilizer estimations, based on the above P in solution requirements, ranged from 0 to 62 kg P/ha. In a later study, Memon et al. (1991) reported that the P requirement of wheat grown on calcareous soils of Pakistan was 0.032 mg/L for 95 percent yield as determined from a composite yield response curve.

The data from P sorption studies (Fig. 7, Table 10) indicate that the soils of Pakistan have a low P sorption capacity according to the scale given by Juo and Fox (1977). The addition of 50-100 kg P_2O_5/ha, in many cases, increases the level of solution P to that desired for optimal production.

While the P sorption approach has merit, practical considerations, such as the period of equilibration, limit the possibility of its adoption in the country. Besides, researchers are quite familiar with the routine Olsen P test. Therefore, it follows that alternate approaches might be used to integrate the principles involved in the P sorption approach with the routine laboratory procedure of Olsen et al. (1954). This will require equilibration of P with soil samples followed by extraction with $NaHCO_3$ or ABDTPA tests. Soil incubation with P can also be used, as reported by Rashid et al. (1988). Such studies should ultimately lead to the formulation of the relationship between some important soil properties (e.g., clay and lime contents, clay mineralogy) and the P buffering capacity of soils.

Phosphorus Fertility Buildup

In view of the accumulation of P residues in soils, it is of practical importance to know the rate of change in available P in relation to the rates of P application in different soils and cropping systems. Such information can be used to determine: 1) the units of fertilizer P needed to raise P

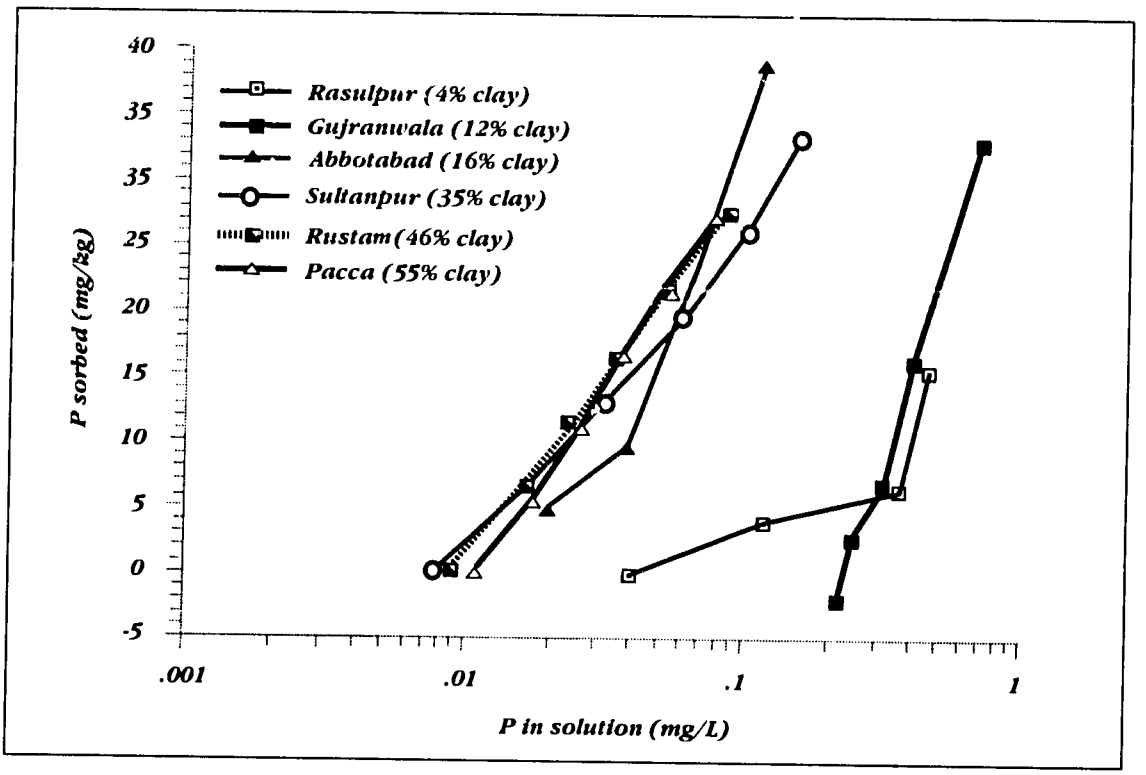

Figure 7. P sorption curves of some soils of Pakistan.

soil test level by one unit; 2) the period required to build the P fertility to adequacy (critical) levels; and 3) the rate of P buildup under different cropping systems. Such data, if available, could be used to determine the relative quantities of fertilizer P required to achieve critical levels in soils differing in their clay content and other characteristics. Tandon (1987) therefore, defined the Phosphorus Fertility Buildup Factor (PFBF) as the units of fertilizer P required to raise the P soil

Table 10. Fertilizer P requirement of some soils of Pakistan at standard P in solution of 0.2 mg/L.

Soil name	Standard P requirement *kg P/ha*	Reference
Rasulpur (4.0% clay)	12.6	Rashid et al.,Unpub.
Abbotabad (16.4% clay)	95	" "
Gujranwala (11.8% clay)	0	" "
Sultanpur (35% clay)	72	Memon et al., 1991
Pacca (55% clay)	88	" "
Rustam (46% clay)	80	" "
Rustam (42% clay)	76	" "

test level by one unit after accounting for P uptake by the crops grown. PFBF can range from 1-224 and for many alluvial soils of India it usually takes about 20-40 units of fertilizer P to raise Olsen P by one unit, after accounting for P uptake under field conditions (Tandon, 1987). The higher the PFBF, the more difficult, or slower, it is to build available P in the soil. The nature of the cropping system may influence the PFBF through differential P uptake by the crops in rotation. This was investigated by Puno (1991) in a long term study involving three annual cropping systems (wheat-maize, wheat-fallow and wheat-soybean) fertilized at 6 rates of P (0, 30, 60, 90, 120, 150 kg P_2O_5/ha) for seven consecutive cropping seasons. The data (Table 11) showed that PFBF values ranged from 11.75 to 49.30. The values were lower under the wheat-fallow system (19.05) compared to those under the wheat-corn (37.43) or the wheat-soybean (25.82) systems, indicating that P fertility could be built up more easily under the wheat-fallow system.

Table 11. Olsen P content and Phosphorus Fertility Buildup Factor (PFBF) in relation to P fertilization and cropping for seven seasons under three cropping systems.

P rate per season *mg/kg*	Total P added *mg/kg*	Olsen P* *mg/kg*	Increase in Olsen P** *mg/kg*	+ PFBF
Wheat-Corn				
6.55	45.9	4.68	1.89	24.3
13.10	91.7	4.86	2.07	44.3
19.65	137.6	5.58	2.79	49.3
26.20	183.4	6.58	3.79	48.4
32.75	229.3	13.77	10.98	20.9
Wheat-Fallow				
6.55	26.2	5.02	2.23	11.8
13.10	52.4	5.02	2.23	23.5
19.65	78.6	6.91	4.12	19.1
26.20	104.8	7.25	4.46	23.5
32.75	131.0	10.32	7.53	17.4
Wheat-Soybean				
6.55	45.9	5.02	2.23	20.6
13.10	91.7	6.24	3.45	26.6
19.65	137.6	7.03	4.24	32.4
26.20	183.4	8.92	6.13	29.9
32.75	229.3	14.50	11.71	19.6

* *Soil P content after seven cropping seasons, original soil P = 2.79 mg/kg.*

** *Increase in Olsen P as a result of fertilization and cropping for 7 seasons.*

\+ *PFBF = Total P added/Increase in Olsen P.*

Conclusion

The majority of soils of Pakistan are deficient (<10 mg/kg Olsen P) in P and well below the critical limits for optimal crop production. Current P fertilization practices and land use patterns and management levels do not hold promise for improvement in P fertility of soils in the near future. Evaluation of various soil P test methods have demonstrated the value of ABDTPA and Mehlich3 methods, in addition to the currently used Olsen method, in diagnosing P deficiencies. Extensive research data are now available regarding the usefulness of the ABDTPA method for analysis of P as well as micronutrients so that it can be adopted as a routine soil test for evaluating P fertility of soils. Its capability for simultaneous extraction of macro- and micro-nutrients can be used to advantage in time, cost and convenience.

The data from numerous crop response experiments continue to provide the basis for generalized P fertilizer recommendations. The need for soil-crop specific fertilizer recommendations is increasingly recognized. Recent research into soil P test-crop response correlation and calibration has generated preliminary data regarding critical levels of P for some important crops. However, such information can not be translated into P fertilizer recommendations unless additional data are available on some measure of P sorption capacity such as *Fertilizer Factor* (units of P fertilizer required to raise P soil test value by one unit). Studies on P sorption properties of soils are rather limited to be of value in formulating P fertilizer recommendations. Further research is needed as proposed below:

1. Continue field and laboratory studies on P soil test calibration and determination/refinement of critical limits for various soils and associated cropping systems. Efforts be made to adopt unified research methodology and data analysis techniques to address research objectives effectively.

2. Study P sorption characteristics of major soil types and relate these to soil properties.

3. Design studies to integrate P sorption aspect of soils into conventional P soil test method(s) to allow for determination of *fertilizer factor* and its relationship with various soil properties.

4. Plan to utilize information on soil test values, critical levels and fertilizer factor to formulate soil-crop specific P fertilizer recommendations.

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Contact Person:

Kazi S. Memon
Texas A&M University
Soil and Crop Science Department
College Station, TX 77843
Telephone: (409) 845-3603
Fax: (409) 845-0456
Electronic Mail: (BITNET) L334RL@TAMVMI.BITNET

Current Research On Organic Phosphorus

F. R. Cox
North Carolina State University, Department of Soil Science

Introduction

A significant amount of phosphorus (P) in soil is contained within the organic fraction. In a review, Schnitzer (1991) estimated that between 20 and 80 percent of the total soil-P in most surface soils may be in organic forms. These forms include not only those common in plant metabolism, but also many esters of phosphoric acid, inositol phosphates, and, especially in the more resistant types of organic matter (OM), many forms are yet to be identified. The importance of organic P (Po) lies in its role in plant nutrition, but that role is not at all clear. Few direct *cause and effect* relationships have been established between Po and plant growth and development. Also, there is usually a strong interrelationship between Po and inorganic P (Pi), which makes it very difficult to ascertain the relative importance of each. Then, too, many correlations exist between OM content and soil properties, such as texture and acidity which may confound the relationship between Po and plant growth and development.

In many studies the relationship between Po and plant growth and development is assumed to be an association between an *available* fraction of soil P and plant growth. Tiessen et al. (1984) used this approach and related an available pool to other forms of soil P in benchmark soils representing eight soil orders. Soil P was fractionated sequentially into resin, bicarbonate, hydroxide (two strengths), acid, and acid-peroxide forms. In each extract, Pi was determined, then, after oxidation, total P was found. Po was calculated from the difference. They hypothesized a conceptual model of the relationships among these forms of Po and Pi and used a path analysis statistical evaluation. The resin extractable P served as the *available* fraction. They found that much of the available P in Mollisols was derived from inorganic bicarbonate- and hydroxide-extractable P forms, whereas in Ultisols, 80 percent of the variability in available P was accounted for by organic P forms. They suggested from their work that in Ultisols the mineralization of organic P may be a major determinant of P fertility.

Sharpley (1985) also stressed the importance of Po as a source of available P in both unfertilized and fertilized soils. He found a seasonal fluctuation of Po, which was higher in winter than in spring, and suggested that this fluctuation was due to changes in the more labile forms of Po. Available P (Bray-1 P in this case) was closely correlated with Po in unfertilized soils, but it was more closely correlated with Pi in fertilized soils.

The Use of Phosphorus in Models

The role of Po in plant nutrition has been stressed in a number of simulations, or models, concerning P. Cole et al. (1977) established daily P requirements taken from pools of labile Pi, but these pools were replenished mainly by mineralization of labile Po. This was in a simulation of P cycling in semiarid grasslands, an unfertilized system. The concept of Cole et al. (1977) was included in the model developed by Jones et al. (1984a) which was designed for use in the Erosion-Productivity Impact Calculator (EPIC) agriculture management model. For a current

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reference, a recent review by Jones et al. (1991) covers not only this simulation, but also previous models on P in the soil-plant system. Critical components that had to be determined or estimated in this simulation were labile P, organic P, and the P sorption capacity. Sharpley et al. (1984) predicted these three factors from extractable P, soil N, and clay or $CaCO_3$ concentrations, respectively. In a later study with both calcareous soils and highly weathered soils, Sharpley et al. (1989) again predicted these three factors; labile P from soil test P, organic P from either organic C or total N, and P sorption from either clay or $CaCO_3$ content. The P model for EPIC has been tested with several sets of data (Jones et al., 1984b), and these have included fertilized crops. It is entirely possible, however, that for fertilized crops, Po is contributing little to the understanding of P cycling.

Beck (1991) also used a fractionation procedure in evaluating Pi and Po transformations during 18 years of cultivation of an Ultisol in the Amazon Basin of Peru. When fertilizer was applied, the rate of P applied was reflected in several Pi pools: available, labile, and moderately available. When fertilizer was not applied, the organic P pools were the main sources of available P, but these sources were not able to maintain available P above the critical level for crops.

Importance of Pi and Po in Plant Uptake of P

Some direct measures of the importance of both Pi and Po forms, as measured by plant uptake of P, have been made. Ayodele (1986) measured P availability in 60 savannah soils of Western Nigeria. For these soils, Po averaged 41 percent of the total P. He found measures of active Pi more related to P uptake than measures of Po. He observed, however, that in soils with rather high OM, at least greater than two (2) percent, organic P mineralization may affect P availability.

Hedley et al. (1982) related P uptake by Rape (*Brassica napus*) seedlings at three and six weeks of growth to various fractions of Pi and Po. At three weeks, resin, bicarbonate, and mild alkali extractable Pi were depleted by plant uptake. At six weeks, these forms plus acid soluble and residual Pi were depleted. At no time in this study was there any evidence of hydrolysis of soil Po. In fact, Po increased slightly with time, perhaps due to inclusion of fine root debris and microbes.

Forms of Pi and Po have also been related to crop response and P uptake in field experiments. Nurwakera (1991) grew corn (*Zea mays*) and cowpeas (*Vigna unguiculata*) for four years on an Oxisol in the Amazon basin of Brazil. Rates of P were applied initially to establish a range in soil P availability during the study. Soil P was extracted with three solutions for soil testing, and also was fractionated into four Pi pools and two Po pools. The two Po pools were with the Bowman (1989) procedure using concentrated sulfuric acid, then dilute base. Most of the Po was in the acid extract, while most of the Pi was in Fe and Al forms. Relative yields and P uptake were highly correlated with soil test P, and the soil tests were linearly related to Po. As before, in fertilized systems it appears that the interrelationship between soil test P and Po negates any benefit from considering forms of organic P.

Conclusions

It appears that Po is most important when considering natural, unfertilized systems in which the dominant transformation of P is uptake by plants and return to soil in residue. In temperate grasslands with considerable Po, this form of P also may be important for several years after cultivation begins. In more highly weathered soils, and in soils that have been cultivated and fertilized for a while, however, Pi appears to be more important. For these conditions, Pi is easier to determine than Po, and routine methods are available for this evaluation. There does not seem to be a routine method for the analysis of Po.

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Contact Person:

Fred Cox
North Carolina State University
Department of Soil Science
Raleigh, NC 27695
Telephone: 919-515-2388
Fax: 919-515-7422
Electronic Mail: (BITNET) ncfcox@ncsumvs.bitnet

Alternative Phosphorus Fertilizers For The Tropics: An Agronomic And Economic Evaluation

D. T. Hellums
International Fertilizer Development Center (IFDC)
C. A. Baanante
International Fertilizer Development Center (IFDC)
S. H. Chien
International Fertilizer Development Center (IFDC)

Abstract

Several phosphate rocks (PRs) and soluble triple superphosphate (TSP) were evaluated as phosphorus (P) fertilizers in multi-year field trials conducted on acid soils in Colombia, Mali, and Indonesia. In the Colombian experiments, on soils with high levels of available P, Huila PR increased yields more than did TSP for the initial bean/maize crop and also provided some residual P to the first wheat crop. When the initial crop was potatoes, TSP improved yields more than did Huila PR, and neither source provided residual P for subsequent crops. Annual applications of Tilemsi PR and TSP, on a P-deficient soil in Mali, provided similar significant yield increases for maize and cotton in two different cropping rotations. The experiments in Indonesia showed that unground North Carolina PR was as effective a source of P nutrition as TSP in both annual and residual maize/soybean trials. Economic analysis showed that in every trial the PRs were as economically effective as soluble TSP in providing available P to all crops under conditions tested.

Introduction

Increasing costs and limited foreign exchange are forcing many developing countries to explore options for the importation of water-soluble phosphorus (P) fertilizers required for food production. For many of the tropical developing countries, this situation means the development of indigenous phosphate rock (PR) reserves or consideration of importation of alternative fertilizers with lower water soluble P levels. One of the most financially attractive alternatives is the direct application of indigenous or imported PR. In the past, finely ground PR has often provided adequate P nutrition for crop growth under tropical conditions. Vast areas of soils in this region have characteristics conducive to PR dissolution including an acidic pH, low levels of soil solution P and exchangeable Ca, and moderate to high levels of P retention (Hammond et al.,1986). In addition, other external factors that enhance the performance of PR, including a warm, moist climate and long cropping patterns, are common to the tropics.

The agronomic, and ultimately the economic, performance of any PR is also dependent on its inherent mineralogy. Of the three types of PR (igneous, metamorphic, and sedimentary), sedimentary PR

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is the most important source for direct application (Howeler and Woodruff, 1968). The most common form of sedimentary PR is known as carbonate apatite or francolite as indicated by the following formula:

$$Ca_{10-a-b}Na_aMg_b(PO_4)_{6-x}(CO_3)_xF_{2+0.4x} \quad (1)$$

The level of isomorphic substitution of carbonate for phosphate within the crystalline lattice of apatite determines the reactivity and potential agronomic performance of the PR. For example, the solubility of PR in neutral ammonium citrate (AOAC method) was found to be directly related to the level of substitution and was indicative of its level of reactivity (Chien, 1977).

Despite the promising performances of various PRs (including indigenous deposits), most developing countries in the tropics continue to import large quantities of water-soluble fertilizers. Factors responsible for this practice have included handling characteristics, transportation costs, and policy decisions promoting subsidies and legislating fertilizer standards that favor water-soluble fertilizers (Chien and Friesen, 1990). Overcoming these obstacles, along with recognizing that direct application of PR under some soil constraints is sound agronomically and economically, will be required for widespread adoption of PR use by farmers.

Objective

From its inception, the International Fertilizer Development Center (IFDC) has sought to provide nutrient inputs at low cost for food crops in developing countries of the tropics. A considerable amount of research has been directed at characterization of indigenous PR reserves and agronomic testing of the more reactive PRs. One theme common to the following field trials was the assessment of the performance of directly applied PR relative to triple superphosphate (TSP) under various conditions (climatic and soil) found in the tropics. It should be noted that the following discussion of results from these three field experiments represents only a small fraction of the conditions evaluated in each of these projects, which in turn represent a small percentage of the work conducted by IFDC in these regions.

Materials and Methods

Three, multi-year field trials were conducted to evaluate the annual and residual performance of three PRs (Huila, Colombia; Tilemsi, Mali; North Carolina, USA) relative to TSP in a rotation

Table 1. Unit-cell a-dimension and the empirical formula of the apatites in phosphate rocks.

Phosphate Rock	Length a-Axis Å	Empirical Formula
Huila	9.340	$Ca_{9.69}Na_{0.22}Mg_{0.09}(PO_4)_{5.14}(CO_3)_{0.96}F_{2.34}$
Tilemsi	9.350-9.358	$Ca_{9.84}Na_{0.12}Mg_{0.05}(PO_4)_{5.51}(CO_3)_{0.49}F_{2.19}$
North Carolina	9.322	$Ca_{9.53}Na_{0.34}Mg_{0.13}(PO_4)_{4.--}(CO_3)_{1.23}F_{2.49}$

Table 2. Chemical characteristics for soils of experimental sites.

	pH	Bray-1 P (ppm)	Ca (meq/100 g)	Organic Matter (%)
Colombia				
Obonuco				
Site 1	5.4	46.0	7.10	5.1
Site 2	5.2	26.7	4.80	2.5
Mali				
Dalabani	5.0	7.5	1.50	1.2
Tieourala	4.3	7.7	1.50	1.2
Samanko	5.3	6.9	2.00	0.7
Sotuba	5.5	2.7	–	0.5
Indonesia				
Taman Bogo	5.4	3.1	1.40	2.8

cropping system. Previous characterization of the PRs utilizing X-ray and infrared absorption showed that phosphate minerals other than apatite were not present (Chien and Hammond, 1978: Van Kauwenbergh et al., 1991). Empirical formulas of apatite for each PR, based on the unit-cell *a*-dimension (Table 1), were derived from X-ray methodology (Lehr and McClellan, 1972).

Trials were conducted in Colombia, Mali, and Indonesia on acid soils which, except for the Obonuco site in Colombia, were low in P and exchangeable Ca (Table 2). All experiments received uniform application of nitrogen, potassium, and micronutrients.

Trials in Colombia and Mali compared indigenous medium-reactive PRs (Huila and Tilemsi, respectively) with TSP as a source of P (Table 3). The trial in Colombia utilized two crop rotations (bean/maize-wheat-potatoes-wheat and potatoes-wheat- potatoes-wheat) to test the initial and residual effect of a less soluble P fertilizer relative to TSP on an acid soil with relatively high P levels. Fertilizers at three non-zero rates were applied point-placed (according to local farmers' practice) to the first crop of each sequence; plots were then plowed to distribute residual fertilizer prior to planting each of the next three crops.

Table 3. Chemical analyses of experimental phosphorus sources.

Phosphorus Source	Total P	Citrate-Soluble P[a]	Water-Soluble P
	(%)		
Huila PR	8.7	1.5	<1
Tilemsi PR	12.1	1.8	<1
North Carolina PR	13.1	3.3	<1
TSP 20.1	20.1	2.2	17.3

[a] *Neutral ammonium citrate (AOAC) method.*

Table 4. Regression estimates for crop yield response to initial and residual effect of phosphorus application – Colombia (Obonuco).

Variables	Coefficient Estimates[a]						
	Sequence 1				Sequence 2		
	Beans 1982	*Maize 1982*	*Wheat 1983*	*Wheat 1985*	*Potatoes 1982*	*Wheat 1983*	*Wheat 1985*
Intercept	864.7	3,176.8	3,922.6	1,391.3	11,467.4	4,290.4	2,116.7
Huila PR	18.79*	31.79*	53.56*	2.66^{ns}	216.37†	13.62^{ns}	1.48^{ns}
TSP	11.60^{ns}	27.77†	6.17^{ns}	9.11^{ns}	273.50*	5.19^{ns}	4.55^{ns}
% R^2	47.7	56.7	31.9	6.3	38.6	7.9	10.2

Source: Martinez and Leon, 1986.

† *Significant at 0.10 level of significance.*
* *Significant at 0.05 level of significance.*
ns *Not significant.*
a $Y = a + bx$.

Unlike the Obonuco site in Colombia, all sites in Mali were highly weathered and low in available P and exchangeable Ca (Table 2). One on-farm experiment conducted at all sites evaluated crop response to annual application of three non-zero rates of Tilemsi PR or TSP in two four-season cropping sequences: maize-cotton-maize-cotton and cotton-maize-cotton-maize.

The trial in Indonesia evaluated a highly reactive imported North Carolina PR and locally produced TSP (using imported PR raw materials) at four non-zero P application rates on acid soils

Table 5. Regression estimates for crop yield response to phosphorus – Mali.

Variables	Coefficient Estimates[a]							
	Sequence 1				Sequence 2			
	Maize 1982	*Cotton 1983*	*Maize 1984*	*Cotton 1985*	*Cotton 1982*	*Maize 1983*	*Cotton 1984*	*Maize 1985*
Intercept	1,345.8	1,361.0	221.6	654.0	1,326.9	778.0	266.0	359.0
Tilemsi PR	154.4*	161.9*	302.1**	160.0**	200.9**	300.6**	207.0**	260.1**
TSP	197.3*	161.0*	351.0**	163.0**	245.0**	310.0**	210.0**	330.9**
% R^2	65	70	82	78	83	86	77	80
SE kg ha^{-1}	63.1	64.1	37.4	42.3	35.2	39.6	33.6	55.2

Source: Baanante and Henao, 1991.

* *Significant at 0.05 level of significance.*
** *Significant at 0.01 level of significance.*
a $Y = a + b \ln X$.

on the island of Sumatra. During the first year, proper fertilizer quantities were broadcast and incorporated. At the beginning of the second year, each plot was split; P was reapplied at its original rate in one strip while crop response to residual P was observed in the other strip. Initial P rates were chosen to allow comparison of a single biennial application of P at rates of 20 and 40 kg/ha with two annual P applications at rates of 10 and 20 kg/ha, respectively. The experiments were sown with two crops per year: maize at the beginning of the rainy season, immediately followed by soybean. All required inputs were applied to the cereal crop, and the grain legume relied on residual nutrients.

Response functions based on statistical analyses of yields were estimated for each P source to provide multiple regression analysis Economic analyses were conducted to calculate optimum rates of application, benefits, and value/cost ratios for each P source. Response function estimates were used to calculate yield increases and agronomic efficiencies associated with each source.

Analysis of Agronomic Effectiveness

The soils of the Obonuco region have relatively high levels of available P; high levels of exchangeable Ca, Mg, and K; and a low P sorption capacity. Low P sorption in these soils is probably due to P fertilization in the past (Leon, 1986). Results of the regression analysis for cropping Sequence 1 at site 1 (Table 4) indicated a larger response to Huila PR than TSP in the initial bean/maize intercrop (fertilized) and the first residual wheat crop. The crop response to Huila with respect to TSP was greater in residual wheat than in the initial bean/maize intercrop. Measurement of soil pH values following the first harvest indicated the pH had dropped from 5.4 to 5.1 for the TSP treatments, while plots receiving Huila PR showed an increased pH to 6.1. These values suggested that overall nutrient availability was greater at pH 6.1; therefore, the Huila PR performed better. In 1984, the residual potato crop was destroyed by drought. In 1985, residual wheat yield dropped dramatically because neither Huila PR nor TSP supplied enough residual P to improve yields over that of the control plots. In Sequence 2 at site 2, application of TSP significantly improved potato yields, whereas less response was observed with the Huila PR. Potatoes require higher levels of available soluble P initially than do some other crops such as maize/bean; therefore, the less soluble Huila PR could not meet this demand. Follow-up residual wheat crops showed that neither P source significantly increased yields over the control treatment, i.e., overall wheat yields in this cropping sequence declined. Again, the 1984 potato crop was destroyed by drought.

On the phosphorus-deficient soils of Mali, the annual application of Tilemsi PR and TSP resulted in significant yield increases for the first two crops in Sequence 1 (maize and cotton) and highly significant yields for the remaining crops in both sequences (Table 5). The response functions indicated that yield increases from TSP were slightly higher than with Tilemsi PR, but standard errors indicated that overall differences between the two sources were insignificant. Yields for maize and cotton were slightly higher when cotton was the first crop in the rotation (Sequence 2).

Estimates of the response functions from experimental data for the first two years of the maize-soybean trials in Indonesia are presented in Table 6. Results indicated that unground (-35 mesh) North Carolina PR was as effective a P source as TSP on this acid soil (pH 5.4) except for the response of the initial maize crop in 1987. Both sources also provided significant residual effects as indicated in all the soybean crops an the maize crop (Option 2).

Economic Analysis

Preliminary economic analysis (using crop and fertilizer prices [Table 7]) was conducted to determine the profitability of using directly applied PR as opposed to the more soluble TSP under

Table 6. Regression estimates for crop yield response to phosphorus – Indonesia (Taman Bogo).

Variables	Coefficient Estimates[a]					
	1987-88[b]		1988-89 Option 1[c]		1988-89 Option 2[c]	
	Maize	*Soybean*	*Maize*	*Soybean*	*Maize*	*Soybean*
Intercept	1,238.0	200.0	545.3	387.5	306.9	285.8
N. Carolina PR	649.0**	122.2**	648.6**	228.5**	349.3**	230.8**
TSP	718.0**	147.6**	560.3**	173.7**	329.2**	168.5**
% R^2	86	80	90	69	70	63
SE kg ha^{-1}	23.4	49.6	42.3	28.9	54.6	33.8

* *Significant at 0.05 level of significance.*
** *Significant at 0.01 level of significance.*
[a] $Y = a + b \ln X$.
[b] *Phosphorus fertilizer applied to maize crop only.*
[c] *Plots (1987/88) split. Maize crop in Option 1 received additional P fertilizer; no additional P applied in Option 2.*

a variety of cropping and soil conditions. In all instances, PRs compared favorably with TSP in net benefit and the value/cost ratio (Table 8). Because the benefits and sometimes costs accrue over several crop seasons, present values of benefits and costs were calculated by discounting the

Table 7. Crop and fertilizer prices used for economic analysis.

	Units	Price[a]
Colombia		
Beans	USD/kg	0.91
Maize	USD/kg	0.18
Wheat	USD/kg	0.24
Potato	USD/kg	0.09
Huila PR	USD/kg P	0.30
TSP	USD/kg P	0.58
Mali		
Cotton	USD/kg	0.18
Maize	USD/kg	0.12
Tilemsi PR	USD/kg P	0.28
TSP	USD/kg P	0.56
Indonesia		
Maize	USD/kg	0.08
Soybean	USD/kg	0.18
North Carolina PR	USD/kg P	0.50
TSP	USD/kg P	0.60

[a] *Average yearly price for year in which trial was conducted.*

flows of benefits and costs associated with the use of each P source in each crop rotation. For Colombia, the benefits and costs were not discounted (data unavailable); however this did not affect the conclusion. In Colombia, differences in net benefits and value/cost ratios for Huila PR and TSP are seen only in the bean/maize-wheat-wheat cropping system. In Mali and Indonesia, there were only slight differences in net benefits and value/cost ratios associated with each source in each cropping sequence. In terms of economic effectiveness, these results would suggest that in Colombia and Mali use of direct application of indigenous PR could supply P required by various crops and at the same time produce foreign exchange savings and reduce dependence on foreign suppliers. In Indonesia, the economic situation is different. Here the North Carolina PR is imported as is the PR (Jordan or Morocco) used in the local production of TSP. In addition, the TSP product is still heavily subsidized by the government. Although economically the North Carolina PR is as effective as the TSP, a final assessment of the advantage of one product over the other will require a better understanding of numerous other economic factors along with the value of residual P supplied by each product.

Conclusions

These particular results have shown that moderately to highly reactive PRs are viable alternatives to soluble P fertilizers under the conditions presented. However, these observations cannot be extrapolated to recommend the use of reactive PRs on all crops of the tropics. As seen in these trials, the availability of P to the plant and the plant's use of P are affected by factors other than fertilizer source solubility; such factors include soil conditions, climatic conditions, crops and cropping sequence, and management strategies. In addition to these agronomic factors, economic factors such as fertilizer subsidies, fertilizer availability, employment generated and foreign exchange saved if indigenous PR deposits are used, transportation cost, and net returns will vary by country. All these factors must be considered in making recommendations for policies regarding the use of directly applied PRs versus soluble P sources on the soils of the tropics.

Table 8. Economic evaluation of fertilizer use strategies.

Country	Crop[a] Rotation	Fertilizer	Net Benefit (US$/ha)	Value/Cost Ratio
Colombia	B/M-W-W	Huila	802	24.6
	B/M-W-W	TSP	577	5.8
	P-W-W	Huila	1,347	15.4
	P-W-W	TSP	1,390	10.2
Mali	M-C-M-C	Tilemsi	225	3.5
	M-C-M-C	TSP	196	3.3
	C-M-C-M	Tilemsi	324	4.0
	C-M-C-M	TSP	295	4.3
Indonesia	M-S-M-S	North Carolina	626	6.8
	M-S-M-S	TSP	581	6.4
	M-S-M-S	North Carolina	580	10.8
	M-S-M-S	TSP	563	9.7

[a]*B = bean, M = maize, W = wheat, P = potato, C = cotton, and S = soybean.*

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Contact Person:

Deborah T. Hellums
Resources Management Research Development Division
International Fertilizer Development Center (IFDC)
Muscle Shoals, AL 35660
Telephone: 205-381-6600
Fax: 205-381-7408
Electronic Mail: (CGNET) 157:CGI072

New Directions In Expert Systems Research

S. Itoga
University of Hawaii, Department of Information and Computer Science

Introduction

Our goal is to investigate expert system software development programming situations for problems that only can be solved with interdisciplinary knowledge. Current expert system shells slight the possibility that diverse and sometimes disparate sources of knowledge may be necessary in certain problem-solving situations. Little provision is made to recognize, manage, and integrate these knowledge sources because of the traditional belief that expert systems should focus on well-defined and restricted domains (Waterman, 1986). Our experience with expert systems has focused on those problems in the agricultural sciences characterized by an abundance of factual information and heuristic knowledge and with an underlying base of fundamental laws. Many such agricultural problems require information from subject areas that superficially have little in common. Often, no one discipline can solve the problem, but a collaborative effort is successful. Nutrient deficiencies in soils is a good example of the need for multiple sources of expertise.

Work in expert systems programming tools (often called shells) has produced many results (Harmon et al., 1988). Systems like KEE, NEXPERT, and EXSYS have successfully produced many expert systems applications. Much of this previous work focused on simple user interfaces that enabled a single expert to create his own system, and it was not the stated intent of such systems to address issues requiring multiple experts to contribute interactively to a solution. Current research focuses on the integration of multiple knowledge sources rather than individual sources, and investigates new ways to blend these sources into cohesive systems that take a broader problem-solving perspective.

The development of the Phosphorus Decision Support System (PDSS) and its integration with previous agronomic expert systems should stimulate more activity in cooperative problem-solving efforts. We believe that many of the hard problems confronting society today depend on solutions outside traditional areas of scientific research, and current research should stimulate efforts to focus diverse sources of knowledge onto these complex problems.

For example, to understand the problem of groundwater contamination, a knowledge of soil physics, hydro-geology, soil chemistry, and environmental biology is needed. Inevitably, questions about economics, legal issues, and governmental policies also become part of any world problem, and hence proposed solutions that ignore any of these topics would be incomplete.

Expert systems software should manage critical aspects of a problem-solving session with a user in a way that provides a simple, integrated view of the problem-solving process. Our previous work on a papaya management system called PROPA (Itoga et al., 1990) that brought together multiple knowledge sources has been expanded to include investigation of more sophisticated systems for modeling and the use of these sources. In our previous work on a soil acidity expert system called ADSS (Yost et al., 1992), we developed a repertoire of programming algorithms. Now we are studying ways to meld these results into a software environment that supports the integration of separate components of knowledge.

In PROPA, we combined knowledge from the areas of soil science, botany, plant nutrition, plant pathology, and entomology and derived several hundred rules (knowledge statements) from these sources and about 50 for the manipulation of the information. The user can view this information in both textual and graphic format. Besides problem solving, PROPA allows users to review and print documents on topics pertinent to the papaya industry. From this work, basic questions about the nature of such highly interdisciplinary systems have been uncovered. Most of our current research is directed toward four objectives:

1. Investigate knowledge representation schemes that clarify the boundaries on specific knowledge components.

2. Explore ways to describe issues concerned with the focus and direction of cross-disciplinary panel discussions.

3. Analyze ways of describing solutions that are sensitive to well established heuristics and user objectives.

4. Study problem-solving issues in areas that lie near, on, or outside the boundaries of interdisciplinary knowledge sources; i.e., focus on ways to do interdisciplinary research.

Discussion

The first objective is to represent expert strategies in such a way that useful comparisons can be made. In the past we imposed a time-varying linear ordering on the relevance of expertise. Each source of expertise was assigned a numerical value representing this relevance. A low number near zero indicated little relevance to the current problem. A high number near one reflected much relevance. These numbers were modified during the execution of the program as the user provided more information. User interaction with the system always followed the problem-solving method of the most relevant knowledge source. This was not appropriate when several subordinate strategies supporting a common theme were more pertinent than the leading strategy. It did not allow for the possibility that a secondary strategy for the leading expert might coincide with those of some of the other experts. Currently, we are analyzing sets of compatible strategies and measures of relevance on these sets. Some of the attributes of strategies include algorithm types, information required from the user, steps to complete a session, and expected system performance (speed of execution, physical storage, hardware requirements). Experts identify their most prominent strategies and the corresponding requirements for user information. We are looking at heuristic algorithms (algorithms based on human intuition) to combine these data, system resources, and user goals to produce algorithms that perform well. Part of our research focuses on investigating ways to compare the performance of these algorithms.

The second objective is to study issues concerned with group dynamics that are present in panel discussions. In such discussions, one expert may defer to another when made aware of the importance of the current problem-solving step. Previously our models allowed experts to view only user information, not the current strategies of other experts, and now we are investigating models that quantify the importance of specific lines of questioning. Experts should be able to articulate strategies conditioned on the state of problem-solving of other experts. We are striving to allow an expert to propose weak strategies ("If no one has a better idea, I propose..."), and we are trying to accommodate the case where an expert has a strong hunch ("In that case, I think I know what the problem is.").

The third objective is to explore ways of capturing and comparing the importance of numerous problem constraints (information that limits the set of possible solutions). We want our diagnoses and recommendations to be correct, although these may not be verifiable. We want the system to minimize dangers to the user, although the possibilities of some of the dangers may be remote. We want the system to refrain from unnecessarily burdening the user with tedious questions, while achieving the previous two goals. These opposing goals suggest a need for a quantitative understanding of the user's objectives and relative preferences, so we would need to know whether the user wants a terse session that quickly identifies the most likely solution, or a protracted session that enumerates all possible solutions and provides accompanying explanations. We would also like the system to be machine-independent and thus be able to run on hardware with different memory attributes, disk capacity, and graphics capabilities.

The fourth objective is to study issues related to problem-solving at the boundaries of domain knowledge sources. This is a difficult problem for very specific topics; it is even more so for interdisciplinary work. We are looking for ways to detect and gracefully handle situations that are outside the experts' collective sphere of knowledge. In the past, the most relevant expert was selected to interact with the user, and this view of the problem determined the confidence that the system had to solve the problem. This simplistic approach was appropriate for most situations, but in highly interdisciplinary cases, we conjecture that more sophisticated schemes are required to handle the interactions among knowledge sources. Work on the first objective (strategy representation) is helping us to identify situations beyond the purview of the system.

Our designs are based on the model of independent processes working simultaneously on a problem while exchanging information and results. Our focus is on the programming algorithms that manage the separate problem-solving activities. Results on distributed computing (Durfee, 1988) (where work is spread over several computing systems), support our work on independent processing of knowledge sources. We are investigating using the message-passing concepts found in object-oriented programming concepts (OOPS) (Shriver and Wegner, 1987) to implement communication links among the experts and the attribute notions of objects to support the storage of hierarchical domain knowledge.

We are also concentrating on modeling the features of problem space and domain knowledge which was first done in the Heresay project (Erman et al., 1980), where the problem was broken into layers, and problem-solving was done at each level. This differs from our approach, where each expert has an independent view of the same user information. Moreover, we are investigating situations where experts have different goals in assisting users; that is, tailoring their responses to be correct, safe, inexpensive, or simple.

Long-Term Goals

Interdisciplinary activity will form a cornerstone of future expert systems development (Sigma Xi, 1988), which we support by our research on methodologies to unite diverse knowledge sources in a constructive manner. The goal is an environment that blends separately developed knowledge components into a seamless whole. Previously, the participation of experts scattered around the world was required (Yost et al., 1988), and much effort focused on collecting, integrating, and then disseminating this knowledge. Current work should ease the development process of similar systems that require the participation of experts located over a wide geographic region, by accessing the appropriate experts to produce better systems that address the needs of users.

This expert system environment would serve as a forum for the exchange of knowledge

among experts, so that within this environment, they would be exposed to viewpoints from other fields. The pros and cons of each decision would be clearly explained within the session objectives. To present a clean line of reasoning to the user, compromises would be made among the requests and needs of the individual knowledge sources.

Current Progress

From the research done in PROPA and ADSS, we are currently automating most of the activities that developed that system and developing shell-like tools for experts to articulate much of their knowledge. The initial goal is a prototype that handles the level of sophistication found in PROPA and ADSS and which addresses known weaknesses of PROPA in the areas of dialogue management and strategic planning.

Current work concentrates on designing tools to build screen designs, text and graphics windows, and menu systems. In addition, we are building facilities to capture and incorporate graphic images with software routines that aid in the construction of these routines for those tasks. In PROPA, the concept of worlds (Nakashima, 1984) separated the sources of knowledge in the systems, where a world was an independent database of knowledge information, and the facts and rules for each source were stored separately. In addition, two common worlds (called main worlds) of general facts and rules existed and access to these knowledge sources was provided through the use of blackboards (Nii, 1986a, b) (programming artifacts to allow the broadcasting of information to all components of a computer program). Ways of developing a routine to organize and control this information are now being investigated and this management routine should identify overlapping concepts among the sources and make the concepts accessible to all sources. For example, in PROPA, the disease and plant nutrition experts required plant age information in their analysis. Because there was enough overlap in their usage, a single concept was stored in the user blackboard and accessed by both knowledge routines.

In the past, where the concept of a moderator to manage multiple sources of knowledge was used, it derived its strength from its ability to judge the relevance of each knowledge source to the current problem. By studying ways of expanding this concept to work with sophisticated, multi-attribute data structures that capture this type of relevancy information, we can attempt, for example, to represent information on expert strategies. This would clarify the procedural objectives for a particular problem-solving approach by specifying the associated presumptions, necessary user information, and session requirements (time, quality of solution, source of expertise) for those strategies. Some of the basic questions that the moderator must address are:

1. How likely is an expert to contribute to a solution?

2. Is an expert's strategy compatible with that of other experts who are interested in this problem?

3. Are the resource requirements for an expert's strategy attainable and in keeping with the user's objectives?

4. Is there any physical or economic danger in overlooking an expert's contribution to the solution?

The notion of *relevance of expertise* is critical to our design of a moderator. Actual field testing in suitable farming situations can help us to evaluate this notion.

An additional goal is to improve the ability to identify and resolve conflicting requests by the experts. Fixed limits on the physical environment (disk space, graphics, RAM) and constraints on what users will tolerate exist for each problem. Even though experts may want extensive plant and soil laboratory analyses, complete historical records of all spraying activities, and data on other cultural practices, users may not be willing or able to obtain this information, or they may not think their goals require it. Previously, when the disease expert wanted a petiole analysis and the nutrition expert preferred a soil chemistry analysis, both, in principle, could be done at some expense of time and money. But if the user's goal is a straightforward solution, we may want to make recommendations without these data. Our approach analyzes ways of identifying overlapping strategies and combining them into a global one. Our objective is to ask questions in a manner that provides the knowledge sources with the information they need to continue their diagnoses. At every step of the session, the current strategy and the underlying individual expert strategies are accessible to users, so that users can modify the global strategy at anytime. For example, in PROPA, the plant nutrient expert usually wants information on the nitrogen, potassium, phosphorus, and calcium contents of plant tissues. In the current system, users may eliminate or re-order the list of requests for this information.

The moderator's role is to serve as an interface between users and experts. At the start of a session, it constructs a panel of experts that addresses the conditions given by the user. During the session this panel is constantly monitored to ensure that it can respond to all the issues. In the past, the moderator only worked with fixed-size panels, using initial user information to construct these panels and adjusting the relative importance of panel experts to reflect user information. In the current research, ways to allow the moderator to add and delete experts from the panel are being studied, with the moderator articulating the line of reasoning that recommended such actions.

Traditional expert systems provide explanation facilities that articulate an individual expert's reasoning. In addition to this facility, ways to show the moderator's strategy and conflict- resolution decisions are being explored, so users can query the system and find out why a session is progressing in a particular manner. This anticipates questions like: "Why in the world are you asking me that?" or "First you talk about...now you're talking about...why?" and allows users to alter the direction of the discussion at will. We foresee the situation where a user may start listing one set of goals, but may wish to change them during the session. For example, "Well, I first thought my problem was...but after listening to you, I now think..." where the planning activities of the moderator are made transparent to the user. In this manner, ways to help the user understand the rationale behind a particular line of questioning are being studied. In effect, moderators are treated as another source of expertise: expert at working with domain experts.

The development process outlined in Waterman (1986) is serving as a guide for observing the basic precepts of software engineering methodology. Within this framework, we are focusing on two stages of development.

Work on the first phase is to develop the expert system for phosphorus management in agriculture. Current work overlaps with portions of this phase, but the major effort will follow the formal evaluation from that phase. Since this is an entirely new endeavor for most of the investigators, we anticipate a steep learning curve.

The second phase is to develop a general architecture for the system. We are designing tools to handle the needs of the user interface (menus, windows, databases), moderator organization,

and knowledge capture. Since our needs for a user interface are modest, we are not dwelling on many issues of current interest. Similarly, the database requirements are well served by any of the currently available relational DBMS packages. The major task of this phase is to evaluate schemes to represent expert strategies and user and system constraints. We are developing algorithms to identify overlapping expert objectives, so experts are cognizant of each others' strategies. The primary objective is the design of a clear and complete system for handling the functions of the moderator.

In summary, our research is an interdisciplinary effort to investigate expert systems software development environments for interdisciplinary problem-solving. The results should extend our knowledge about the issues inherent in this area of knowledge-based systems and benefit agricultural and environmental scientists.

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Contact Person:

Stephen Itoga
Dept. of Information and Computer Science
University of Hawaii
2565 The Mall, Keller 310
Honolulu, HI. 96822

Telephone: 808-956-3494
Electronic Mail:
(BITNET) Itoga@uhunix.bitnet
(INTERNET) itoga@uhunix.uhcc.hawaii.edu

Writing Agricultural Software

W. Shaw Reid
Cornell University, Department of Soil, Crop & Atmospheric Science

Introduction

Commercial computer software has set very high standards for ease of use, instructions that are part of the menu system and programs that provide valuable, accurate, and timely information to the user. Since the introduction of desktop microcomputers, expectations for computer software have risen yearly in direct proportion to increased machine memory, speed and storage capacity, improved software development and increased user knowledge. These expectations place responsibilities on those who plan and implement a computer project.

Writing good agricultural software needs the same careful consideration that writing software for the non-agricultural environment does. Developers of agricultural software have an advantage in that the competition for commercial software is not acute. In most agricultural areas, computer programs compete more for user time and attention than they do with other software. In the past, work accomplished by agricultural software could be done better without computers, and therefore, it is necessary to remember that our potential Phosphorus Decision Support System (PDSS) user will require effort to learn to use the computer and the program. If PDSS is to succeed, it must be easy to use, provide information, and a service that is difficult to obtain in some other manner.

Planning the Project

The PDSS project needs careful planning. Some of the more critical components to include in the plan are: a) purpose of the program; b) the developmental environment; c) who and how the program will be used; d) when and how program will be documented; e) how a users manual will be prepared; f) how the program will be distributed and supported and g) what is the project goal. The more accurately and completely the plan is prepared, the fewer changes in the program that will have to be made and the faster it will be completed.

Purpose of the Program

The PDSS program should be developed carefully and completely before any code is programmed. PDSS still suffers from an incompletely developed mission statement. For example, is PDSS to make P recommendations for the grower on any soil in the world, or is it only to provide educational materials to the agronomist in countries where TropSoils has worked? One of the reasons for uncertainty in this area is the increasing capabilities of decision support systems and, concomitantly, our increasing level of effectiveness in using them to provide information on soils. We realize PDSS needs to keep pace with these increase capabilities, and this illustrates why planning is of vital importance.

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The Developmental Environment

A number of factors influence the developmental environment. The size of the project and the type of data are two of the more important. Minimum and standard hardware requirements for the program should be decided as part of the overall plan. The minimum configuration would be a 640K IBM P-C™ or IBM-compatible computer with a 20 megabyte hard disk and an EGA monitor. Certain features of PDSS would probably not be available to the user without this hardware. Thus, the program requires some type of configuration software to determine the equipment available and how to best handle the minimum hardware restrictions.

Program Use

Program use influences the type of interface, help system and speed of operations that are desirable. A program which is not used more than a few days a month, or one which is used frequently but with long stretches of non-use in between, needs both a visual menu system and menu bypass commands. For a program used occasionally, access only through a menu system is adequate. One that is used frequently, but intermittently, however, needs a menu program for instructions at first and then a bypass menu once these instructions are learned and remembered.

Program Documentation

Program documentation is like record-keeping and needs to be started during the program planning stages. Properly written program plans provide excellent introductions for program documentation. The documentation needs to be written for the user as well as for the system programmer, and it is important to document the purpose of the program, as well as the individual program components.

Users Manual

The users manual provides a good first impression to users. It should be well written in non-programmer's language with excellent examples for using the program. Likewise, it should be started during the planning process. The users manual can teach people about the program. For example, we are examining the possibilities of putting digitized color photos of the nutrient deficiency symptoms in PDSS. This would require a large amount of disk space. Photos could be placed in the users manual and referenced in the program, which would save disk space and still give the user detailed and accurate illustrations to assess nutrient deficiency.

Distribution and Support

Software distribution often influences how the software is written, and it certainly influences how the software is packaged. It is often desirable to package the software with the manual, on disk. This type of packaging, however, does not permit using color photos in the manual to serve as a reference to the software for the user. The distribution method needs to be planned in the early stages of program development.

A program such as PDSS also requires user support. The amount of support available should be stated in the software documentation. If good manuals are prepared, it will decrease the amount of support needed, but will not eliminate it.

Project End

Every project should have a planned end. With software, there is always something that can be improved, made faster, more efficient or made to do better things. A deadline and schedule should be planned, and additional improvements slated for another project.

User's Reactions

Most commercial software evaluation is based upon a user's first look at the package. In many cases, this is the first screen the user sees. To obtain a favorable first impression, PDSS must have easy loading and setup, an attractive opening menu that provides sufficient information to use the program and sufficient defaults so that an example can run with minimum effort.

The User Interface

A program's easy interface with a user makes a favorable first impression. PDSS must provide an easy way to navigate through the program and a quick and easy method to quit. One of the more annoying quirks of many programs is having to back all the way out of the deepest menus to quit. With careful planning, quitting PDSS can be made easy from anywhere within the menu system. Also, a consistent method of moving through the program is necessary.

A frequent user of PDSS will not want to go through many levels of menus to be able to run the program. Therefore, a fast movement method is necessary. The occasional user and the novice must have menus. Examples of these types of interfaces are common in spreadsheet and or database software. A PDSS user will appreciate and expect attractive and efficient interfaces.

Help

Because users tend not to read manuals, an on-line context sensitive help system should be a part of PDSS. Most educational software has a two-level help system. The two levels consist of a program help system explaining how to use the program, and an educational help system providing information on the "agronomy" within the program. Good help systems are appreciated, especially by the novice and infrequent user. Beyond initial training, help systems are of limited usefulness to the expert user.

Educational Information

We need to ask ourselves what information and types of information should be included in PDSS. This is often difficult to decide. Information that can be garnered from a small table to make a data conversion should not be included. Information stored in very large databases needed to make decisions should be included in PDSS. Likewise, if we are going to use information to make further decisions or computations within a program, these data should be included. For example, to convert from pounds to grams of weight, it is seldom worth the effort to start up a computer program to look up the conversion factor and make the multiplication. We can use

the calculator faster. But if we want to compute the corn yields in kilograms from several measurements in ounces and then run a statistical analysis on the data, it is worthwhile to include the conversion factors within the program.

A computer program that estimates and/or evaluates information beyond a user's capability is certainly one of the appropriate uses of software. PDSS should be able to both estimate an answer and give some indication of the confidence or accuracy we have in that answer. This permits us to use what we know, what we can obtain from the user, and any relationships we can estimate in providing the best information. This approach depends upon many factors, such as the accuracy the program can provide, relative accuracy required, the consequences suffered if the answer is incorrect, user knowledge, other sources of information, and the ability to improve the answers with better data. These factors accurately describe using PDSS to predict P fertilizer requirement. PDSS should be able to predict the P required better than the user and the consequences of being wrong are not likely to be life threatening. If the user knows that a PDSS answer is incorrect, he/she can improve the predictions by providing better information to the program. A difficulty with system programs is in determining the relative accuracy of the data. The user needs to be provided with an estimate of the program's accuracy and the need for precise information relative to his knowledge.

Evaluations and Updates

PDSS needs to be evaluated by users at various levels of computer competence and educational skills and experience, with the expectation that changes will be made.

Once the program is up and running, packaged and distributed, will improvements be made? If so, how will users be informed of the improvements. How can the user obtain an updated copy of the software? Answers to these questions need to be decided well before the project has been completed.

Some Useful Features

There are several features that have proven helpful to the author.

1. A sign-on screen explaining briefly what the program does and giving names and addresses of the contact for support is helpful. Also helpful are instructions on how to start, customize and quit the program.

2. A sign-off screen asking if the user really wants to quit. The sign-off screen should list the options for saving any data. It should tell where the data is to be stored, how to restart the program using the saved data and how to make backup copies.

3. The program should not lose information beyond incomplete input caused by a power failure. Likewise, the user should be able to restart the program and pick up data analysis where he left off.

4. A word processor type (page text) editor for major corrections to the user files is a must for efficient input.

Summary

Programming for the agricultural software market requires, basically, the same types of programming skills as for any other market. PDSS must permit the user to accomplish work easier, faster, and better than without it. In addition, PDSS must allow the user to accomplish tasks in about the same amount of time as he would without a computer. PDSS should be a tool that enables a user to do better work, while it teaches him something about soils and helps to produce a better crop for the farmer.

Contact Person:

W. Shaw Reid
Cornell University
Department of Soil, Crop and Atmospheric Science
Ithaca, NY 14853
Telephone:

Appendix: Discussion, Summary And Workshop Recommendations

Several questions were considered during the final session of the work shop. Among those questions were the following:

1. Who Are the Intended Clientele of the PDSS (Phosphorus Decision Support System)?

The people we expect to use the system first are the agronomists/soil scientists who can validate the diagnostic approach and the recommendations for their region, provide us with feedback on its suitability, and to oversee its application in their region if they find the software useful and acceptable. Hopefully, these people would continue to informally support other users in the region and would also inform us on the performance of the system, needed changes, and suggested improvements. Others who might use the system include non governmental organizations such as consultants, policy makers, Peace Corps volunteers who are in close contact with farmers. In short, all those who need site specific, expert knowledge to help make crop management decisions.

2. Is There Some Continuity Between the Various Systems that TropSoils is Developing?

For example, are there some common features between the ADSS and the PDSS systems? We seek to present a unified interface to the users. This might be done using a common set of data, for example, we anticipate using the same soil data base (which, by the way has been generously contributed by the SCS and SMSS) for all systems. The specific soil database can be altered to include local data and other irrelevant data excluded. We are considering developing a training kit on how to make this sort of local adaptation. We are trying to think about the future in terms of databases that might not only support the PDSS and ADSS but other decision-aids, including those developed by other institutions – TropSoils and otherwise.

3. How Do We Deal With the Highly Variable Availability of Data to Determine the Best P Management?

We expect a wide range in availability of data: soil, crop, support information has been considered in developing PDSS. This is one reason we have separated diagnosis from recommendation. We do not want the lack of a soil test, which many poor farmers do not have, to keep the user from continuing with the diagnosis. The minimum data set to achieve a diagnosis or to make a recommendation is called the 'minimum dataset' a concept supported by the IBSNAT Project. We have defined the 'minimum dataset' for the PDSS to meaningfully

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diagnose and recommend P management. Far less data as well as data of a different sort are needed for these two phases of problem- solving (diagnosis and recommendation). We believe a useful inference can be obtained by comparing previous crop yields with regional norms, together with previous P fertilization history, and the likelihood of P deficiency in the region due to the soil classification, type of mineralogy, etc. If these factors point to a deficiency then more definitive analysis such as plant and soil analysis are considered if available or recommended if not available. From time to time the observational information may not lead to the correct diagnosis and for this we have given the various sources of information individual ratings reflecting relative impact on the weight of evidence for or against a deficiency. We consider the time and convenience involved in the diagnosis. Experience shows that a 75 to perhaps 95 percent sure diagnosis can be obtained by both soil and plant analyses, but practical reality is that probably 95 percent of the farmers in West Africa will never have both plant and soil analyses on their crops. Consequently, a balance between practical problem-solving and perfection in diagnosis must be struck. Our struggle is to ascertain this balance in the TropSoils regions.

4. What Do We Really Want PDSS to Do?

The goal is to provide the knowledge TropSoils scientists take for granted, accessible to the largest possible audience. PDSS is one way of integrating soil, crop, economic knowledge and making it portable and accessible to users. Of first priority is the ability to diagnose P deficient situations represented by the TropSoils' regions. This is, in part, due to our conviction that there are many situations where a significant P response can be obtained but the local growers, farmers, and extension people don't realize it. Thus we believe that there are numerous situations where an economic benefit is possible but it goes undetected due to lack of experience and lack of knowing what to look for. We also believe that there are many facets of P fertilization that both agricultural planners and agriculturists may not realize: the P buildup phenomena, P residual effects, the tremendous variation in P requirement due to varying soil properties, the huge differences in P requirements among the agricultural crops, and finally the impacts of all of these factors together on an economic analysis that considers residual effects. It is clearly a big job to present all this information in a coherent, usable fashion, but we think that it is possible using knowledge engineering principles and practices. Said another way, we want PDSS to help improve the diagnosis of yield limiting and of economically inefficient P management (either too little or too much P fertilizer application). By means of step by step procedure of examining the data and observations we expect to be teaching fertilization diagnosis and recommendation. The review literature contained in the system will have the express purpose to describe the principles behind the approach. In addition, we expect that the groundworks 2, the supplementary manual, will be designed to provide an overview of the concepts involved in P fertilization and management as well as provide helpful suggestions to diagnose P deficiency.

Storing Global Data

I'm not sure we are emphasizing this so much. Of importance, however, is for us to store the user's field data and history. I think we'll also be providing a mechanism for collecting, collating, and analyzing the field data if a group of users seeks to combine their specific data. This will probably be done in the form of a database management system. By our requesting data we are already identifying research gaps in phosphorus management for a region. But research gaps can include both problems of insufficient data but also of failure of the methodology to successful diagnose or to incorrectly recommend. These methodology failures are the research gaps that will need attention.

Economic Analysis Module

We are explicitly developing an economic analysis module that will be unique in that it will provide an economic analysis far beyond that usually provided by agronomists soil scientists -- it will explicitly consider residual effects, opportunity costs, and permit site specific evaluation of trade-offs of whether it is better to apply large amounts of P now and wait for residual benefits or whether gradual buildup of available P is better. The overall combination of soil, plant, observations, historical data with a realistic economic analysis should permit a new level of 'what if' analysis for planners, extensionists, and researchers.

5. What Are the Plans to Verify the Diagnoses and Recommendations of PDSS?

The verification of deficiency diagnoses and of generating appropriate recommendations is already under way. This is first being done with the key data sets that we use in developing the program. As we have more and more people test and compare the program results with their own we will be exactly verifying the diagnoses and the recommendations.

6. How Will the Software Be Distributed?

We have decided to proceed with a distribution of the ADSS software through the Winrock Software Distribution program. The ADSS will be appearing in their promotional literature and will be available for a small fee. It is intended that the funds will be returned to the TropSoils program.

7. What is Required to Include Nitrogen Diagnosis and Recommendations With PDSS?

We are seriously considering this in another project at the University of Hawaii. The objective of the other project is to explore ways of combining rather different diagnostic information and recommendations as an integrated unit. This becomes challenging when there is ambiguity in the diagnosis and insufficient data to resolve the ambiguity. Dr. Itoga is particularly interested in these sort of problems and has research that should provide some assistance in combining other systems such as a NDSS together with the ADSS and PDSS. One current limitation is the memory capacity of the PC is not sufficient to handle all of this information simultaneously.

8. Data Necessary to Diagnose and Develop a Recommendation Using PDSS.

Diagnosis: From Most Reliable (1) to Least Reliable (5):

1. Soil analysis, plant analysis
2. Presence of typical deficiency symptoms
3. Previous crop yields that were quite high (indicates no problem)
4. Soils being known to be P deficient and no known fertilization
5. Presence of plants whose presence suggests P deficiency

Any of these observations, except #5, is considered sufficient for a diagnosis.

Data Needed For a Recommendation:

1. Intended crop (crop P requirements vary with crop)

2. Existing soil test P level by a recognized P extractant (usually Mehlich 1 or 3, Bray 1, Olsen, Truog, or resin)

3. Buffer coefficient for the soil (relates P added to the increase in soil test P) (We are trying to develop a predictive equation to estimate buffering coefficient from soil properties such as clay content and soil mineralogy).

9. Major Information Gaps So Far Identified In the Development of the PDSS:

1. Buffer coefficients have been empirically estimated by those calibrating soil tests. There is, so far, relatively little effort in predicting buffer coefficients from soil properties.

2. Rates of decline of available P with time is of prime importance in evaluating the economic benefit to P fertilizer additions.

3. How critical levels of P from various extractants for various crops vary with soil properties.

4. A method is needed that will permit an economic evaluation that explicitly considers P residual effects (perhaps a dynamic programming approach).

These Questions Were Discussed and the Above Thoughts Were Recorded.

Several Specific Actions Were Taken:

1. It was decided to proceed with "Groundworks 2" publication, which follows the ADSS publication "Groundworks 1," which explains the concepts of acid soils and their management.

2. Mr. Tim McBride will draft the "Groundworks 2" outline and circulate for comments.

3. A preliminary release of PDSS will be targeted for the summer of 1992.

Notes: