Fertilizer phosphorus: sorption and residual value in tropical African soils (NRI Bulletin 37)

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Bulletin 37

FERTILIZER PHOSPHORUS SORPTION AND RESIDUAL VALUE IN TROPICAL AFRICAN SOILS

Overseas
Development
Administration

FERTILIZER PHOSPHORUS: SORPTION AND RESIDUAL VALUE IN TROPICAL AFRICAN SOILS

G. P. Warren
(University of Reading)

Bulletin 37

NRI
Natural Resources Institute

The scientific arm of the
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Abbreviations

Al	aluminium
Al_d	aluminium oxides extracted by sodium citrate/dithionate/ bicarbonate
Al_{ox}	aluminium oxides extracted by acid oxalate
C	carbon
Ca	calcium
$Ca(H_2PO_4).H_2O$	monocalcium phosphate
CEC	cation exchange capacity
CIAT	Centro Internacional de Agricultura Tropical
conc	concentrated
EP	external P
FAO	Food and Agriculture Organization of the United Nations
Fe	iron
Fe_d	iron oxides extracted by sodium citrate/dithionate/ bicarbonate
Fe_{ox}	iron oxides extracted by acid oxalate
FP	fertilizer P
FYM	farmyard manure
h	hour
ha	hectare
IAEA	International Atomic Energy Agency
IFDC	International Fertilizer Development Corporation
ISMA	International Superphosphate and compound Manufacturers' Association
K	potassium
kg	kilogram
l	litre
LP	labile P
Mg	magnesium
mg	milligram
min	minute
ml	millilitre
N/N_2	nitrogen
$NaHCO_3$	sodium bicarbonate
nm	nanometre
NRI	Natural Resources Institute
ODA	Overseas Development Administration
^{32}P	phophorus-32 (a radioactive isotope)
P	phosphorus – (see Introduction)
P_2O_5	phosphorus pentoxide
PE	effective P
ppm	parts per million
PR	phosphate rock
PU	P uptake
rpm	revolutions per minute
S	sulphur
soln	solution
SP	stable P
SPR	standard P requirement
SSP	single superphosphate

t	tonne
USA	United States of America
USDA	United States Department of Agriculture
VAM	vesicular arbuscular mycorrhizas
vol	volume
Y	dry matter yield

Summaries

SUMMARY

African soils are commonly short of phosphorus (P). Additions of fertilizer P can increase yields on most soils which have not previously received additional P. Agroforestry and management of mycorrhizas have the potential to improve the P nutrition of crops in tropical Africa but they cannot, however, replace P removed in additional crop yields. This review deals with two main problems:

- Assessment of fertilizer P requirements (Sections 1-4)
- Residual effects of fertilizer P (Sections 5-8).

Assessment of fertilizer P requirements

The use of an extractant to predict crop response to P is likely to be most successful in a region where soils are similar in nature but of varying fertilization and cropping history. Where agriculture has involved the use of fertilizer (including manures, phosphate rock and fallowing) available residual fertilizer P can be assessed by a simple extractant. The amount of extractable P has to be calibrated against yield and/or response to fertilizer in regional field trials. The reagent of Olsen (0.5M $NaHCO_3$) has proved to be suitable for assessing residues in calcareous soils; other common reagents such as those of Bray and Mehlich are more appropriate in acid soils.

Measurements of phosphate sorption are a useful way of taking into account the soil properties that determine fertilizer P needs. Data now available show that P requirements vary greatly in tropical African soils. The highest P requirements are found in volcanic ash soils, rich in disordered minerals such as allophane, as found elsewhere in the world. Volcanic ash soils are important locally but large areas, especially in West Africa, are dominated by soils with low phosphate sorption capacity. Poor availability of fertilizer P is not a widespread problem in these soils, comprising alfisols, some ultisols (United States Department of Agriculture, USDA, classes) and all sandy soils, and equivalent soil types in other classification systems. Modest applications only are needed, perhaps 25-50 kg/ha P for maximum yield, and the economic applications for optimum return will be less than that. Phosphate sorption is often correlated with the clay content of the soil.

Crop responses to P and phosphate sorption are related to soil type. Phosphate sorption and hence P requirement tend to follow the order oxisols > ultisols > alfisols > entisols. Inceptisols may show a particularly wide range, since their classification is not dependent on inherent chemical properties. There is great variation within soil classes and wide overlap between classes.

Residual effects of fertilizer P

Field experiments in tropical Africa show that residual fertilizer P normally gives significant yield increases in the first year or two after application. If an experiment is extended without further P addition, the residual effects can be shown to last for several years. The sum of the residual responses is likely to exceed the direct response within two or three years after application. Numerical assessment of the residual value is difficult because the size of the response depends on (a) control yield and (b) potential response, both of which fluctuate between seasons, and (c) the rate of fertilizer application. The residual effect of a low rate of fertilizer P lasts a shorter time than a high rate because the fertilizer is depleted more quickly by crop uptake.

All crops that have been tested can use residual P. Most work has used maize and groundnuts and there appears to be no difference between them. There is some evidence that the residual value differs between soils within Africa and elsewhere in the tropics. Residual effects can equal the direct response but appear small in some soils. It is not possible to relate residual value to soil properties at present, but strong phosphate sorption and a consequent high fertilizer P requirement is not incompatible with good residual effects, at least in soils rich in iron minerals. Good residual effects are also found in flooded soils. Differences in residual effects are not clearly associated with particular climates or farming systems but, because of experimental variability, it is difficult to quantify the residual value in a single experiment.

Results of a single experiment are specific to the soil, site and weather conditions and are of limited use for extrapolation to other locations. Mathematical models are used to make a numerical rationalization of the results, such that they can be summarized in a few parameters which describe the influences of soil, climate and management on the crop. Adjustment of the parameters should then enable the model to describe a wide range of conditions so that experimental results can be extrapolated to other sites. Simple yet adequately realistic and precise models for P residual value have been developed recently and could be applied to African conditions.

The requirements for the application of such models are (a) measurement of the direct and residual effects of fertilizer P by field experiment at a small number of key sites over at least three years and (b) measurement of relevant soil properties. In particular, phosphate sorption is related to the direct response and soil mineralogy appears to influence the residual value. These measurements are needed at the experimental sites and to characterize soils regionally. As a tentative guideline, it is suggested that soils with a standard P requirement (SPR, defined as phosphate-P sorbed at a solution concentration of 0.2 mg/l P in a laboratory experiment) less than 200 mg/kg P are low sorbing for this purpose. Quantification of the residual value is necessary and at present this can only be done by field work. When more data become available, definitions of high and low residual value should become possible. It may then be possible to use standard values of the parameters related to soil classification and properties to predict the future effects and full value of fertilizer P.

Modelling studies indicate that for low-input systems, different fertilization strategies may be more appropriate for different soil types. The efficiency of soluble fertilizer P is unaffected by variations in annual fertilizer additions in soils with a good direct efficiency and high residual value. Thus, if fertilizer application is excessive, deficient or completely omitted in one year, the fertilizer will not be lost or wasted, but overall will continue to be useful. If, however, the P residual value is low, then it is important to keep supplying P every year or the overall efficiency of fertilizer application is reduced. If the soil has a low direct efficiency for fertilizer P but high residual value, opportunities exist for improvement of the efficiency of fertilizer use by unequal distribution of fertilizer P over the years of a cropping programme.

Modelling indicates that the use of partly soluble fertilizer, such as phosphate rock or partially acidulated rock, can sometimes improve efficiency and the effects are particularly beneficial in soils with a low residual value. The potential for improvement appears best with rocks of intermediate solubility.

RÉSUMÉ

On observe fréquemment la pénurie en phosphore (P) dans les sols africains. Les adjonctions d'engrais P peuvent augmenter les rendements sur la plupart des sols n'ayant auparavent pas reçu de P complémentaires. L'agroforesterie et la gestion des mycorhizes présentent un potentiel d'amélioration de la nutrition en P des cultures en Afrique tropicale mais ils ne pouvent pas, toutefois, remplacer P, qui a été enlevé des rendements supplementaires des cultures. Ce document passe en revue deux problémes principaux à savoir:

- Evaluation des exigences en matière d'engrais P (Sections 1-4)
- Effets résiduels de l'engrais P (Sections 5-8)

Evaluation des exigences en matière d'engrais P

L'utilisation d'un réactif pour prévoir la réaction des cultures à P sera vraisemblablement la plus réussie dans une région où les sols sont de nature similaire, mais ayant des antécédents différents en matiére de fertilisation et d'assolement. Lorsque l'agriculture a fait intervenir l'utilisation d'engrais (y compris les fumures, phosphates et jachères) l'engrais P résiduel disponible peut alors être évalué grâce à un simple réactif. Il est nécessaire d'étalonner le volume de P extractible en regard du rendement et-ou de la réaction à l'engrais dans des essais régionaux sur le terrain. Le réactif d'Olsen (0.5M $NaHCO_3$) s'est avéré excellent pour l'évaluation des résidus dans les sols calcaires et d'autres réactifs, ceux de Bray et Mehlich par exemple, conviennet dans les sols acides.

Les mesures d'adsorption de phosphate constituent un méthode utile permettant la prise en compte des propriétés des sols, propriétés qui déterminent les besoins en engrais P. Des données désormais disponibles montrent que les exigences en engrais P sont trés variables dans les sols africains tropicaux. Les exigences en P les plus élevées sont observées dans les sols de cendres volcaniques, riches en minéraux désordonnés, tels que l'allophane, comme il est observé ailleurs dans le monde. Les sols à cendres volcaniques sont localement importants, toutefois les larges superficies, et plus particuliérement en Afrique occidentale, sont dominées par des sols caractérises par une faible capacité d'adsorption en P. La faible disponibilité de l'engrais P dans ces sols ne constitute pas un problème répandu, ces sols comprenant les alfisols, certains ultisols (classes USDA) ainsi que tous les sols sableux et les types de sols équivalents dans d'autres systémes de classement. Seules des applications modestes sont exigées; allant peut-être de 25-50 kg/ha P pour obtenir le rendement maximum, et les applications écononiques pour obtenir un résultat optimum seront inférieures à ce chiffre. L'adsorption en P est fréquemment mise en corrélation avec la teneur en argile du sol.

Les réactions des cultures à P et l'adsorption de phosphate se rattachent au type de sol. L'adsorption de phosphate et les besoins en P par conséquent, ont tendance à suivre l'ordre oxisols > utisols > alfisols > entisols. Les inceptisols peuvent montrer une plage particuliérement large, du fiat que leur classement ne dépend pas de leurs propriétés chimiques propres. Il existe une importante variation au sein des classes de sols et un large chevauchement entre les classes.

Effets résiduels de l'engrais P

Les expériences sur le terrain exécutées en Afrique tropicale ont montré que l'engrais P résiduel fournit d'ordinaire des augmentations significatives de rendements lors de la première ou de la deuxième année après l'application. Si l'expérience est prolongée sans adjonctions complémentaire de P, il peut être démontré que les effets résiduels durent pendant plusieurs années. Il est vraisemblable que la somme des réactions résiduelles dépassera la réaction directe dans les deux ou trois années résiduelles. L'évaluation numérique de la valeur résiduelle est complexe car l'envergure de la réaction dépend (a) du rendement témoin (b) de la réaction potentielle, tous deux étant variables selon les saisons et (c) du taux d'application de l'engrais. L'effet résiduel d'un faible taux de l'engrais P dure moins longtemps qu'un taux élevé car l'engrais est épuisé plus rapidement par suite de son absorption par les cultures.

Toutes les cultures ayant fait l'objet de tests peuvent utiliser le P résiduel. Les travaux ont en grande partie porté sur le maïs et l'arachide et il ne semble y avoir aucune différence entre ces cultures. Il existe certaines preuves que la valeur résiduelle varie entre les sols, en Afrique et ailleurs dans les régions tropicales. Les effets résiduels peuvent être égaux à la réaction directe, mais semblent faibles dans certains sols. Il n'est pas actuellement possible de rattacher la valeur résiduelle aux propriétés des sols, toutefois une forte adsorption de phosphate et un besoin élevé en engrais ultérieur ne sont pas incompatibles avec de bons effets résiduels, du moins dans les sols riches en minéraux ferreux. Il est aussi observé de bons effets résiduels dans les sols inondés. Les écarts entre les effets résiduels ne sont pas clairement associés à des climats ou systèmes d'exploitation agricole particuliers mais, en raison des écarts entre les expériences, il est difficile de quantifier la valeur résiduelle dans une seule expérience.

Les résultats d'une seule expérience sont spécifiques au sol, au site et aux conditions météorologiques et n'ont qu'un emploi restreint pour l'extrapolation des conclusions applicables à d'autres sites. Il est fait appel aux modèles mathématiques pour exécuter une rationalisation numérique des résultats, de sorte qu'ils puissent être récapitulés dans quelques paramètres décrivant les influences exercées sur la culture par le sol, le climat et la gestion. L'ajustement des paramétres doit alors permettre au modéle de décrire une gamme étendue de conditions, de sorte à permettre l'extrapolation à d'autres sites des résultats expérimentaux. Il a récemment été élaboré des modéles simples, mais néanmoins suffisamment réalistes et précis pour la valeur résiduelle de P et ces modéles pourraient être appliques aux conditions en Afrique.

Les exigences en matière d'application de tels modèles sont (a) la mesure des effets directs et résiduels des engrais P au moyen d'expériences de terrain dans un petit nombre de sites clés pendant au moins trois années et (b) la mesure des propriétés pertinentes des sols. L'adorption de phosphate, en particulier, est rattachée à la réaction directe, et il semble que la minéralogie des sols exerce une influence sur la valeur résiduelle. Ces mesures sont exigées sur les sites expérimentaux et pour caractériser les sols à titre régional. Il est suggéré, à titre de directive provisoire, que des sols ayant un besoin standard en P (SPR, ce besoin étant défini en tant que phosphate P adsorbé à une concentration de solution de 0.2 mg/1 dans une expérience en laboratoire), inférieur à 200 mg/kg, sont de faible adsorption dans ce but. La quantification de la valeur résiduelle est nécessaire et, à l'heure actuelle, elle ne peut être effectuée qu'au moyen de travaux sur le terrain. Lorsque davantage de données seront disponibles, il devra être possible d'obtenir des définitions de la faible et haute valeur résiduelle. Il pourra alors être possible d'employer les valeurs standards des paramètres, rattachées au classement et aux propriétés des sols pour calculer les prévisions des effets futurs et la valeur totale de l'engrais P.

Les études de modélisation indiquent que dans le cas des systémes à faibles apports, des stratégies d'application d'engrais différentes pourront être préférables pour les divers types de sols. L'efficacité de l'engrais P soluble est insensible aux variations des adjonctions annuels d'engrais dans les sols présentatnt une bonne efficacité directe et une valeur résiduelle élevée. Ainsi, si l'application d'engrais est excessive, insuffisante ou totalement absente pendant une année, l'engrais ne sera ni perdu ni gaspillé, mais il continuera généralement à être utile. Si, toutefois, la valeur résiduelle de P est faible, il est alors important de maintenir l'application de P chaque année, car on réduit sinon l'efficacité globale de l'application de l'engrais. Si le sol présente une faible efficacité directe pour l'engrais P mais une valeur résiduelle élevée, il existe alors des possibilités quant à améliorer l'efficacité de l'emploi d'engrais grâce à la répartition inégale de l'engrais P au cours des années d'un programme de culture.

La modélisation indique que l'utilisation d'engrais partiellement soluble, phosphate ou phosphate partiellement acidulé par exemple, peut parfois améliorer l'efficacité et que les effets sont particulièrement salutaires dans les sols présentant une faible valeur résiduelle. Il semble que le potentiel d'amélioration optimum se situe avec les phosphates de solubilité intermédiaire.

RESUMEN

Por regla general, las tierras de Africa manifiestan escasez de fósforo (P). La adición de fertilizantes fostatados puede incrementar las producciones de los cultivos en la mayoría de los suelos que anteriormente no han recibido fósforo adicional. La agrosilvicultura y manejo de micorrizas poseen el potencial para mejorar la nutrición fósforica de los cultivos en el Africa tropical sin embargo, estos no reemplazan el fósforo removido debido a los rendimientos adicionales. Esta revisión enfoca dos problemas principales:

- Evaluación de los requerimientos de fertilizantes fosfatados (Secciones 1-4)
- Efectos residuales de los fertilizantes fosfatados (Secciones 5-8)

Evaluación de los requerimientos de fertilizantes fosfatados

Es probable que el empleo de un extractor para predecir la reacción del cultivo al fósforo sea particularmente satisfactorio en regiones en donde los suelos son de naturaleza similar, pero con un historial distinto de fertilización y de cultivos. En aquellos lugares en que la agricultura ha llevado consigo el empleo de fertilizantes (incluyendo estiércol, roca fósforica y barbecho), será posible establecer la disponiblidad de fertilizante fosfatado residual mediante el empleo de un sencillo extractor. Deberá calibrarse la cantidad de P extraíble contra el rendimiento y/o la respuesta al fertilizante en las pruebas regionales sobre el terreno. El reactivo de Olsen (0,5M $NaHCO_3$) ha demostrado ser de utilidad en la evaluación de residuos de tierras calcáreas, mientras que otros reactivos comunes, tales como los de Bray y Mehlich, son más apropiados para suelos ácidos.

Las mediciones de la absorción de fosfato son un método útil de tomar en consideración las propiedades del suelo, que determinan las necesidades de abonos fosfatados. De acuerdo con datos disponibles hoy en día los requerimentos de fósforo varían considerablemente en los suelos tropicales africanos. Los más altos requerimientos de fósforo se encuentran en los suelos constituidos por cenizas volcánicas, ricos en minerales desordenados, tales como la alófana, al igual que en otras partes del mundo. Aunque las tierras de cenizas volcánicas poseen importancia local, existen grandes extensiones, particularmente, en el Africa Occidental, dominadas por suelos con baja capacidad de absorción de fósforo. Una baja disponibilidad de abonos fosfatados no es un problema generalizado en estas tierras, constituidas por alfisoles, algunos ultisoles (clases USDA) y todas las tierras arenosas, así como en los tipos de suelos equivalentes en otros sistemas de clasificación. Las aplicaciones requeridas para obtener un rendimiento máximo son modestas – tal vez entre 25-50 kg/ha P y las aplicaciones económicas para la obtención de beneficios óptimos será todavía menores. A menudo, la absorción de fosfato se halla relacionada con el contenido de arcilla en el suelo.

La respuesta de los cultivos al P y la absorción de fosfato guardan relación con el tipo de suelo. La absorción de fosfato y, en consecuencia, los requisitos de fósforo tienden a seguir el orden de oxisoles > ultisoles > alfisoles > entisoles. La gama de absorción de los inceptisoles puede ser particularmente amplia, debido a que su clasificación no depende de las propiedades químicas inherentes. Existe gran variación entre clases de suelos y una superposición generalizada entre clases.

Efectos residuales de los fertilizantes fosfatados

Los experimentos de campo en el Africa tropical muestran que, por regla general, los fertilizantes fosfatados residuales proporcionan incrementos significativos en el rendimiento en el primero o dos primeros años después de la aplicación. Cuando el experimento se prolonga sin nueva aplicación de fosfato, los efectos residuales pueden mostrarse por varios años. Es probable que la suma de las respuestas residuales exceda la respuesta directa en dos o tres años después de la aplicación. Resulta difícil realizar una evaluación numérica de los valores residuales, debido a que la magnitud de la reacción depende de (a) el rendimiento del control y (b) la respuesta potencial, factores que fluctúan de una temporada a otra, y (c) el porcentaje de aplicación del fertilizante. El efecto residual de un bajo porcentaje de fertilizante fosfatado dura un tiempo más corto que la aplicación de un porcentaje elevado, ya que el abono es absorbido con mayor rapidez por los cultivos.

Todos los cultivos que han sido probados pueden utilizar fósforo residual, habiéndose realizado la mayor parte de los trabajos con maíz y cacahuetes, sin que parezca existir diferencia alguna entre ellos. Existen indicios de que el valor residual difiere entre suelos, tanto en Africa como en otras partes de los Trópicos. Los efectos residuales pueden ser iguales a la respuesta directa, pero parecen ser reducidos en algunos suelos. En la actualidad, no es posible relacionar el valor residual con las propiedades de los suelos, pero una fuerte absorción de fosfato y el consecuente alto requerimiento de fertilizante fosfatado es compatible con buenos efectos residuales, al menos en suelos ricos en minerales de hierro. También se han observado buenos efectos residuales en tierras de inundación. Si bien las diferencias en efectos residuales no están claramente asociadas con climas o sistemas agrícolas determinados, dada la variabilidad experimental, resulta difícil de cuantificar el valor residual en un solo experimento.

Los resultados de un solo experimento son específicos para el suelo, emplazamiento y condiciones meteorológicas, siendo de valor limitado para poder extrapolar las conclusiones a otras ubicaciones. Se utilizan modelos matemáticos para conseguir una racionalización numérica de los resultados, de manera que puedan resumirse en un reducido número de parámetros, que describan las influencias del suelo, clima y gestión sobre el cultivo. En consecuencia, el ajuste de los parámetros podría hacer que el modelo describiera una amplia gama de condiciones, con objeto de que los resultados experimentales puedan ser extrapolados a otros sitios. En fechas recientes, se han desarrollado modelos sencillos, precisos y adecuadamente realistas para el valor del fósforo residual, que podrían tener aplicación en las condiciones africanas.

Los requisitos para la aplicación de dichos modelos son (a) la medición de los efectos directos y residuales de los fertilizantes fosfatados mediante experimentos de campo en un pequeño número de emplazamientos clave, durante un período mínimo de tres años y (b) la medición de las propiedades relevantes de los suelos. En particular, la absorción de fosfato se halla relacionada con la respuesta directa, mientras que la mineralogía del suelo parece influenciar el valor residual. Estas mediciones se necesitan en los sitios experimentales y para la caracterización de los suelos a nivel regional. A manera de directriz aproximada, se sugiere que tierras con un requerimiento estándar de fósforo (SPR: definido como el fosfato absorbido a una solución de concentración de 0,2 mg/l en un experimento de laboratorio) inferior a 200 mg/kg son tierras con baja absorción para dicho fin. Se requiere una cuantificación del valor residual que, en la actualidad, solamente puede realizarse sobre el terreno. Una vez que se cuente con un mayor número de datos, será posible establecer las definiciones de valor residual alto o bajo. Cuando esto ocurra, será posible utilizar valores normalizados de los parámetros, relacionados con la clasificación y propiedades del suelo para predecir los efectos futuros y el valor completo de los fertilizantes fosfatados.

Los estudios con modelos parecen indicar que, para sistemas con bajas cantidades de suministro, tal vez sea mejor utilizar distintas estrategias de fertilización para distintos tipos de suelo. La eficiencia de los fertilizantes fosfatados solubles no se ve afectada por variaciones en las adiciones anuales de fertilizantes en suelos con una buena eficiencia directa y elevado valor residual. Así, pues, cuando la aplicación de fertilizantes es excesiva, deficiente o totalmente omitida en un año, no se perderá o desperdiciará el fertilizante, sino que, en general, seguirá siendo de utilidad. Sin embargo, cuando el valor residual de fósforo sea bajo, es importante mantener el suministro anual del mismo ya que, de otro modo, se reducirá la eficiencia general de la aplicación del fertilizante. Cuando el suelo tenga una baja eficiencia directa para fertilizantes fosfatados, pero un elevado valor residual, existirán oportunidades para mejorar la eficiencia del empleo de fertilizantes, mediante distribución desigual de fertilizante fosfatado a lo largo de la duración de un programa de cultivo.

Los modelos indican que el empleo de fertilizantes parcialmente solubles, tales como la roca fósforica o la roca parcialmente acidulada, pueden, a veces, mejorar la eficiencia, con resultados particularmente beneficiosos en suelos con un valor residual bajo. El potencial de mejora parece ser mejor con rocas de solubilidad intermedia.

Introduction

Little work has been done on the residual value of fertilizer phosphorus (P) in the soils of tropical Africa, which is taken to be Africa outside the Mediterranean countries and South Africa. A number of measurements of phosphate sorption have been made, but the data have not previously been collated. Examples from Africa will therefore be compared to relevant results obtained on tropical soils elsewhere.

Information on soil P and responses to fertilizer P in Africa has been reviewed a number of times. Nye and Greenland (1960) discussed soil properties and available nutrients under shifting cultivation based on many examples from West and East Africa. Russell (1968) gave an overview of the potential for fertilizer use in Africa and problems associated with its introduction. This review collated early examples of residual responses to fertilizer P. Jones and Wild (1975) provided a wide-ranging survey of soils in the savanna regions of West Africa and their use. More recent results in the same region are reviewed in several chapters of the proceedings of an International Fertilizer Development Corporation (IFDC) symposium (Mokwunye and Vlek, 1986). Pichot and Roche (1972) gave an overview of soil P and responses to fertilizer in francophone Africa.

Soil P status, responses to fertilizer P and fertilizer management possibilities, relevant to the improvement of African subsistence agriculture, are reviewed briefly as a background to the residual value and sorption data. References to detailed reviews on the subjects are given for further information.

Phosphate sorption data are of major help in understanding the availability of fertilizer P. Data in the literature and now available from recent Overseas Development Administration and Natural Resources Institute (ODA/NRI) projects at the University of Reading are reviewed. Suggestions are made for future research on phosphate sorption that would be relevant to tropical soils in Africa.

Various examples from Africa which demonstrate the residual effects of fertilizer P are reviewed. Recent research has shown how residual value may be quantified more exactly and methods for its assessment are discussed. It is anticipated that more work will be undertaken and suitable experimental designs, methods and procedures for calculation and presentation of the results are given. Finally, some examples of the impact of fertilizer management on fertilizer efficiency, as influenced by phosphate sorption and residual value, will be examined by modelling methods.

P convention

In this Bulletin the use of P is always intended as an abbreviation for 'phosphorus'. Although in the discussion of fertilizer and soil there are many occasions when the context is not changed by the use of either 'phosphorus' or 'phosphate', where 'phosphate' is the more appropriate (as in 'phosphate sorption'), it is written in full.

Units

The literature reviewed covers a period of considerable change in reporting practices. To facilitate comparison of results, the current terminology, names and units have been used as far as possible. In particular, amounts of fertilizer P or phosphate have been recalculated into kilograms of elemental P, where phosphorus pentoxide (P_2O_5) or weights of fertilizer were previously quoted. Areas and weights have been converted to metric units.

Section 1

Responses to fertilizer phosphorus

INTRODUCTION

Prior to 1951, the use of fertilizer P in Africa was negligible outside South Africa and countries bordering the Mediterranean (Greene, 1954). By 1987/88, annual fertilizer consumption had risen to 353 000 tonnes/annum P_2O_5 (154 000 tonnes/annum P) (FAO Fertilizer Yearbook, 1988), but this was still less than 0.9% world-wide use. Much of this is on cash rather than food crops. Large areas of Africa are an old land surface and low in P content. In West Africa, the mean total soil P of 503 soil samples was 140 mg/kg, while comparable data for Australia and the USA showed total P contents of 350 and 568 mg/kg respectively (Jones and Wild, 1975). The low existing soil P combined with little fertilizer use suggests that nutrient P shortage is a typical situation.

INCIDENCE OF P DEFICIENCY IN SOILS

In unfertilized soils, responses to fertilizer P have commonly been reported from experimental stations for many decades. However, the good yields obtained under intensive management emphasize nutrient deficiencies and the best way to examine the practical incidence of crops and soils for which P fertilization could be beneficial is through multicentre trials in farmers' fields. An early example of this, for Africa, was in Kenya (Bellis, 1954) where response to P was widespread, particularly in graminaceous crops.

In the 1960s, an extensive programme of trials was set up in many African countries by the Food and Agriculture Organization (FAO) in farmers' fields. These were intended principally as demonstration plots and to calculate economic returns (FAO, 1971). The results need to be treated with some caution, since they were not conducted as rigorously as normal agronomic trials, or for long periods, and the averages quoted in most published results hide much variability and important differences in responses (Ahn, 1970). Nevertheless, the results are valuable because they indicate the potential effects of fertilization over a whole region while results from the few agricultural research centres cannot. Results obtained in Ethiopia illustrate two important points: (a) response to P is widespread and (b) balanced fertilization with all major nutrients is needed, otherwise the response to fertilizer P is often inhibited (Ato Girma Belaineh *et al.*, 1971). These trials were on a mixture of ferralitic soils and vertisols, and on average the largest response by wheat (Table 1) was to P, the response to nitrogen (N) was less while there was little average response to potassium (K).

Results for teff and barley were similar and economic analysis showed profits from N and P, though profits were greatest for teff. The mean data given indicate a small N x P interaction on average, since the response to N + P was 10% greater than the sum of the individual N and P responses. However, more detailed analysis of a limited number of sites with adequate replication showed that there was a significant response to N only at 45% of sites, and P only at 56% of sites, but to N + P at 93% of sites (Birch and Ato Desta Hamito, 1971). This showed that N and P were often simultaneously deficient. N (Nitrogen) is commonly regarded as the most important plant nutrient, but 48% of sites (93-45%) were so deficient in P that the response to N was inhibited. Conversely, 37% of sites were so deficient in N that response to P was inhibited. In Botswana and Lesotho during a particularly dry year (1969) the largest responses by maize and sorghum to

Table 1 Response of wheat to fertilizer in the FAO programme in Ethiopia (Ato Girma Belaineh *et al.*, 1971)

Year	No. of observations	Wheat grain yield (kg/ha) Control	N	P	N+P	N+P+K
1967/68	181	990	1290	1400	1800	1860
1968/69	155	900	1210	1290	1680	1740
1969/70	154	920	1220	1320	1640	1740
Mean response over control			300	400	770	840

fertilizer were for P, and only P fertilizer was economically justifiable (Doyle, 1971).

Legumes are able to supply much of their own N through fixation of atmospheric N_2, and are often regarded as a potentially valuable means of increasing soil fertility, but the need for P may be accentuated. Groundnut yield and response to P was examined at 30 centres over eight years in Uganda (Foster, 1980). The yield of nuts on unfertilized soil was most closely correlated with extractable P, and no other soil or meteorological measurement could account for much yield variation. At 17 of the sites, the response to fertilizer P was significant and economically viable but, at the other 13 sites, an economic response to fertilizer was not present. Even if fertilizer could not be justified economically at all sites, soil P was clearly the major limiting factor. It therefore seemed that fertilizer P could significantly increase crop yields over wide areas and certainly on a country-wide scale. However, the size of response is variable from site to site and depends on many variables such as soil, climate and crops. Prediction of a response to fertilizer P at a particular location is a very much more difficult task.

RESPONSE TO P IN DIFFERENT SOILS

Earlier reviews attempted to relate fertilizer responses to climate and land use. Nye and Greenland (1960) considered that response to P depends more on the inherent soil properties than the recent cropping history. Response is more likely where land has been settled and cropped for a long time, and less likely in alluvial soils (possibly hydromorphic soils in general) and vertisols. Comparisons of forest and savanna soils of Nigeria showed that the forest soils had higher amounts of P and a higher proportion of organic P (Enwezor and Moore, 1966; Enwezor, 1977b). Response to P was consequently more likely on savanna than forest soils.

Survey and classification of Africa's soils has made substantial progress since the 1960s and large areas are now mapped according to the classifications of FAO and/or United States Department of Agriculture (USDA). If soil properties related to P availability could be keyed to soil class, then more effective prediction of the potential for fertilizer P use should be possible with less empirical agronomy. Phosphate sorption properties have potential as a method for the keying process thereby acting as a link from classification to practical fertilizer recommendations. The relationships for soils of tropical Africa are examined below (Section 3). A particular problem in relating phosphate sorption (and residual P value) to soil classification is that FAO, USDA and French classifications are in simultaneous use and the terms used do not correspond directly to one another, while only simpler descriptions are given in the older literature. The choice of classification system may influence the conclusions and interpretations, as will be seen for isotopically exchangeable P data in Section 3. Despite the obvious difficulty that occurs in comparisons, the original soil classifications will be used to avoid misrepresentation.

DIFFERENCES BETWEEN CROPS

Different crops have different offtakes of P which will affect maintenance requirements for nutrients. The effectiveness of P uptake might be improved by breeding plants with more efficient root systems which explore the soil more thoroughly. The efficiency of P use, on the other hand, might be improved by breeding crops with a lower P content in the harvested parts and a lower metabolic requirement for P in the roots and shoots. The lower P contents, however, might well lead to nutritional problems for the consumers of food and fodder crops (Godwin and Wilson, 1976). Few original data are available for P offtakes by African crops, probably a consequence of the large amount of work required to make such measurements. The most studied crop is maize and Weinmann (1956) found that, although fertilization with P slightly increased P concentration in the grain, the total P uptake by field-grown maize in Zimbabwe was almost directly proportional to grain yield over a wide yield range, 780-6800 kg/ha. His estimate of 13.5 kg/ha P removed for a good crop of 4500 kg/ha grain corresponds to a somewhat lower concentration of P than the estimate of 21 kg/ha P for a 'typical' yield for the USA of 5000 kg/ha grain by Hanway and Olson (1980).

Probably the most important food crops which are grown in most countries of tropical Africa are maize, sorghum, field beans and groundnuts. Estimates of P offtakes from the fields for maize, sorghum and groundnuts have been compiled, assuming that P uptake is directly proportional to yield, and presented in Table 2. It can be assumed that in Africa virtually all the above ground parts of the crop have a use and it follows that the applications of P required to maintain soil fertility should equal the annual removal of P from the land, which tends to increase in the order groundnuts < sorghum < maize. It can be seen from Table 2 that the main factor determining P offtake is the crop yield and, therefore, non-fertilizer methods of increasing yield must accelerate the depletion of soil P.

However, the maintenance requirement is not the same as the P needed to bring the fertility of a deficient soil up to the fertility which is adequate for a reasonable yield, because different crops have different abilities to extract P from the soil. This arises in two ways: (a) from exploration of the soils by roots with different geometry and (b) differing ability to extract P from the soil solution. The

Table 2 Estimates of typical yields (grain) and P offtakes (total crop) by some major crops of tropical Africa

Location	Yield (kg/ha)	P offtake (kg/ha)	Source
Maize			
USA, typical	5000	21	Hanway and Olson (1980)
Zimbabwe	780-6800	3.9-19.6	Weinmann (1956)
Zimbabwe	6900	20.2	Tanner (1984)
Range of African yields	236-2056	1-9*	FAO Production Yearbook (1989)
Sorghum			
USA, typical	4000	16	Hanway and Olsen (1980)
	3500	21	ISMA
Range of African yields (National averages, 1989)	289-2375	1.1-9.5*	FAO Production Yearbook (1989)
Groundnuts (all yields as unshelled nuts)			
Nigeria	3456	9.2	Bromfield (1973)
Tanzania	1285	4.4	Bunting and Anderson (1960)
World average, 1976	958	3.06	Nelson (1980)
Range of African yields (National averages, 1989)	135-1333	0.4-4.3*	FAO Production Yearbook (1989)

* Author's estimate

latter can be demonstrated best by flowing solution culture. For example, a comparison of five tropical grain legumes (Fist *et al.*, 1987) showed that the lowest concentration of phosphate in solution that would reach the yield plateau varied by a factor of more than 3:

Crop	P concentration required (µM)
Cowpea	0.8
Soybean	0.8
Pigeonpea	1.0
Mungbean	2.0
Guar	3.0

The concentration of P in solution that is needed to obtain the maximum yield is usually known as the external P requirement. An alternative approach is that established by Fox and Kamprath (1970) in which plants are grown in pots or field plots fertilized at different rates and the P concentration in solution is estimated separately by means of the phosphate sorption isotherm (see Section 3). The external P requirement of maize has been studied in several locations but, regrettably, there are no comparative data for the major African crops, based on a selection of representative varieties and growing conditions.

PLACEMENT OF FERTILIZER

There has been substantial investigation into the possibility of improving the efficiency of fertilizer P uptake by placement, i.e. a non-uniform distribution of fertilizer in the field. The fertilizer may be distributed in many ways: most commonly in bands along crop rows, circles around individual plants or spot placed with or adjacent to the seed. The main advantages of placement are (a) the fertilizer is diluted by a smaller volume of soil, reducing the extent of reaction with soil and (b) the density of fertilizer granules around each plant may more nearly reflect the pattern of rooting density. Matar and Brown (1989) concluded that the second mechanism was more important in a Syrian soil where wheat responded significantly to the banding. Particularly during the important early stages of growth when the root system is small, an increased density of fertilizer granules increases the interception of fertilizer by roots and hence the P supply. On the other hand, when the crop is more fully grown, placement reduces the proportion of root system in contact with fertilized soil. Yost *et al.* (1979) found that banding significantly reduced yields of maize in a strongly sorbing Brazilian soil. This was attributed to the restriction of root growth outside the fertilized zone, resulting in greater susceptibility of the crop to subsequent drought.

Results of experiments in Africa confirm that positive responses to placement can be obtained, but not consistently. Fox and Kang (1978) worked with maize on a sandy alfisol in Nigeria which had a modest phosphate sorption capacity. Banding of fertilizer was only beneficial at suboptimal P rates (8 or 16 kg/ha); with enough P (32 kg/ha) to reach the maximum yield (3750 kg/ha grain), it was better to incorporate the fertilizer in the full soil volume. In Zimbabwe, Tanner (1984) found that the effects of placement varied considerably according to growth stage. Spot placement gave increased early growth (at four weeks) compared to broadcast fertilizer, but the advantage diminished as growth continued and was not significant by ten weeks. At harvest (23 weeks) broadcasting gave the better yield. Tanner concluded that placement might still be beneficial if early development was vital; this could be the case when late season drought is a common problem. In direct contrast, Nyamakye (1990) found that maize in a Ghanaian alfisol made better early growth with broadcast compared to spot-placed fertilizer but, as found by Tanner, the differences in treatments diminished as the season continued.

Barber (1980) concluded that if the rate of supply of P to the roots by mass flow and diffusion was less than half the rate that the root needed to take up P, then placement could be advantageous. The rate of movement of phosphate depends largely on the water content and phosphate sorption by the soil (see 'Sorption isotherms: uses and methods' in Section 3). The greater the water content and lower the sorption, the greater the rate of movement, so it follows that banding is more likely to be of value in drier climates and strongly sorbing soils. Because the outcome of placement depends on a balance of different effects, the subject is best investigated by modelling. A number of mechanistic models (Claassen and Barber, 1976; Costigan, 1987) have been developed but the potential for further such work seems great. Because assessment of P mobility is an important part of the process, measurements of phosphate sorption are needed. Quantitative knowledge of the phosphate sorption of a soil is therefore likely to be required in deciding the chance of success with banding and in the interpretation of experimental results.

PREDICTION OF FERTILIZER P REQUIREMENTS BY EXTRACTANTS

For practical purposes, agronomists and extension workers require a simple and reliable method to predict the fertilizer requirement of a soil. The most common approach has been to analyse the soil with chemical extractants in the hope of finding a reagent which extracts an amount of P that correlates well with the P that plants take up. A wide variety has been tried (see Table 3); Kamprath and Watson (1980) discuss the most popular extractants and their application. An extractant can assess the P status of the soil but does not show the amount of phosphate required to make up any deficiency. Tables of measurements of extractable P are therefore of limited use by themselves: for practical application, the measured extractable P must be calibrated against results of field trials. The use of extractants to predict responses to fertilizer P has generally been more successful on previously fertilized sites than on unfertilized sites.

Table 3 Trials in African soils of various chemical extractants for P

Common name	Extractant	Original reference	Examples of application in African soils
Bray 1	0.025M HCl + 0.03M NH_4F	Bray and Kurtz (1945)	Enwezor (1977a)
Bray 2	0.1M HCl + 0.03M NH_4F	Bray and Kurtz (1945)	Nye (1952), Brown (1966), Friend and Birch (1960), Le Mare (1959) Enwezor (1977a)
Olsen	0.5M $NaHCO_3$ pH 8.5	Olsen *et al.* (1954)	Friend and Birch (1960), Enwezor (1977a)
Truog	0.002N H_2SO_4 pH 3.0	Truog (1930)	Friend and Birch (1960), Enwezor (1977a)
Citric acid	1% citric acid	Dyer (1894)	Friend and Birch (1960)
NaOH	0.1N NaOH	Saunder (1956)	Saunder (1956), Friend and Birch (1960), Enwezor (1977a)
Anion resin	Anion exchange resin (usually Amberlite IRA-400) and water	Amer *et al.* (1955)	Friend and Birch (1960), Enwezor (1977a)

Previously fertilized soils

Calibration field trials need to cover all soils in the area of interest and a wide range of fertilities. The objective is to distinguish between soils where responses will and will not be found; there will be a negative relationship between response to fertilizer P and extractable P. The results then need to be presented and interpreted in a suitable manner, such as in this example by Brown (1966) for maize in Malawi:

Bray-P (mg/kg)	Interpretation
12	No response expected
8-10	Response possible but probably not economic
<8	Economic response probable
<5	Response to other fertilizers likely to be prevented.

This kind of relationship is very convenient to use, but is entirely empirical and relies on appropriate field calibration in the soils for which it will be used. The approach depends on the assumption that the relationship between the labile P, as measured by extractable P, and crop response is the same for all the soils. In other words, P nutrition depends solely on the amount of labile P. However, this is not always the case, as will be seen from Section 3. It is possible that in different soils the same amount of labile P gives different concentrations of P in solution and different mobilities to phosphate and, hence, different availabilities. In this case, the relationships between extractable P and crop response will vary between soils.

The calibration of extractable P should therefore be most successful in regions where soil types are relatively homogeneous and the differences between soils (so far as P nutrition is concerned) depend strongly on fertilization history. It may therefore be expected that extractants will be successful in assessing available P in soils with varying amounts of fertilizer residues. Long-term experiments (of up to 100 years) were carried out on UK soils at Rothamsted, Woburn and Saxmundham, and Mattingly (1968) concluded that Olsen-P in particular provided a rapid and reliable method for assessment of fertilizer P residues in these soils. Olsen-P has been adopted as the standard method for available P assessment in the UK. This would seem to confirm that where an extractant gives a good indication of available P it is really assessing residual fertilizer phosphate.

The chemical extractant methods have served temperate agriculture well, but it must be recognized that they have been optimized for previously fertilized soils. Farmers have had access to fertilizer P sources such as manure, bone or artificial fertilizers which were already widely applied.

Unfertilized soils

Attempts to calibrate extractable P in African soils in the 1950s were generally disappointing (Friend and Birch, 1960), although Nye and Bertheux (1957) found Bray-P to be of some use, and Olsen-P became popular in francophone Africa (Pichot and Roche, 1972). Probably, a substantial part of the variation in response to fertilizer P was due to deficiency of other nutrients (Jones and Wild, 1975), which inhibited the response to P where one might otherwise be observed. Unexpected positive correlations were sometimes found, for example Friend and Birch found that Olsen-P, Truog-P and resin-P increased significantly with response to fertilizer P in 31 Kenyan soils, in contrast to the expected finding that the more extractable P, the less the fertilizer response. In some agreement with this tendency, were the following data for isotopically exchangeable P (using ^{32}P) noted by Pichot and Roche (1972):

Exchangeable P (mg/kg)	Soil class
4.4-26	Sols ferrigineaux tropicaux (approximating to alfisols)
15-120	Sols ferralitiques (approximating to ultisols)
50-200	Sols hydromorphes de riziere (hydromorphic soils)

Pichot and Roche then noted that ferralitic and hydromorphic soils often needed more fertilizer P for good yields, suggesting that the soils which had a greater P requirement also had more isotopically exchangeable P. The general low fertility and the particular selection of the soils may have played a part in producing these results. Since the objective is to divide soils into responsive and non-responsive categories, an extractant must be calibrated in a full range of soil fertility to observe the difference. The earlier attempts were on soils almost all of which were low in P. It is suggested that the soils had substantial differences in both phosphate sorption ability and amount of labile P. Soils with high sorption would be more likely to give a response to P, but at the same time might contain a large reserve of strongly held P that could be removed by an extractant, but which was difficult for plants to obtain. It is probable that in this early African work, the fundamental assumption that the relationship between labile P (as represented by extractable P) and plant available P was the same in all soils did not hold.

Another reason for poor correlations of plant available P with extractable P is that the soil organic phosphorus provides a major reserve of P which is not assessed by the usual extractants. It can supply much P on mineralization: in pot experiments with maize on unfertilized Nigerian soils, Adepetu and Corey (1976) found that P uptake was correlated better with organic phosphorus than Bray-P, and the measured decline in organic P would supply most of the available P. This is almost inevitable in land recently cleared from bush or bush fallow, when soil organic matter declines in any case.

CONCLUSIONS

- The use of an extractant to predict a crop response to added fertilizer P is likely to be most successful in a region where soils are similar in type but of varying fertilization and cropping history. Where agriculture has involved the use of fertilizer (including manures, phosphate rock and fallowing), it should be possible to relate assessment of soil P status by a simple extractant to yield and/or response to fertilizer. However, the soils used by the poorer farmers of the tropics are normally deficient in P. Since the variability of tropical soils can be high, the response to fertilizer P does not depend solely on labile or extractable P. Difficulty, indicated by poor correlations, is therefore to be expected in this approach.
- It would be more satisfactory if fertilizer P requirements could be derived from appropriate assessments of the initial P status of the soil and knowledge of the P status that would be satisfactory for adequate crop growth. For this objective, the phosphate sorption isotherm offers a potential route.

Section 2

Alternatives to conventional fertilization

INTRODUCTION

Because of the high cost and poor supplies of conventional chemical fertilizer in developing countries, alternative ways of improving the P nutrition of crops need to be considered. Organic manures and phosphate rock are attractive alternatives because of local availability and lower cost, but they are not always effective. For phosphate rock, allowance can be made for the slow release of P in modelling, as described in Section 8, but the predictions are not yet confirmed in the field.

Agroforestry, management of mycorrhizas and fertilizer placement are possible ways to improve the P nutrition of crops. The benefits of fertilizer placement probably interact with phosphate sorption, as mentioned in Section 1, while agroforestry may improve the residual effects by increasing the cycling of P in the soil. Research on phosphate sorption and P residual value is therefore necessary to understand and develop the application of these techniques. However, they are most effective at yields well below the potential maximum and in the long term are no substitute for fertilizer. They cannot replace P removed in additional crop yields, particularly if the crop is taken from the farm for cash income.

ORGANIC MANURES

Farmyard manure (FYM) is a very good source of plant nutrients and Dennison (1961) reviewed the results of trials in Nigeria conducted for over 20 years. He concluded that the evidence was indecisive as to whether FYM or correct inorganic fertilization gave the highest yields but, in long-term cropping under continuous cultivation, manure had greater effect than inorganic fertilizer, and the effect was probably more than the sum of the N, P and K in the manure. Similarly, manure, which could be either grass mulch or cattle manure, was especially effective in improving yield in long-term experiments (three to nine years) at 30 sites in Ghana (Djokoto and Stephens, 1961). Dennison noted that the source and hence composition of the manure was important, cattle manure being best, but some crops, like groundnuts, seemed to benefit little from it. Recommendations varying from 2000 – 5000 kg/ha manure, depending on crop, could be made to provide good yields. The ability of manure to sustain and improve yields over 16 years may be seen in the results of Lombin and Abdullahi (1977) at Samaru, Nigeria. Without manure, sorghum yield fell by around 67% over this period (Figure 1). Annual application of 2500 kg/ha manure maintained sorghum yield at a substantially higher level, while higher rates of manure application led to a steady build-up of soil fertility and yield. Complete soil analysis data were not available, but the high manure treatments caused a build-up of soil organic carbon, P, K, magnesium (Mg) and calcium (Ca), and also increased pH and cation exchange capacity (CEC). By 1969, organic carbon was 0.22 and 0.82% in unmanured and manured (12 500 kg/ha) plots respectively; the corresponding figures for N were 0.016 and 0.066%. With this increase of organic matter, it is inevitable that organic phosphorus reserves would also be greatly increased.

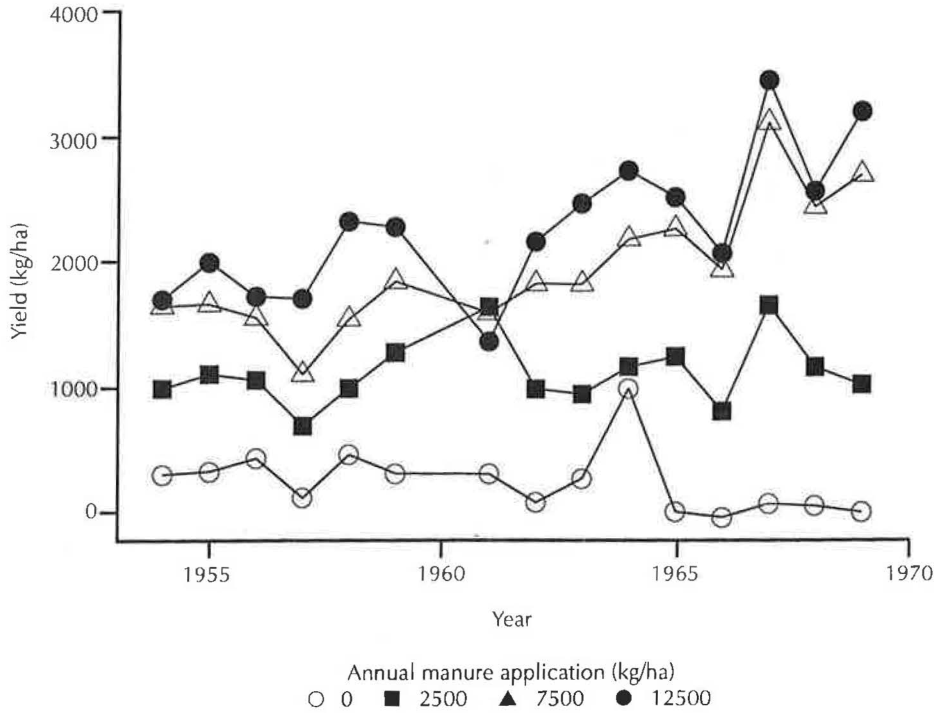

Figure 1 Effects of long-term application of farmyard manure on sorghum grain yield at Samaru, Nigeria (Lombin and Abdullahi, 1977)

The main problem, however, is that manure supplies have been inadequate for a long time and are unlikely to increase. Most crop residues are already used, e.g. as animal feed, energy source or building materials. Green manures can also be of value, as noted by Djokoto and Stephens (1961), but land and time are then lost from arable cultivation especially in drier areas. In general, an increase in supply is needed before organic residues can make a major contribution to nutrient P. Nevertheless, any opportunity to improve cropping systems and increase the supply or recycling of even small amounts of organic material could help to arrest the decline in soil P fertility.

PHOSPHATE ROCK

The direct application of phosphate rock (PR) to soil is normally a cheaper way of adding P and continues to attract attention. Khasawneh and Doll (1978) fully reviewed the potential of direct application, while Hammond *et al.* (1986) examined the possibilities with special reference to the tropics. There are many possible local sources of PR and those in East and Southeast Africa were listed and reviewed in a special issue of *Fertilizer Research* (Van Kauwenbergh *et al.*, 1991) along with aspects of their processing and use. The most important points are as follows:

- The composition of the PR is very important and therefore a local source needs to be properly characterized to determine its likely solubility. A survey of availability and chemical properties of seven West African rocks found substantial differences in composition and effectiveness (Truong Binh *et al.*, 1977).
- The soil itself imposes major limitations on PR use. The effectiveness of phosphate rock is determined by the soil pH and the amounts of soluble P and Ca in the soil; if any one of these is not conducive to dissolution of the rock, it will be ineffective as a fertilizer. Low pH and low concentrations of P and Ca are needed. Where conditions are right, as for example with Minjingu PR at Ukiriguru (Tanzania), yields after PR application will be high (Scaife, 1968).

- Correct assessment of soil P status is therefore helpful in understanding the effectiveness of PR, and phosphate sorption studies are at present one of the best ways of doing this. Because release of available P is slow and likely to extend over many seasons, the residual value of PR may be expected to be significant. Allowing for the slow release of phosphate from PR, as part of modelling P availability, will be looked at in Sections 6 and 8.

AGROFORESTRY

It sometimes appears that agroforestry systems offer a way of improving yield without inputs. On reviewing the literature of agroforestry methods, Young (1989) concluded that inadequate data are at present available to judge their potential accurately. He identified mechanisms by which agroforestry could help the nutrient supply, in particular by maintaining a larger and more closed nutrient cycle in the soil, so that the immediately available P (for example) was higher and crop yield improved. Thus for the same nutrient capital, a higher proportion would be available. However, if extra yield is removed, nutrients must be replaced or fertility will decline again. Although better cropping systems should improve the efficiency of nutrient use, they cannot correct any imbalance in the gain and loss of nutrients to and from a field and some fertilizer is likely to be needed in the long run.

MYCORRHIZAL ASSOCIATIONS

The manipulation of the association of crop plant roots with the vesicular arbuscular mycorrhizas (VAM) has often been seen as a way of improving the P nutrition of crops. Alternatively, such manipulation might allow crops to be grown using less fertilizer or fertilizer of lower solubility. The possible ways of doing this are as follows:

1 Inoculation of seeds or soil with selected, improved VAM

2 Selection of crop varieties which are more effectively colonized by VAM

3 Management of the cropping system, e.g. by the choice and rotation of crops, fallowing and irrigation management.

There is no unequivocal evidence that mycorrhizas can gain special access to firmly held soil P fractions such as organic P, or P in phosphate rock fertilizer (Tinker, 1975; Barrow *et al.*, 1977). Instead, the VAM help by improving the transport of P to the roots. The supply of P to roots is largely limited by the diffusive mobility of the phosphate in solution, and the VAM hyphae which ramify out from the infected roots explore a greater volume of soil than the roots or root hairs. When the P status of the soil is good enough to supply adequate P directly, VAM have no beneficial effect. Yost and Fox (1979) found that VAM ceased to give any benefit at a concentration of P in solution between 0.1 and 1.6 mg/l, depending on the crop. Thus VAM are only of major benefit when yields are suboptimum. Conversely, when the P status of the soil is extremely low, even VAM are unable to effect much improvement in P uptake and the response to VAM may improve upon addition of a small amount of fertilizer. In general, low levels of fertilizer addition do not alter the levels of mycorrhizal infection under monoculture (Strzemska, 1975).

Although many varieties of VAM have been described, there is little specificity in the association and most VAM can infect most potential hosts (Mosse, 1975). This means that, in contrast to the situation for rhizobium bacteria and legumes, the potential benefit of introducing a new VAM species to any one soil is likely to be small because the VAM already there will infect the crop, even an exotic one. Hayman (1982) reviewed the prospects for practical use of VAM by inoculation and noted that although pot experiments demonstrating enhancement of yield and P uptake are numerous, results in the rather few field experiments do not match those obtained in pots. In Nigeria, tests with cowpea in three soils showed good responses to VAM in pots, where the utilization of phosphate rock was improved, but in the field, significant improvements were obtained in one soil only (Islam *et al.*, 1980). Cassava is very dependent on mycorrhizae and, in the absence of fertilizer P, yield improvements of >100% were found in pots of sterilized Egbeda alfisol (also used in the cowpea experiment mentioned above). However, both imported *Glomus mossae* and inoculum isolated from local soil were effective and inoculation of unsterilized soil in the field had little effect (Kang *et al.*, 1980). These results support the contention that the indigenous VAM species present and the actual infective potential of the soil could not be greatly improved on. Finally, there is at present no accepted practical way to produce and transport inoculum, even in developed countries. Thus option 1 is unlikely to be of use to farmers in developing countries.

Vesicular arbuscular mycorrhizas depend obligately on the host plants for energy and, although some VAM inoculation potential is provided by spores, the highest potential is provided by living material, present on live or recently dead roots. Therefore, the potential of the soil to inoculate the next crop is diminished by (a) crops which are unfavourable hosts and (b) long breaks between crops. Because crops vary widely in their ability to act as hosts to VAM, there would seem to be possibilities for manipulating the crop varieties (option 2) and rotations (option 3) to maximize the continuity of VAM infective potential and so improve the mycorrhizal condition of the soil (Thompson, 1991). However, long fallow periods are an almost inevitable part of arable farming in arid and semi-arid climates and, while use of a crop with a longer growing period or a catch crop might improve VAM infection and hence P availability, this could be in conflict with water conservation objectives.

Most subsistence farmers of tropical Africa are likely to continue to use relatively little P fertilizer in the immediate future because of economic constraints. As they are working in a situation of soil P deficiency, the loss of response to VAM through high fertilization will not occur, except perhaps on very sandy soils of exceptionally low phosphate sorption capacity. Thus crop management to take advantage of VAM is likely to be beneficial (option 3), irrespective of soil phosphate sorption properties. Provided yields remain well below the maximum attainable, the interaction of fertilizer P management with VAM management is probably not great.

CONCLUSIONS

- Organic manures and phosphate rock are important as alternative inputs of P to the soil but, because their P is released slowly, they are not necessarily direct substitutes for soluble phosphate. Explicit allowance may need to be made for the rate of release of P.
- Agroforestry and management of mycorrhizas have potential to improve the P nutrition of crops in tropical Africa. However, they are most effective at suboptimal crop yields and are most useful in the early development of agriculture. In the long term, it is probable that improved but suboptimal yields will still be inadequate for some crops and certain countries. If farmers sell additional yields in order to provide cash income and to feed people in the cities – a logical development strategy – nutrient depletion from the land will be accelerated and sustainability diminished. Improved cropping systems should therefore be managed to improve the efficiency of fertilizer and not be seen as substitutes.

Section 3

Prediction of fertilizer P requirements by sorption isotherms

SORPTION ISOTHERMS: DEFINITIONS, USES AND METHODS

Definitions

A sorption isotherm for P is the curve which describes the relationship between phosphate taken up by a soil surface and the concentration of phosphate remaining in solution, measured after addition of phosphate in a laboratory experiment. It has been found that this relationship can differ greatly between soils (Figure 2). The sorption isotherm describes the quantity-intensity relationship for phosphate in soil (Figure 3). 'Quantity' is understood to be the labile P which is freely exchanging with dissolved P and may therefore be limited by the number of suitable sites on the soil surface. 'Intensity' is the free energy level at which the phosphate is held in the soil and is directly related to the concentration of phosphate-P in the soil solution. These concepts and their practical implications were discussed fully by Bache (1977); the main points are discussed below.

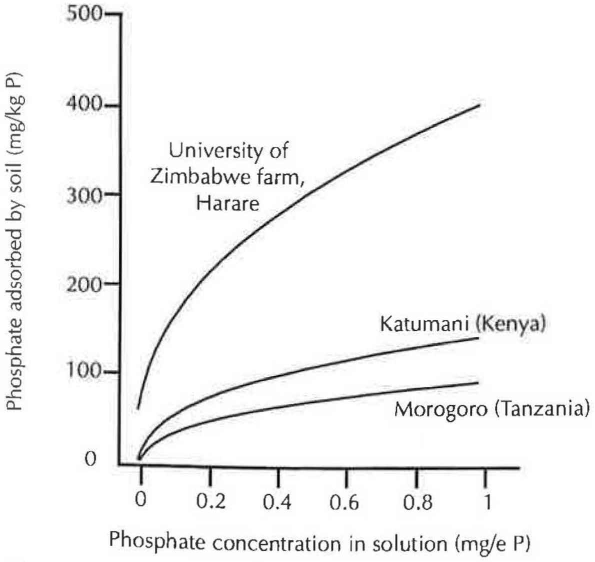

Figure 2 Examples of phosphate adsorption isotherms for some African soils

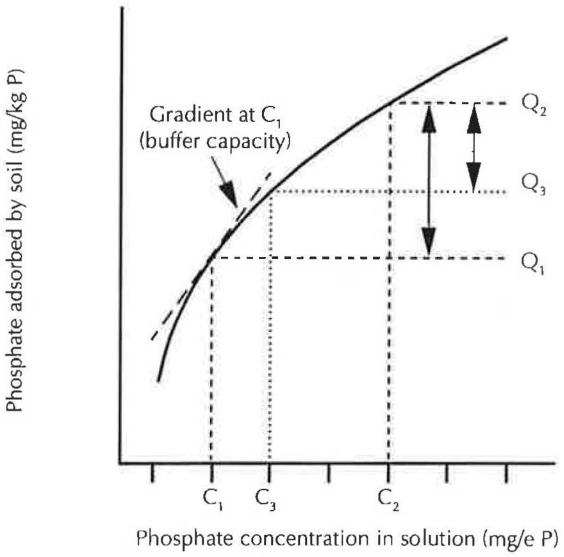

Figure 3 Quantity-intensity relationship in soil

Uses

Phosphate sorption data were first used by soil chemists with the aim of describing the nature of the phosphate sorbing sites and components of soils. However, sorption isotherms can also be used to predict the amount of fertilizer P required. This arises from the understanding that the immediate source of P taken up by plants is the soil solution, which is itself supplied from the soil, rather than by direct transfer of P from the solid components of the soil to the roots.

In principle, the amount of available soil P could be calculated from a quantity-intensity curve, as illustrated in Figure 3. Knowledge of two relevant concentrations, C_1 and C_2, is needed where C_2 is the initial concentration in the soil and C_1 is the lowest concentration at which the plant can take up P. Then Figure 3 shows that the amount of available P equals $Q_2 - Q_1$. Now suppose instead that $Q_2 - Q_1$ is adequate for the P uptake of the crop and that the initial concentration of P in the soil solution is only C_3. Then $Q_2 - Q_3$ equals the amount of fertilizer P to be added so that there is enough P in total to supply the crop's needs. There are some theoretical and practical difficulties in the application of these concepts.

- A sorption isotherm with adsorption of phosphate can be measured readily. But when P leaves the soil surfaces, it is being desorbed and the relationship between P remaining and concentration in solution can be, and usually is, different. The actual mechanisms of retention of phosphate are not precisely characterized and in all probability both physical adsorption and chemical precipitation are involved. For these reasons, it is now usual to speak of 'sorption' to indicate that the exact mechanisms are not known.
- The uptake of P is also limited by the mass flow and diffusion of P to the roots thus, in practice, it is impossible to recover all fertilizer P in one season.
- It is easy to measure an isotherm in laboratory conditions, but this may differ from the real quantity-intensity relationship where soil has spatial and temporal variability.
- Values for C_1 and C_2 may be found from flowing solution culture, but they could vary according to the weather and health of the plant.

A simpler empirical approach was suggested by Beckwith (1965): enough fertilizer P should be added to raise the concentration of phosphate in solution to an initial value that was adequate for obtaining the maximum yield in a field experiment. Thus the fertilizer P requirement is the amount of fertilizer needed to give a standard, adequate concentration of P in solution. This caters for the differences between soils in their capacity to adsorb phosphate. Fox and Kamprath (1970) confirmed this approach by showing that the concentration of P in the soil solution determined the yield of millet irrespective of soil type or fertilization. Other factors are important as they influence the amount of fertilizer P required to establish a given soil solution concentration. Different crops may need different concentrations of P in solution (see 'Differences between crops' in Section 1), so the method can be calibrated more exactly for different crops. However, a concentration of 0.2 ppm in solution is in practice more than enough P to supply most crops. The amount of added P (calculated from the sorption isotherm) that gives this concentration can be used as a guideline for the fertilizer requirement of a soil, and is called the standard P requirement (SPR) by Juo and Fox (1977). Differences between soils are often large and the concepts do help to understand why responses to fertilizer P differ between soils. Vander Zaag *et al.* (1979) found that the method could be used to make predictions of fertilizer requirements in diverse soils.

Methods

The methods for measuring sorption isotherms vary (a detailed experimental procedure is given in Appendix 1). The increase in phosphate uptake by the soil becomes quite slow after around 24 h. This includes the more strongly sorbing tropical soils, for example the Cerrado dark red latosol from Brazil (Malla, 1988), where the amount of P adsorbed increased rapidly up to around 16 hours, then became slower and was still continuing slowly after 96 hours (Figure 4). Adsorption of phosphate also became slow after 24 hours in some oxisols of

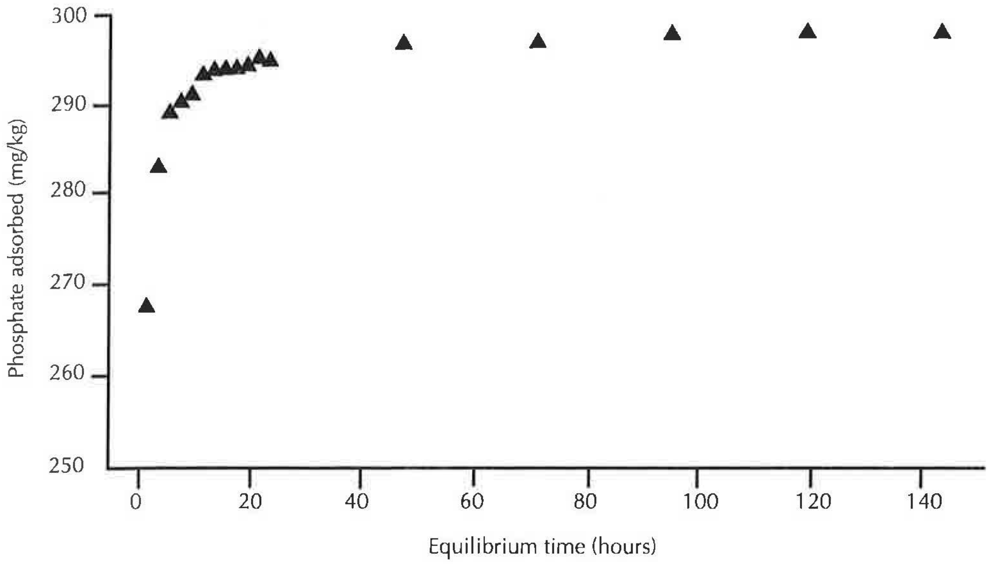

Figure 4 Relationship between equilibration time and uptake of P by sorption on Cerrado dark red latosol from Brazil (Malla, 1987)

Tanzania (Gama *et al.*, 1987). Therefore differences between methods are probably not too important provided the equilibration period is about 24 h or more.

The methods used for equilibration of soil and solution can vary substantially. The major variations in recent use are as follows:

1. Six days' equilibration of a suspension (1:20) with intermittant vigorous agitation, usually 30 minutes twice per day (Fox and Kamprath, 1970)
2. Two days' equilibration as a suspension (1:20) with continuous gentle agitation (Le Mare, 1982)
3. Equilibration as moistened, aerobic soil (1-300 days), followed by assessment of soil solution phosphate by the 'null point' method (Barrow and Shaw, 1975). To do this, subsamples are taken and solutions of several phosphate concentrations, which are around the expected concentration in soil, are added. The phosphate actually adsorbed or desorbed is measured and the concentration of added solution that would experience no change on addition to soil is estimated by interpolation.

Method 3 most closely approaches field conditions since the soil retains some of its structure. But it requires further work to estimate and control the required water content, and in the measurement of the soil solution concentration for all the subsamples.

Method 1 is the most popular but intermittent shaking is not entirely satisfactory. During the rapid uptake of phosphate in the first few hours, the phosphate sorbed will not be evenly distributed in the soil sample, being preferentially adsorbed on the layer of soil in immediate contact with the solution. Vigorous shaking breaks up soil particles and can cause a progressive increase in sorption capacity by exposing additional surfaces (Barrow and Shaw, 1979).

Method 2 is straightforward and relatively quick to perform, but the agitation must be as gentle as possible (the author uses rotation end-over-end at 1 rpm). Appropriate agitation equipment is not readily available commercially but can be made easily in a workshop from a motor and basic materials.

Equations used

Graphical presentation (e.g. Figures 2 and 3) is a good way to convey the form of the quantity-intensity relationship and assists interpretation, but does not lend itself to the formulation of quantitative relationships with plant response and soil properties. To do this, it is necessary to fit the data to an equation and the data can then be summarized by a few fitted parameters. Several equations have been used and the more popular ones are as follows:

Equation	**Name**
$P = \dfrac{k\,x_m\,C}{(1 + k\,C)}$	Langmuir
$P = \dfrac{k_1\,x_{m1}\,C}{(1 + k_1\,C)} + \dfrac{k_2\,x_{m2}\,C}{(1 + k_2\,C)}$	'Double' Langmuir
$P = a\,C^{(1/n)}$	Freundlich
$P = a\,C^{(1/n)} - k$	Modified Freundlich
$P = a + b\ln C$	Temkin

Where P = P sorbed (mg/kg)
C = P concentration in solution (mg/l)

and a, b, k, n, and x_m are fitted parameters, the meaning of which may differ between equations. The equation which gives the best fit varies between soils, even where standard conditions are used. When these equations are compared on the basis of goodness-of-fit (residual mean squares) for a group of soils, the Freundlich equation is frequently the one that gives the best fit in the most soils, although there may be little to choose between the equations. For example, in eight West African soils analysed by Mokwunye *et al.* (1986), Freundlich, Langmuir and Temkin equations were tested, and the Freundlich gave the best fit in the majority of soils. An analysis of statistical properties of eight equations, using Australian soil data showed that the Freundlich equation was to be recommended on the grounds of less bias, even in comparison with the Double Langmuir equation, which gave a better apparent fit, partly because the latter has twice as many parameters that can be optimized (Ratkowsky, 1985).

The Langmuir equation has often been used because its derivation indicates clearly a physicochemical interpretation for each of the fitted parameters. Parameter x_m is the maximum sorption capacity, while parameter k describes the affinity between the surface and phosphate. Thus relationships between x_m and measured soil fractions are used to indicate the major phosphate sorbing components of the soil. The two Freundlich parameters may be interpreted similarly, because this equation can be derived from the same assumptions as the Langmuir equation, if it is assumed that instead of there being no interaction between adsorbing sites, the affinity declines logarithmically with the increase in the proportion of surface covered (Hayward and Trapnell, 1964). Freundlich parameter a represents the sorption capacity and parameter n, the inverse of the exponent of C, the affinity. Holford (1982) found that in several Australian and UK soils, the Langmuir and Freundlich capacity parameters were well related, but the affinity parameters were well related only within relatively homogeneous groups of soils. If the Freundlich exponent ($1/n$) is written instead as b/a, then parameter b equals the gradient of the curve when C = 1 mg/l, while a equals the amount of P adsorbed at C = 1 mg/l. Parameter n does not refer to the same concentration for every soil. This way of presenting the parameters is helpful because a and b can then be used to compare amount and buffer capacity for phosphate sorption in diverse soils, as will be done below.

For the purpose of estimating P adsorbed at a particular concentration, as in estimating the SPR, any equation will suffice as long as it fits smoothly to the data points. The Freundlich equation can be fitted easily, either by regression or graphically, when in the logarithmic form:

$$\log P = \log a + 1/n \log C$$

The Freundlich equation is therefore recommended for presentation of phosphate sorption results whenever a practical interpretation is desired.

Buffer capacity

In the quantity-intensity relationship, the gradient of the curve (dP/dC), illustrated in Figure 3 and often known also as the buffer power or buffer capacity, is also of vital importance to phosphate availability because of its influence on the mobility of phosphate. The diffusion coefficient for an adsorbable solute in the soil (D_s) is proportional to the inverse of the buffer capacity, according to the following equation (Bache, 1977):

$$D_s = D_l \, \theta \, f(1/b)$$

where D_l = diffusion coefficient in solution
θ = volumetric water content
f = tortuosity factor
b = buffer capacity

Thus, the greater the buffer capacity for phosphate, the lower its mobility and hence availability. A full derivation is described by Nye (1968) and depends on the assumptions that (a) the mobility of adsorbed solute on the soil surface is neglible compared to passage through the solution and (b) ($1/b$) is a close approximation to the term (dC_l/dC) of Nye, in which C is the concentration of all diffusible solute in the soil, not just the adsorbed phosphate, and C_l equals the concentration in solution, which is being called C throughout this bulletin. Therefore, buffer capacity b should be derived using data for P in solution plus a mobile fraction on the soil. It is considered that the approximations are close, since adsorbed P is strongly held and solution P accounts for very little of the total diffusible phosphate in the system, and repeated extraction will remove most added P eventually.

Measurements of buffer capacity do not normally correlate directly with plant uptake of P or yield. However, the correlation between extractable P and actual P uptake by plants is significantly improved by including buffer capacity in multiple regressions (Holford, 1979). The fraction of fertilizer P that can be taken up is directly correlated with buffer capacity (Warren, 1990). This suggests that, next to the amount of labile P present, the mobility of P is the most important factor.

STANDARD P REQUIREMENTS

There is a steadily increasing body of published phosphate sorption data for African soils, although much of it refers to West Africa, but there has been little systematic validation of the concepts for its use in Africa. Mokwunye (1977) showed that for maize grown at Samaru, Nigeria, the P sorbed at 0.3 mg/l (75 mg/kg, equivalent to 150 kg/ha) indicated the P required for maximum yield, and the method worked for both unfertilized soil and soil with one-year-old fertilizer residues. However, in the USA, 0.13 mg/l P was an appropriate target concentration (Jones and Benson, 1975). Pot experiments with six Nigerian inceptisols and alfisols showed that the requirement for cowpea was between 0.12 and 0.27 mg/l (Anyaduba and Adepetu, 1983). In contrast to these two crops, Kang *et al.* (1980) found that only 0.04 mg/l was needed for 95% maximum yield with cassava in Egbeda alfisol (one of the soils used in the cowpea pot experiment); even 0.01 mg/l P was enough for an acceptable tuber yield of 35 t/ha, the maximum being about 47 t/ha. This result was attributed to the very effective mycorrhizal symbiosis formed by cassava and also to the long growing period (15 months) which meant that the mean daily P requirement was thought to be modest compared with annual crops.

Since a solution concentration of 0.2 mg/l P is now widely accepted as a suitable value for the target concentration, and from the limited evidence is not unreasonable at least for maize in Nigerian soils, Standard P Requirements (SPR) will be compared on this basis. The SPR values from the literature were normally either taken as given by authors or calculated using the authors' best fitted equations. Where examples were given without fitted equations, SPR values were estimated graphically from authors' figures. For data from recent projects at the University of Reading, SPR values are calculated from fitted equations. The SPR data for almost 200 African soils are now available and are presented in Table 4.

The following guidelines for comparing the SPR of different soils were proposed by Juo and Fox (1977):

SPR (mg/kg)	Scale of phosphate sorption	Usual mineralogy encountered
<10	Very low	Quartz, organic materials
10-100	Low	2:1 clays, quartz, 1:1 clays
100-500	Medium	1:1 clays with oxides
500-1000	High	Oxides, moderately weathered ash
>1000	Very high	Desilicated amorphous material

Authors of published phosphate sorption data generally remark on the great variation between soils within each study, and this is evident here. In most studies, the soils were grouped by some method, usually classification, but a wide range of overlap was observed in all cases. Most assessments of SPR fall within the low to medium phosphate sorption range, 10-500 mg/kg P, but the distribution of values is weighted towards the lower end of this range. Of 199 soils only a small minority of eight soils fall into the high or very high sorption categories; many are in the <50 mg/kg range. In considering the soils of West and East Africa, the following conclusions can be drawn from the information in Table 4:

West Africa Within West Africa (reports from Nigeria westwards) no soils fell into the high or very high categories, and almost all the West African soils had SPR < 250 mg/kg. The mean SPR over all reports was 71 mg/kg, if the relatively strong sorption by alfisols and ultisols of basic rocks reported by Juo and Fox was omitted. This follows from the fact that this is an old land surface where the available nutrients have been severely depleted but, because leaching is moderate through much of the region, there is an absence of the strongly leached soils (oxisols and ferralsols) which are normally noted for high phosphate sorption capability. The conclusion of Juo and Fox (1977) that soils of West Africa have modest P requirements compared to many other soils of the humid tropics is therefore confirmed by the other sorption studies for the region. Juo and Fox established that the main reason for the greater phosphate sorption in the alfisols and ultisols on basic rocks in Nigeria was their greater content of fine clay; its greater surface area giving more sorption. In agreement with this, Owusu-Bennoah and Acquaye (1989) found that for 16 Ghanaian soils, the fitted Langmuir maximum sorption was significantly correlated with clay content.

East Africa Results for the soils of East Africa (Sudan southwards to Zimbabwe) are more varied, reflecting the more varied geology and climate of these countries. Of the 69 soils for which SPR values could be tabulated, there were 27 with low SPR, 34 with medium SPR and eight with high or very high SPR. Since most soils fall into the medium or high SPR categories, the need for fertilizer P may be expected to occur more commonly and be greater in East Africa than West Africa. As might be expected from work in South America and New Zealand, the three examples of andisols (in Ethiopia and Rwanda) show high or very high SPR. The SPR values for the two Ethiopian andisols are directly comparable to those found in some well characterized Colombian andisols which are noted for very high phosphate sorption (Le Mare, 1982; McKean, 1989)*. Three nitosols (one Kenyan and two Ethiopian) also show high SPR, and

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*See also Table 6

Table 4 Standard P requirements (SPR) of African soils assessed by phosphate sorption at 0.2 mg/l

Location, Source Soil type	Number of samples	SPR (mg/kg)	
		range	mean
Nigeria (Udo and Uzu, 1972)*	8	25-400	
Nigeria, Togo and Liberia (Juo and Fox, 1977)			
Alfisols from acidic rocks	9	0-85	32
Ultisols from acidic rocks	9	15-110	55
Alfisols and ultisols from basic rocks	6	190-430	253
Hydromorphic soils	4	0-50	35
Nigeria Ondo State (Adepetu, 1981)	11	8.3-127	38
Nigeria SW (Anyaduba and Adepetu, 1983)			
Alfisols	2	45, 305#	175
Inceptisols	4	51-119	87
Nigeria western (*Ayodele et al.*, 1984)			
Savanna	10	0.8-23	4.3
Nigeria and Mali (Mokwunye *et al.*, 1986)*			
Savanna zone	8	25-88	44
Nigeria (Loganathan *et al.*, 1987)			
Coastal Plains (Ultisols)	24	40-240	115
Sombreiro-Warri terrace (Ultisols)	8	30-220	110
Meander belt (Inceptisols)	10	50-100	132
All soils	42	30-240	118
Ghana (Owusu-Bennoah and Acquaye, 1989)			
On acid rocks	3		29
On basic rocks	3		110
On Birrimian rocks and phyllite	3		62
On sandstones	6		32
On alluvium	1		9
All soils	16		50
Ghana (Nyamekye, 1990)*			
Tingoli series, Tamale; Alfisol (savanna)	1	10	
Sudan (Warren: ODA projects)			
Very sandy soils, Nakhara and Dimsu regions	5	15-23	19
Ethiopia (Mamo and Haque, 1987)			
Andosols	2	1250, 1500#	1375
Nitosols	9	84-580	427
Vertisols	8	105-600	290
Gleysol	1	350	
Luvisol	1	540	
Fluvisols, Mollisols, Phaeozem, Regosols, Xerosols	10	13-360	
Rwanda (Vander Zaag *et al.*, 1984)			
4 representative soils			
Eutrustox		80	
Humult		150	
Tropept		360	
Eutrandept		>500	
Soils from volcanic materials	–		370
Gikongoro region (Tropepts and Humults)	–		234
Kenya and Tanzania (Warren: ODA projects)			
Nitosols	2	330, 508#	
Ferralsols	2	35, 75#	
Acrisol, luvisol	2	10, 49#	
All soils	6	10-108	168
Kenya (Ntuma and Ssali, 1985)*			
Andosols	2	151, 369#	
Nitosols	2	215, 270#	
Ferralsol, Oxisol	2	10, 109	
Vertisol	1	129	
All soils	7	10-369	179
Zimbabwe (Dhliwayo, 1989)			
Clay soils	2	210, 236#	
Sandy/loamy soils	6	32-39	35
Malawi (Karim and Adams, 1984)			
Oxisols of a catena, Bunda	6	150-430	238
Malawi (Warren: ODA projects)			
Ferralsols, Mubangwe	2	53, 60#	

Note Data may be (a) as given by the authors, (b) calculated from the authors' fitted equations or (c) if indicated * estimated graphically from the published sorption curves

\# Only 2 values available

other nitosols tend to have SPR values at the higher end of the medium SPR range; none are in the low SPR category. While an identifying feature of nitosols is an argillic B horizon, the greater phosphate sorption in the upper horizon is probably related to the likelihood of a high clay content there as well. The Ruiru soil (Kenya: SPR = 330 mg/kg; Table 4*) certainly contains much clay (50-80%) throughout the profile (Keter and Ahn, 1986). The influence of clay content was remarked upon previously for West African soils and may also be seen in the much greater SPR in clay soils compared to sandy soils of Zimbabwe (Table 4; Dhliwayo, 1989). Notable at the bottom end of the SPR scale are some very sandy soils from the Sudan.

Oxisols and ferralsols are soils which are strongly weathered and commonly regarded as typical soils for strong phosphate sorption (Sanchez and Uehara, 1980). Examination of the SPR from such soils shows that this is not inevitable. Ferralsols of Mubangwe (Malawi), and some oxisols of other locations show low SPR: the mean SPR for the six ferralsols (Kenya and Malawi) is 57 mg/kg. In contrast, the 13 nitosols (Ethiopia and Kenya) have a mean SPR of 400 mg/kg, although both types of soil contain substantial amounts of iron sesquioxide minerals. In the case of the Kwale soil (Kenya: SPR = 35 mg/kg) the soil is basically sandy. Although the sesquioxide minerals may have a large specific sorption capacity, they are not always dominant in the soil matrix, particularly in sandy soils. Therefore, the sorption of oxisols and ferralsols also depends on the texture of the soil. Examples of soils classified as alfisols, acrisols and luvisols usually have low SPR values in both East and West Africa.

ISOTOPICALLY EXCHANGEABLE P

The introduction of radioactive phosphorus (^{32}P) as a tracer made possible the assessment of a pool of P in the soil that exchanges with the added isotope, i.e. without any gross chemical alteration to the soil. Measured exchangeable phosphate is usually well related to plant available P, but not infallibly so. Plant available P is frequently overestimated by exchangeable phosphate in tropical soils with a high sorption capacity (Amer *et al.*, 1969; Tran *et al.*, 1988). Using ^{32}P it is possible to partition previously added phosphate into exchangeable and non-exchangeable components (Le Mare, 1981a, 1981b, 1982). This technique enabled better relationships to be obtained between phosphate sorption parameters and soil components in Nigerian soils (Le Mare, 1981a, 1981b). The effects of liming and green manuring in strongly sorbing soils of Brazil (Le Mare *et al.*, 1987) were explained because these field treatments tended to reduce the extent of non-exchangeable sorption and therefore less fertilizer P was in the strongly held fraction, resulting in a better yield.

Presentation of Le Mare's (1981a) data for exchangeable phosphate sorption, according to USDA soil classification (Table 5) indicates that phosphate sorption, assessed by amount and buffer capacity of phosphate sorbed at 1 mg/l (Freundlich parameters *a* and *b*, see above), decreased in the order ultisols > alfisols > entisols and mollisols. This is roughly in line with the declining degree of weathering, since highly weathered soils generally sorb much phosphate unless they are largely composed of quartz (Fox and Li, 1986). Presentation of these data by the FAO system suggests the order nitosols > luvisols and gleysols > acrisols > others, again in order of declining degree of weathering. There were only two nitosols but the results are consistent with relatively high phosphate sorption, as noted in 'Standard P requirements'. A useful feature of presentation by FAO class is that gleysols were identified; phosphate sorption did not increase greatly with depth, unlike in other soil classes.

Apart from the above studies, measurements of exchangeable phosphate and non-exchangeable phosphate for African soils are very limited in number. Table 6 gives data for adsorption isotherms, split into exchangeable and non-exchangeable components, derived from ODA and NRI funded projects at the University of Reading. All soils were analysed with the same procedure; data for

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*See also Table 6

Table 5 Sorption parameters for exchangeable P in 38 Nigerian soils, recalculated from data of Le Mare (1981a)

Soil type	Number of soils		Surface soils Freundlich parameter *a*	*b*	Subsoils *a*	*b*
Tabulation according to USDA classification						
Ultisols	11	mean	89	41	351	128
		range	21-188	8-97	104-738	25-248
Alfisols	13	mean	67	25	200	59
		range	21-159	8-70	35-533	7-203
Inceptisols	4	mean	84	35	97	31
		range	58-25	17-50	60-132	17-60
Entisols and Mollisols	10	mean	47	17	99	23
		range	19-89	8-36	2-191	0.4-64
Tabulation according to FAO classification						
Nitosols	2	mean	109	45	441	181
		range	43-174	15-74	145-738	40-322
Acrisols	12	mean	65	28	259	88
		range	21-188	8-97	104-578	25-248
Luvisols	12	mean	72	25	204	59
		range	33-159	11-70	35-533	7-203
Gleysols	6	mean	73	31	91	24
		range	31-125	13-50	2-144	0.4-60
Others (Cambisols,	6	mean	45	16	78	21
Regosols, Phaeozems)		range	19-64	8-25	60-94	11-34

selected tropical soils from other continents are included for comparison since there are few data for African soils. The data for different soil types are arranged in three groups, broadly based on the SPR values in Table 4:

Group 1 contains all soils which are known or believed to be influenced by volcanic ash, irrespective of the formal classification provided by the soil surveyor

Group 2 contains other soil classes generally thought to make P unavailable, although it is already clear from the SPR values that there is a great diversity of sorption capacity in this category

Group 3 comprises some classes of soils which are widespread and important in agriculture but which generally adsorb little P.

The main objective of the projects was to study soils where P nutrition is difficult and Group 3 is under-represented in Table 4. The data for total adsorbed phosphate, i.e. phosphate taken up from solution, without considering the exchangeable fraction, were fitted to the modified Freundlich equation ($\Delta P_t = a_t C^{(b_t/a_t)} - K_t$) for calculation of SPR values. Comparison of the mean SPR values showed that Groups 1 and 2 can adsorb about 10 and 3 times respectively more P than Group 3.

The fitted parameters a_e and b_e of the Freundlich sorption isotherms ($P_e = a_e C^{(b_e/a_e)}$) for isotopically exchangeable phosphate, represent the amount of exchangeable phosphate at a concentration of 1 mg/l and the buffer capacity, respectively. The fitted parameters a_n and b_n are obtained from fitting the Temkin isotherm ($\Delta P_n = a_n + b_n \log C$) to the data for the fraction of adsorbed P that apparently did not exchange with tracer amounts of ^{32}P during a 22 h period. The ratio a_n/a_e was calculated as a measure of the ratio of non-exchangeable to exchangeable phosphate sorption. This ratio increased in the order Group 3 < Group 2 < Group 1, suggesting that not only did the SPR increase in this order but also that a greater proportion of the adsorbed phosphate is held so strongly that it is apparently not exchangeable to ^{32}P. Thus an increasing fraction of fertilizer P might be held in a form that is not immediately available.

Table 6 Sorption parameters for total, exchangeable and non-exchangeable P in some tropical soils (ODA/NRI projects)

			Sorbed phosphate									
			Total			Exchangeable		Non-exchangeable		Ratios		
Soil type	Country	Class	a_t	b_t	k_t	a_e	b_e	a_n	b_n	a_n/a_e	b_n/b_e	SPR
Group 1: Andisols and soils affected by volcanic ash												
Popayán '2'	Colombia	Andisol	6798	1436	2174	2548	1106	2107	408	0.83	0.37	2665
Unidad Chinchina	Colombia	Andisol	3344	621	1183	1722	788	658	112	0.38	0.14	1297
Sitiung 1A	Indonesia	Inceptisol	1343	260	409	648	224	382	62	0.59	0.28	574
La Montaña	Costa Rica	Inceptisol	1223	266	483	632	237	267	57	0.42	0.24	379
Barombi Kang	Cameroon	Ultisol	1031	142	486	453	117	260	40	0.57	0.34	340
Mean										0.56	0.27	1051
Group 2: Oxisols, Ferralsols and Nitosols												
Morogoro	Tanzania	Oxisol	185	56	39	120	58	33	6	0.28	0.10	75
Kwale	Kenya	Ferralsol	84	16	27	53	17	8	1	0.15	0.06	35
Kiamokama	Kenya	Nitosol	1206	286	315	706	270	341	38	0.48	0.14	508
Ruiru	Kenya	Nitosol	672	197	89	491	194	112	16	0.23	0.08	330
Munchong	Malaysia	Oxisol	1414	184	636	565	170	308	48	0.55	0.28	510
Segamat	Malaysia	Oxisol	683	187	129	430	176	139	23	0.32	0.13	311
Manaus	Brazil	Oxisol	227	104	28	188	103	22	5	0.12	0.05	82
Cerrado DRL*	Brazil	Oxisol	635	246	59	434	210	134	24	0.31	0.11	281
Cerrado RYL#	Brazil	Oxisol	1335	262	455	914	367	382	66	0.42	0.18	518
Jardinopolis	Brazil	Oxisol	1161	202	430	533	184	283	45	0.53	0.24	448
H. Cristalino	Brazil	Oxisol	486	111	130	261	99	125	20	0.48	0.20	207
Mean										0.35	0.14	300
Group 3: Ultisols, Acrisols, Luvisols, Alfisols												
Kichaka	Kenya	Acrisol	33	15	6	24	10	7	2	0.29	0.20	10
Katumani	Kenya	Luvisol	133	36	37	90	44	21	4	0.23	0.09	49
Patancheru	India	Alfisol	58	30	4	56	21	nil	nil	–	–	22
Sepilok	Malaysia	Acrisol	376	119	55	259	109	72	12	0.28	0.11	170
Keningau	Malaysia	Acrisol	703	225	123	462	211	127	25	0.27	0.12	297
Rengam	Malaysia	Ultisol	289	74	99	168	73	42	9	0.25	0.12	93
Mean										0.22	0.11	107

* dark red latosol

\# red yellow latosol

Soils from Cameroon, Costa Rica and Indonesia, not originally identified as andisols, are logically grouped with the two Colombian andisols which are definitive examples of andisols having high phosphate sorption. All have high or very high SPR values and substantial non-exchangeable phosphate sorption.

PHOSPHATE SORPTION BY SOIL COMPONENTS

The importance of the quantity of clay in determining sorption capacity has been observed already (see 'East Africa' above). The composition of the clay fraction is also of major importance and strong sorption of phosphate has been associated with the hydrous sesquioxides of Al and Fe, in particular those which are often described as amorphous, disordered or of short-range order. Al and Fe oxides are normally assessed quantitatively by the Al and Fe extracted by acid oxalate (Al_{ox} and Fe_{ox}) and sodium citrate/dithionite/bicarbonate (Al_d and Fe_d). These reagents have been in use for some decades to assess the disordered and total oxides respectively. Parfitt and Childs (1988) reviewed their use and tested them in strongly sorbing soils in New Zealand. It appears that Al_{ox} is closely related to Al in the short-range order minerals allophane and imogolite, plus Al in humus complexes; Fe_{ox} is largely ferrihydrite, a short-range order iron oxide, and Fe_d can be attributed to both the crystalline oxides goethite and hematite, and also to ferrihydrite. In general, these reagents have proved useful in characterizing soil with regard to phosphate sorption, and the same result is evident for African soils.

In Nigerian soils, Adepetu (1981) found that SPR tended to be high with high Fe_d, and Juo and Fox (1977) found that Fe_d was significantly correlated with the Langmuir sorption capacity, except for a small group of hydromorphic soils. In another group of Nigerian soils, SPR was correlated to both Fe_d and Al_d (Ayodele *et al.*, 1984). Aluminium oxides were not assessed in the former report. As the Fe_d includes both crystalline and disordered oxides, this does not indicate the relative roles of these components. Mokwunye *et al.* (1986) found that Langmuir sorption capacity in some West African soils was significantly related to both Al_{ox} and Fe_{ox}, emphasizing the role of the disordered oxides. Similarly, Owusu-Bennoah and Acquaye (1989) found that for 16 Ghanaian soils, Langmuir sorption maximum was best correlated with Al_{ox} and significantly correlated with Fe_{ox}. They also found a correlation between sorption maximum and organic C. Closer examination of the role of soil organic matter elsewhere has found that Al_{ox} and organically associated Al (normally determined by pyrophosphate extraction) dominate the phosphate sorption characteristics (Moody and Radcliffe, 1986; Wada and Gunjigake, 1979), but if the amounts of disordered oxides are low, then sorption by the crystalline oxides can be dominant, as in a catena of Malawian oxisols (Karim and Adams, 1984).

Le Mare (1982) related Al_{ox} and Fe_{ox} to both capacity and affinity parameters of the Freundlich equations for exchangeable phosphate sorption in Nigerian soils. The capacity parameter was better related to Fe_{ox} than Al_{ox}, whereas the affinity parameter was better related to Al_{ox}. As described above in 'Buffer capacity', the affinity parameter has a direct influence on P uptake because it controls the buffer capacity and hence rate of diffusion of phosphate through the soil/solution matrix. The strongly held phosphate, assessed from the sorption parameters for non-exchangeable phosphate, was much better related to Al in organic complexes than Al_{ox}. Phosphate sorption in the Nigerian soils was controlled by the same processes as in some Brazilian and Colombian soils with very high phosphate sorption, but the iron oxides were relatively more influential in the Nigerian soils. Similarly, in five Zimbabwean soils exchangeable phosphate was best related to Fe_{ox} (Sibanda and Le Mare, 1985); non-exchangeable phosphate was best related to Al_{ox} and it increased with the amounts of gibbsite present.

Although only limited data are available, it can be concluded that attempts to relate phosphate sorption to the hydrous oxides, particularly in African soils, have been fairly successful. Measurements of Al_{ox} and Fe_{ox} especially could provide some indication of the likely sorption capacity of soils but the quantitative relationships between extractable Al and Fe evidently differ between soil types. This is shown by the relationships between Fe_{ox} and parameters of the Freundlich equations $P_e = aC^{(b/a)}$ for exchangeably sorbed phosphate in some Nigerian ultisols, alfisols and entisols (Le Mare, 1981b):

Ultisols $a = 792\ Fe_{ox} - 15$
$b = 361\ Fe_{ox} - 7$
Alfisols $a = 535\ Fe_{ox} - 2$
$b = 249\ Fe_{ox} - 6$
Entisols $a = 243\ Fe_{ox} + 19$
$b = 112\ Fe_{ox} + 5$

With a more extensive database, this kind of relationship could become of practical use notably for soils which are classified as having high phosphate sorption. The Al_{ox} and Fe_{ox} would be measured and used to estimate sorption parameters with equations like those above. The estimated sorption parameters would then be used to calculate the SPR.

CONCLUSIONS

- It can be concluded that the P requirements of African soils vary greatly. Worldwide, the highest P requirements are found in volcanic ash soils, rich in disordered minerals particularly allophane. This is also the case in African soils. Volcanic ash soils are important locally but relatively unimportant overall since most soils are old and well weathered. Large areas, especially in West Africa, are dominated by soils with low phosphate sorption capacity and the low availability of fertilizer P is, therefore, not a widespread problem in these soils. For these soils, comprising alfisols, some ultisols, all very sandy soils (USDA classes) and the approximately equivalent soils in other classification systems, a higher clay content seems to be correlated with greater phosphate sorption. Modest P applications only are needed, perhaps 25-50 kg/ha for the maximum yield in previously unfertilized soil, and the economic applications for optimum return will be less.

- Phosphate sorption is related to soil type. Phosphate sorption and, hence, P requirement tends to follow the order oxisols > ultisols > alfisols > entisols. Inceptisols may show a particularly wide range since their classification is not dependent on inherent chemical properties. However, it is important to note that there is great variation in phosphate sorption between soils and within classes of soils, and there is a wide overlap between soil classes.

- Measurements of phosphate sorption are a useful way of characterizing the likely fertilizer P needs of a soil, and enough data are becoming available to make widescale comparisons possible and valuable. More soils should be analysed by phosphate sorption isotherms to add to this base of data and increase its value. Such projects could usefully investigate many aspects of the interaction of phosphorus, soils and crop nutrition. These include variations in phosphate sorption over small and large areas, particularly in relation to land use or soil properties and local classification. More work is greatly needed to relate measured phosphate sorption to crop growth and to estimate appropriate values for target P concentrations in solution for various crops. It can be carried out in conjunction with any agronomic experiment where a few different rates of application of fertilizer P are to be used.

- Ideally, the methods should be standardized and that introduced by Fox and Kamprath (1970) will probably become the basic method, despite some objections. In all cases, the equilibration time must be around 24 h or more; 24 h is an experimentally convenient period. A fairly detailed experimental procedure is given in Appendix 1 to supplement the brief descriptions in journal papers. It can be adapted to suit local equipment and conditions. Data must be examined graphically and should be fitted to an equation; the Freundlich equation is almost always acceptable. Fitted parameters and graphs should be published for all soils of such studies. At present, SPR based on 0.2 mg/l is the most acceptable common ground for presentation of results as a single number. However, crops differ in their external P requirements and future comparisons will be greatly facilitated if results are presented with fitted equations so that calculation of SPR values based on different concentrations can be done easily.

- The time required to make phosphate sorption measurements ensures that it will remain a research rather than a routine method. However, it is evident that the hydrous sesquioxides of Al and Fe play an important part in determining phosphate sorption in African soils and their measurement can be easily undertaken. The disordered oxides, assessed by Fe and Al extracted by acid oxalate in dark conditions, are especially important. Therefore, it is recommended that Fe_{ox} and Al_{ox} should be measured in studies related to P availability in tropical African soils. Measurements of Al_d and Fe_d are also useful.

Section 4

Recovery of fertilizer P by crops

INTRODUCTION

Annual crops usually take up 5-25% of phosphate from soluble fertilizers in the year of application (Wild, 1988) but data on the recovery of fertilizer P from African soils are very scarce. The literature indicates that fertilizer recovery within the first year is likely to be in this range and, if cropping is continued, very high recoveries in the field are possible. Child *et al.* (1955) found that on an acid laterized red earth soil at Kericho, Kenya, Napier grass recovered 21.8% of an application of 14.7 kg/ha P within six months. After four years and four fertilizations totalling 58.7 kg/ha P, eight cuts of the grass recovered 67.2% of added P. On an alfisol in Ghana, Nyamekye (1990) found that no less than 68% of 25 kg/ha fertilizer P could be recovered in grain and stover of two consecutive crops of maize. Good recoveries of P may be expected in a short time in pot experiments where the intensity of root exploration is high. Data of Bache and Rogers (1970) for two Nigerian soils from Samaru and Yandev, a loamy fine sand and a coarse sand respectively, showed that about 44 and 37% of applications of 38.75 and 25.83 mg/kg respectively could be recovered in three months' grass growth with three or four cuttings. The main exceptions to P recovery better than 10% are on the highly sorbing soils derived from volcanic ash, where P recovery is poor. In line with this expectation, potatoes on a Rwandan andosol recovered only 1.2% of 84 kg/ha fertilizer P (Vander Zaag and Kagenzi, 1986).

It appears that although many soils are P deficient, fertilizer efficiency can still be good. It would therefore be wrong to conclude that 'P fixation', suggesting that fertilizer P is lost forever, is always a serious problem. Nevertheless, the phosphate sorption studies previously described show that most added P is retained by the soil, and it is normally found that P which is unused by the crop or sorbed on the soil becomes less available or extractable with increasing time in the soil. Sorption studies on a relatively short timescale show that once sorbed, P is not so readily desorbed. The fate of unused fertilizer P is discussed in standard soil chemistry texts (e.g. Wild, 1988; Brady, 1984) and it is evident that the residual P may be held in several forms, since P moves through a cycle in the soil components.

THE P CYCLE

The phosphorus cycle differs from the well characterized carbon and nitrogen cycles in that mineral components provide a major reservoir of P and more pools of P are therefore involved. On the other hand, there is no gaseous loss of the element and the soil solution holds a very small part of the soil P, so leaching loss is small and not normally agriculturally significant. This also makes it probable that the P turnover does not proceed as quickly as for C and N because so little P is immediately available to rapid soil processes. Phosphorus cycles may appear quite complex, since flows of P occur between many soil, plant and animal components. A straightforward example devised for soil research purposes is given in Figure 5.

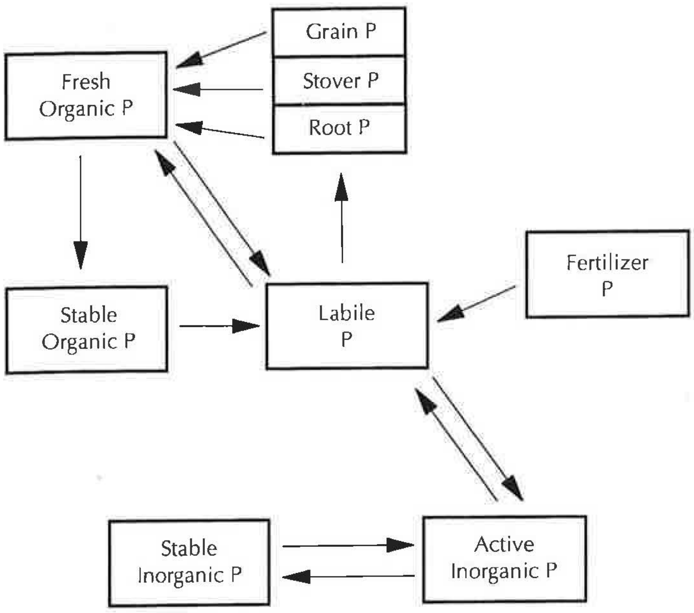


Figure 5 The main flows and pools in the soil P cycle illustrated by the model of Jones *et al.* (1984)

Three inorganic pools are normally postulated:

1 Phosphate in solution;

2 Phosphate held in a pool that is considered labile and readily desorbed over a growing season to supply plants; and

3 Firmly held phosphate that is combined so that it is only slowly released.

Additionally, much phosphate, usually the majority of the soil total P, is combined within mineral particles and is unavailable on a year-to-year timescale because it is released only by weathering. Fraction 2 is generally considered to be mainly phosphate adsorbed on mineral surfaces and combined in slightly soluble minerals such as the calcium phosphates. The exact nature of fraction 3 is less certain but suggestions include sparingly soluble minerals, surface and precipitated phosphate, that is inaccessible because it is trapped inside soil aggregates, and phosphate that has undergone solid state diffusion into other mineral particles.

The source of organic P is plant material. In the model of P cycling devised by Jones *et al.* (1984) the soil microbes that decompose plant residues and the undecomposed plant litter constitute the pool of fresh organic P (Figure 5). Decomposition of fresh organic P releases phosphate which contributes to the labile (plant available) pool. Decomposed organic material forms a stable pool of organic P from which progressive decay can slowly release more phosphate. Eventually the material remaining is resistant to further microbial breakdown and forms humified soil organic matter. Although this model uses two fraction of soil organic P – the fresh and the stable – in reality there is a continuous spectrum of materials of different composition.

REACTIONS OF P WITH SOIL

The reaction of added P with soil may be studied by soil incubation. The amount of P available after incubation may be assessed by extractions with a reagent or less frequently by a pot experiment. Incubation studies on the reaction of added phosphate with soil show that large amounts of phosphate are taken out of solution very quickly, but that uptake of P by soil continues at an ever decreasing pace for many days (see Figure 4). The study of the rates of reaction of added phosphate with soil has always been considered in terms of the reactions with inorganic components only, generally by considering a dynamic equilibrium between three main components:

$$\text{Solution P} \rightleftharpoons \text{Labile P} \rightleftharpoons \text{Firmly held P}$$

In describing the course of phosphate sorption with time in incubation experiments, a simple empirical equation of the following form is usually the best description (Barrow, 1983):

$$P = k\, C^{b1}\, T^{b2}$$

where P = observed sorption
C = concentration of phosphate in solution
T = time
k and superscripts b1 and b2 are constants

In developing a fuller understanding of phosphate sorption it is also necessary to account for the effects of changing pH, ionic strength and temperature on sorbed phosphate and also to account for the differences between results under adsorption and desorption. For example, the rate of interchange of P between pools increases with increasing temperature, and the solution/labile equilibrium shifts towards the solution side of the equation; the labile to firmly-held P equilibrium is much slower. Barrow (1983) synthesized all the known major effects into a model form. It is accepted that the initial fast exchange between solution P and labile P is some form of ligand-exchange (Munns and Fox, 1976; Hsu, 1964) but the chemical nature of the slow reaction has been the subject of speculation. For his model, Barrow favoured solid state diffusion by phosphate ions into the mineral crystal lattice (Muljadi *et al.*, 1966; Holford and Mattingly, 1976). The slow reaction might also be due to precipitation or recrystallization of sparingly soluble phosphate salts (Van Riemsdijk *et al.*, 1977), or migration of phosphate to surface sites of low accessibility within soil aggregates (Willett *et al.*, 1988). A combination of all mechanisms is possible.

It may be expected that a relatively quick forward reaction (labile to firmly held P) will give a poor residual availability as the labile pool is depleted. However, the reaction is not irreversible and slow desorption of firmly held P influences results of laboratory soil incubation experiments (Madrid and Posner, 1979; Hingston *et al.*, 1974). By its nature, it is more difficult to study than the adsorption reaction but, from the point of view of the residual effects of fertilizer P on plants, the slow desorption is of special importance. Slow desorption will have greater influence on the P supply to crops than may be indicated by incubation experiments because roots are in the soil for longer periods of many months. During depletion of the labile pool by roots, the slow desorption replenishes the labile pool, countering the initial decline in P availability. Thus over an adequate period of time, slow desorption might eliminate initial differences between soils. This concept agrees with the results of Enwezor (1977c) on Nigerian soils, which also demonstrate that the concept of a slow reaction reducing P availability is applicable to typical African soils and that differences between soils can be found. Ten soils were incubated for up to six months with added phosphate and then available P was assessed by maize in pots. Yield was inversely related to phosphate sorption, as would be expected, and response to the phosphate fertilizer decreased with ageing of the phosphate in the soil. There was a positive relationship between phosphate sorption capacity and the decrease in availability over the ageing period. Two more maize crops were grown in sequence and, in these, the yield differences due to ageing disappeared, as fertilizer P was remobilized by slow desorption. However, residual P gave significant yield increases only in soils with low phosphate sorption. High sorption capacity thus appeared to be associated with low residual effect.

CONCLUSION

- Experiments demonstrate that P becomes less available on prolonged contact with soil. But such work has been carried out mainly with the objective of examining soil chemistry and the results have not been quantitatively related to residual value in the field. Because a major objective of studying the reactions of phosphate with soil is to explain the immediate and long-term availability of fertilizer P, assessments of P residual value in the field will be considered in greater detail in the next Section.

Section 5

Residual effects of fertilizer P

NEED FOR FIELD MEASUREMENTS

Field experimentation for the practical assessment of P residual effects is scarce; in temperate countries, most soils have previously received P fertilization at high rates and current fertilizer P applications are usually maintenance requirements. Historically, the desire to quantify residual value, in Europe, was created by the need to allow for the value of nutrients purchased by an outgoing tenant farmer in the price paid by the incoming farmer. In high-intensity farming systems, fertilization is required on a regular basis but the frequency of application may be altered. Therefore, some studies (e.g. Mattingly, 1968) have compared the relative effects of (a) fertilizer P applied annually with (b) fertilizer P at three times the annual rate, applied only once every three years. The second management method relies upon the residual value to maintain the P supply to crops. It requires a higher initial investment in fertilizer but the costs of application are lower.

However, the situation is different in developing countries. The subsistence farmer needs to improve his yields and soil fertility from a low resource base of nutrients in the soil, rather than just maintain the existing level of fertility. In tropical Africa there are particular environmental and economic constraints. In areas of uncertain rainfall, achieving reliability in food production is usually more important than obtaining the maximum yield. The cost of fertilizer to the farmer is much higher and the system of supply is often inadequate. It is, therefore, important that farmers are enabled to take account of residual value and get the best advantage from it. Assessment of residual value could be of increased importance if tropical agroforestry systems are successful in improving the efficiency of nutrient use. Inputs of fertilizer could then become less frequent (desirable in remote regions with transport problems for inputs) than would be needed under conventionally improved agriculture.

PRINCIPLES AND PROBLEMS

As the recovery of P in the first year of application is almost always less than 25% and loss of P by leaching or gaseous evolution is negligible, the unused P must build up in the soil, provided erosion does not take place. Although most of the fertilizer P that is added may seem to be unavailable to the first crop, its effects can last a very long time. A most striking example of this was provided from the Rothamsted (UK) long-term experiments reported by Johnston *et al.* (1969). Residues of P fertilizer, either single superphosphate (SSP) or FYM, applied in the period 1858 to 1901 gave significant increases in yields of barley and sugar beet after an interval of more than 50 years without further P fertilization. The situation need not be greatly different in tropical soils, even in soils that are extremely deficient in P and highly phosphate sorbing, such as those of Hawaii.

There, the effects of massive doses of P applied in 1958 were significant nine years later (Fox *et al.*, 1968); and some effects were still apparent in 1990 (R. L. Fox, personal communication).

Soil incubation and pot experiments show that added P becomes less extractable and available with time. An important part of the literature on soil P is taken up by studies of the diminution of extractability of added P; the quantitative and correct assessment of the residual value to crops under practical conditions in the field is difficult. Because of the reaction of P with soil, the residual response in any one year is expected to be less than the fresh response but random and season-to-season variations caused by the weather tend to be large in tropical conditions. This means that the ratio of the responses of fresh and residual P is likely to be highly variable. Since yield response varies from year to year with the weather and other factors unconnected with nutrient P supply, both fresh and residual value should be measured and compared in the same year (Barrow and Campbell, 1972). This is rarely done because of difficulties in designing and doing such an experiment.

In most agronomic experiments, P is applied every year. It is then impossible to distinguish between the effects of fresh and residual applications. Some indication that the residual effect is working is given by the diminishing response to fresh P as residues build up, but the only way to show clearly the residual effect is by discontinuing fertilizer application. It is then fairly straightforward to demonstrate the effects of residues of fertilizer P simply by adding fertilizer and cropping for a few seasons. But, as outlined above it is more difficult to make a quantitative comparison of residual and fresh phosphate.

The terms 'residual effect' and 'residual value' are often used in a rather loose way to indicate benefits from old fertilizer. For clarity in the subsequent Sections, an important distinction will be drawn by the following usage:

- Residual effect is the current increase in crop growth, yield or P uptake caused by fertilizer P applied in earlier seasons;
- Residual value is the proportion of fertilizer P that remains in the soil and stays effective after the season of application. This definition is more restrictive than current common use of the term.

This is done because residual effects can vary from year to year influenced by factors other than P nutrition, making it difficult to infer the fertilizer residual value as defined here.

RESIDUAL EFFECTS IN TROPICAL AFRICA

Field assessments of P residual effects in African soils are sparse but there are enough examples to show that residual effects, under a range of crops and locations, are often large. In long-term experiments, the residual effect is usually significant for several years and the effects of fertilizer P residues have been observed for up to at least nine years after application.

Modest rates of P fertilization

In Tanzania, Le Mare (1959) compared fresh and residual P directly in the same year using the yield responses. In 1951, for groundnuts following maize, 28 kg/ha P applied in 1950 gave 60% of the effect of the same amount of freshly applied P. Maize following groundnuts did not seem to respond to the residues (an unusual event) but Le Mare remarked that a positive response was observed in two of the three experiments (the mean of which was presented), but this was counteracted by a negative response (that may be exceptional) at the third site.

In almost all other reports reviewed, direct comparison of fresh and residual P in the same season was not made but indications of the residual effects were obtained by applying P in the first year and continuing cropping for several seasons without further application of fertilizer P. To make some allowance for the inevitable fluctuations in yields between years, results can be expressed as the response to residues, either in kg/ha over a control or as a percentage of the control yield. Indicated this way, data of Le Mare (1959) show that the response by groundnuts to P applied in 1950 declined from 52% of the control in 1950 to 23% in 1951. Similarly, in a Nigerian experiment, a decline in the residual effect for groundnuts was clear after three years (Table 7a) at all rates of fertilization.

Table 7 Residual effects at modest rates of fertilization

a) Groundnuts at Kano, Nigeria*

		Yield (kg/ha)				Response (kg/ha)			(% of control)		
Rate of P application Year	Crop *(kg/ha)*	0	3.9	7.8	15.7	3.9	7.8	15.7	3.9	7.8	15.7
1947	Sorghum	870	1130	1245	1277	260	376	407	30	43	47
1948	Groundnuts	927	1276	1269	1374	349	342	447	38	37	48
1949	Groundnuts	529	723	732	702	194	203	173	37	38	33
1950	Groundnuts	510	611	608	621	101	98	111	21	19	22

* Yield response to three rates of P applied in 1947; mean of banded and spot-placed treatments (Greenwood, 1951)

b) Beans, maize or millet at Makaveti, Kenya#

		Yield of grain (kg/ha)			Response (kg/ha)		(% of control)	
Rate of P application Year	Crop *(kg/ha)*	0	19.6	39.2	19.6	39.2	19.6	39.2
1952	Millet	405	930	1123	525	718	130	178
1953	Maize	173	326	448	153	275	89	160
	Beans	757	916	1007	159	250	21	33
1954	Maize	1923	2509	2706	586	783	30	41
	Millet	411	529	587	118	176	29	43
1955	Maize	917	917	1106	0	189	0	21
	Millet	1249	1356	1440	107	191	9	15
1956	Maize	603	659	730	6	127	9	21
	Millet	787	871	912	84	125	11	16
1957	Beans	785	826	908	41	123	5	16

\# P applied in 1952 only (Boswinkle, 1961)

Demonstration of the disappearance of the residual response may require a field experiment of many years' duration. At Sambwa in the Dodoma region, Tanzania, on a red-brown coarse sandy loam, an initial application of 23.4 kg/ha P was effective for four maize crops over four years as shown by the following effects of P applied in 1962 (Anderson, 1970a):

	Main effect of P: grain yield response Response		
Year	(kg/ha)	(% of control)	Comment
1962/3	470	20	Direct effect – year of application
1963/4	500	22	
1964/5	120	30	Drought
1965/6	65	11	
1966/7	nil	nil	

In a companion experiment with groundnuts (Anderson, 1970b), large phosphate x lime interactions were evident, which complicate exact comparisons, but superphosphate (46 kg/ha P) increased the yield by 15.6% in the first two years and by 5.7% in years three and four.

If a cropping frequency greater than one crop per year is practised, the decline in residues may be quicker and can be followed more closely. A rapid initial decline in residual effect is suggested by results of Boswinkle (1961) on a dark red friable clay loam at Makaveti, Kenya (Table 7b). The response to 19.6 kg/ha P declined from 130% (fresh) to 29% over five seasons, after which the response was no longer significant, while at a rate of 39.2 kg/ha P, the response was still significant after five years and nine crops. Substantial variation in the control yields will be noted, due to rainfall variations, but expression of residual effects in relation to the control reduced the impact of this variation. These data show that the residual effect can make a substantial contribution to the overall benefits of fertilization. The immediate benefit of 19.6 kg/ha P was a response of 525 kg/ha millet but, over the next nine crops, a total extra response of 309 kg/ha millet, 795 kg/ha maize and 200 kg/ha beans was obtained. Similarly, 39.2 kg/ha P fertilizer provided not just the initial 718 kg/ha millet but also another 492 kg/ha millet, 1374 kg/ha maize and 373 kg/ha beans.

These results suggest that at modest rates of fertilization, around 20 kg/ha P, the residual value is substantial for the first year or two, but the residual P may become ineffective after four or five crops on both sandy and clay soils.

High rates of P fertilization

High residual effects were also found on the alfisol at Nyankpala, Ghana (Nyamekye, 1990), where the unusually high uptake of P in both years indicates that fertilizer P remains effective at rates of application well above that required for maximum yield in the first year (Table 8). This example also shows the difficulty of making a numerical assessment of residual value, because the assessment is affected greatly by the control yield and maximum response. Control yield and P uptake dropped in 1988 relative to 1987, probably because of depletion of the native soil P. Comparing 1988 to 1987, 25 kg/ha fertilizer P gave a reduced yield response (down by 401 kg/ha) and P uptake response (down by 4.8 kg/ha) but, in percentage terms, the response in 1988 was similar or even greater because of the lower control yield. The lower yield response could be due to depletion of the remaining fertilizer P by plant uptake, reaction of P with soil, or reduced maximum yield potential from other limitations. Higher fertilizer rates did not completely restore yield and P uptake to the 1987 values: the maximum yield was probably limited by other factors. However, the apparent response, both in kg/ha and especially as a percentage of control yield, was in most cases much greater in 1988, due in part to the much lower control yield and the consequent increased gap between control and maximum yield. Fertilizer P continued to be effective at all rates in 1988, as demonstrated by the continued responses in P uptake. Thus, numerical assessment depends on control yield and potential yield and also on the rate of fertilizer used.

The experiments reported by Velly and Roche (1974) on residual effects are of particular interest since, geographically, they were exceptionally comprehensive with some 14 sites in Madagascar, and all experiments were conducted with enough rates of fertilizer to plot good response curves. Since the major crop was rice, many of the soils were hydromorphic, but dryland agriculture was examined at seven locations and the soils there were described as ferralitic or ferrugineous. At all sites, P was applied only in the first year; a control and five

Table 8 Residual effects at high rates of fertilization using maize at Nyankpala, Ghana*

Rate of P application	Yield/P uptake (kg/ha)				Response (kg/ha)			(% of control)		
Year *(kg/ha)*	0	25	50	100	25	50	100	25	50	100
Direct and residual response of grain										
1987	2969	4544	4528	5020	1575	1559	2051	53	53	69
1988	1323	2497	4014	3843	1174	2691	2520	89	203	190
Direct and residual uptake of fertilizer P										
1987	10.1	19.5	20.3	28.4	9.4	10.1	18.2	93	100	180
1988	5.7	10.3	18.1	22.0	4.6	12.5	16.4	81	220	289
Cumulative uptake	15.8	29.8	38.4	50.4	14.0	22.6	34.6	89	143	219

* P applied in 1987 only on Tingoli series soil, classed as alfisol (USDA) or luvisol (FAO); results for flat plots with broadcast fertilizer (Nyamekye, 1990)

rates of P application (up to 279 or 437 kg/ha P) allowed changes in the response curves over the years to be examined. In general, three phases in the development of the response curve could be distinguished (Figure 6). In the first and second years, less than 131 kg/ha P was usually sufficient for the maximum yield. In the third year, the response curve rose less abruptly and the yields increased progressively from one end of the curve to the other. For the fourth and fifth years, there were only small differences in the yields from residues of the lowest rates of applied P but the highest rates of applied P still gave significant responses. This development is as would be expected from progressive exhaustion of the lowest rates of P by plant uptake, but with continued availability of residues from the high rates. However, the maximum attainable yield tended to decline over the years, suggesting that the availability of the remaining P was reduced by reaction with the soil.

In the dryland experiments, crops were often varied between years, making comparison of changes in response to residues difficult, but it was clear that all the crops, i.e. maize, groundnut, soya, cotton, upland rice, oats, wheat and *Stylosanthes*, were capable of responding to fertilizer P residues. In five experiments, maize was grown in both the first two years and these results demonstrate that in all soils the lowest rate of applied P gave a significant residual effect (Table 9). With the measurement of a full response curve, the highest yield can be taken to be close to the potential maximum. The percentage relative yield response was calculated:

$$\text{Relative response} = \frac{\text{Response to P for a particular treatment}}{\text{Maximum response}} \times 100\ (\%)$$

In the D'Ihosy soil, the maximum and control yields were approximately constant from year to year and the residual effects were almost as good as the direct effects when calculated as either the yield response or the relative response. These data show clearly that the residual value of fertilizer P can provide great benefits in addition to the direct response. Often, control and/or maximum yields change between years for reasons probably unrelated to P supply. The resulting difficulty of making comparisons without a direct measure of the effect of fresh P can be seen. For example at Cap Diégo, all yields declined

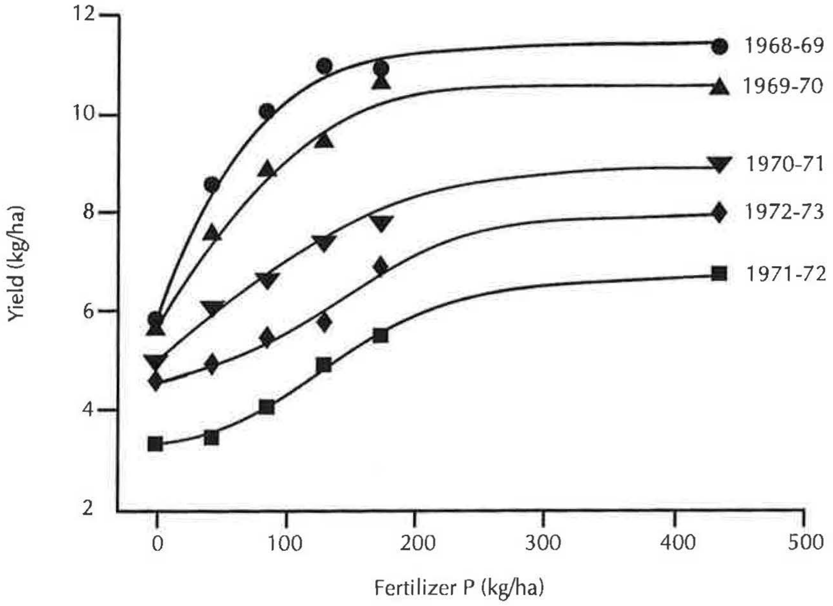


Figure 6 Development over five years of the response curves relating rice yield and fertilizer P added in 1967 at Belanitra, Madagascar (Velly and Roche, 1974)

Table 9 Direct and residual responses to P by maize grain in five soils of Madagascar (Velly and Roche, 1974)

Fertilizer P (kg/ha)	Yield (kg/ha)	Direct response (kg/ha)	Relative response (%)	Yield (kg/ha)	Residual response (kg/ha)	Relative response (%)	Yield (kg/ha)	Residual response (kg/ha)	Relative response (%)
Year	1965-1966			1966-1967			1967-1968		
La Sakay sol ferralitique									
0	3087	–	–	4160	–	–	3466	–	–
44	4080	993	42	4756	596	36	4924	1458	45
87	4317	1230	52	5286	1126	67	5263	1797	55
131	5030	1943	83	5498	1338	80	6115	2840	87
175	5440	2353	100	5838	1678	100	6507	3041	93
437	5310	2223	94	5569	1409	84	6741	3275	100
	1967-1968			1968-1969					
Cap Diégo sol ferrugineux tropical									
0	4007	–	–	2385	–	–			
35	4822	815	35	3623	1238	62			
70	5188	1181	51	3722	1337	66			
105	5201	1194	52	4270	1885	93			
140	5434	1427	62	4240	1855	92			
280	6310	2303	100	4404	2019	100			
	1964-1965			1965-1966					
D'Ihosy sol ferrugineux tropical									
0	418	–	–	569	–	–			
35	2532	2114	94	2517	1948	86			
70	2372	1954	87	2463	1894	84			
105	2668	2250	100	2387	1818	81			
140	2385	1967	87	2455	1886	84			
280	2649	2231	99	2827	2255	100			
	1964-1965			1965-1966					
D'Anketrakabe sol ferralitique									
0	2119	–	–	2979	–	–			
35	4024	1905	66	4810	1831	40			
70	4218	2099	73	4911	1932	42			
105	4360	2241	78	5980	3001	66			
140	4607	2488	86	6520	3541	78			
280	5003	2884	100	7541	4562	100			
	1967-1968			1968-1969					
Fianarantosa-Matriatra sol ferralitique									
0	323	–	–	1617	–	–			
44	1984	1661	44	4965	3348	47			
87	2608	2285	60	6902	5285	74			
131	2364	2041	54	7214	5597	78			
175	3265	2942	77	8042	6425	90			
437	4120	3979	100	8751	7134	100			

from year one to year two but, at all fertilization rates less than maximum, residual response (kg/ha) was higher in year two. Because the maximum response was lower in year two, the relative responses were even higher. If crop growth had not been restricted by another factor in year two, then perhaps P would have been more limiting and the residual effects not so good. Conversely, at D'Anketrakabe, the maximum yield rose substantially and the relative response was generally lower although the residual responses in kg/ha were similar or somewhat higher. At Fianarantosa the yields rose substantially from year one to year two and the residual response also rose considerably; the residual value of P in this soil was obviously excellent because old fertilizer could support much larger yields and responses in year two.

A particularly dramatic yield response was given by the lowest rate of P (fresh or residual) at D'Ihosy, a hydromorphic ferruginous soil. This suggests that the soil had a very low phosphate sorption capacity and that all the fertilizer P remained fully available, but there is no additional information to support that possibility. In general, it seems that the residual value in the second year was high for all soils. The relative responses to direct and residual P could vary from the first to second year, suggesting that soils might differ in the residual value, but it is not possible to confirm this without simultaneous assessment of direct and residual effects in the same year.

Other examples

Further qualitative support for the existence of valuable residual responses is given by other experiments with various crops and cropping systems. Near Machakos, Kenya, fertilizers, including about 60 kg/ha P as double superphosphate, were applied over three years to grazed pasture and the residues increased subsequent yields of beans, sorghum and maize by 200-300% (Pereira *et al.*, 1961). Phosphorus was the most limiting nutrient on this soil. Unfertilized groundnuts following maize fertilized with N, P, K, lime and organic matter responded significantly to residual P on a forest ochrosol in Ghana (Ofori, 1973) in each of two years. For tobacco at Kutsaga, Zimbabwe, residues of 234 kg/ha P were equivalent to 55 kg/ha fresh P after an interval of at least three years with a grass cover crop between application and cropping (Ryding, 1983).

Where soil P is already at an adequate level, there may be no initial response to fertilizer P but, as cropping depletes the labile P, the fertilizer P added earlier becomes effective. Thus, in a four-year experiment at Kadawa, Nigeria, 60 kg/ha P had no effect at first, but it started to give significant increases in wheat yield after the third crop, two years later, and in maize yield after the fifth crop, three years later (Singh and Balasubramanian, 1983). Similarly, in Sierra Leone upland soils, cassava yield was not increased by the initial P application but the tuber yield later increased in response to the fertilizer because of its residual effect (Haque and Walker, 1980). In a Sierra Leone alluvial soil, Brams (1973) found that an initial application of 19 kg/ha P (giving significant responses) was sufficient for three subsequent years and crops (maize/rice/groundnut) as there was no further response to fresh P, indicating a residual value sufficient to feed the crops. However, as this soil initially contained about 27 mg/kg Bray-P, it was already well supplied with P.

Comparisons between soils

Multicentre trials to a standard design are used to reveal differences in fertilizer response. However, such comparisons are not so easy for residual value as there is no generally accepted method for quantifying it. The work of Velly and Roche (1974) indicates that residual values in the second year differed little between Madagascar soils.

Some evidence that P residual effects can vary between soils was given by Le Mare (1974) from multicentre experiments with cotton in Tanzania during 1964-67. In most regions, the first and second residual responses made important contributions to the total effect of 448 kg/ha P as superphosphate (Table 10). Residual responses were always less than the direct effect but were insignificant only in the Kahama group of soils. In Geita, Musama and Biharamulo soils, the residual effects seemed to be smaller than in the remaining groups, where the sum of first and second residual effects (in years two and three after fertilizer application) equalled or exceeded the direct effects. Thus, there were differences between soils in the residual effects of P but these could not be related to soil properties.

Soils of five countries (Bangladesh, Ghana, Thailand, Indonesia and Turkey) were compared in an experiment to a standard cropping pattern of maize/legume intercrop in the first year and maize alone in the second year (IAEA, 1986). In the first year, responses to P (30 kg/ha) were obtained at all sites and with both maize and legumes. More fertilizer (30 kg/ha; ^{32}P labelled) was added

Table 10 Residual effects of 448 kg/ha P fertilizer on cotton in different zones of Tanzania during 1964-67 (Le Mare, 1974)

	Response in yield of seed cotton		
Zone(s)	Direct effect (kg/ha)	First residual effect (kg/ha)	Second residual effect (kg/ha)
Mwanza, Kwimba, western Maswa (29 experiments)	333	206	146
Geita, Musoma, Biharamulo (36 experiments)	178	73	21
Kahama (4 experiments)	404	negligible	negligible
Shinyanga (5 experiments)	235	104	157
Nzega (3 experiments)	637	444	353

in the second year and only maize was grown. Residues of the first P application gave no significant increases in P in the grain, total dry matter yield or P uptake, although there was a non-significant tendency for fresh P uptake to be greater where a legume had been the previous crop at all sites; this might be a result of the greater removal of P in the previous year by maize. The soil supply of phosphorus was estimated by isotopic dilution of the labelled fertilizer and this did not reveal any apparent increase in the soil phosphorus supply. Since the amount of fertilizer used gave modest yield increases, there are two possible interpretations: (a) there were no significant residual effects or (b) more likely, since residual effects are found in most soils, the residual effects were overshadowed by the provision of a large fresh supply in the second year; this design did not allow the residual fertilizer to be effective.

Pot experiments at Reading

Sites differ not only in soil type but also in climatic and other factors. The only way to make a precise direct comparison between soil types is by a pot experiment in a glasshouse, which eliminates environmental differences, although it has, of course, to be recognized that the yields obtained from the fertilizer residues will not correspond directly with yields and effectiveness in the field. Despite the evident diversity of tropical soils, such a direct comparison of residual values has not been performed. Therefore, a recent project for ODA and NRI at the University of Reading compared six tropical soils in a pot experiment designed to minimize the effects of differences in weather between seasons. The experiment and results will be reported in detail in scientific papers: the main features are given here.

In the first cropping season, residues of fertilizer P were created in pots of soil under grass. In the second season, the same pots were cropped to grass again without adding fertilizer P in order to assess the effectiveness of the residues. The response to residues was assessed in comparison with the response to fresh P in soil that had been stored during the previous season. For each soil, there were six treatments, comprising nil and five rates of fertilizer P (as monocalcium phosphate) with basal dressings of N and K. A preliminary experiment showed no response to micronutrients. The maximum rate of fertilizer P ranged from 200-900 mg/kg, and varied between soils because of differences in plant response. For each treatment there were triplicate pots containing the equivalent of 200 g oven-dry soil, except for Sitiung soil where duplicates were used. *Panicum maximum* grass (CIAT variety #604) was grown from seed for eight weeks in a glasshouse and watered daily to field capacity. At harvest, the roots were separated from the soil and total P uptake by herbage and roots was measured.

One African soil, a ferralsol (pH = 6.5) from Kwale, Kenya, and the Cerrado dark red latosol from Planaltina, Brazil, a well characterized high sorbing oxisol, were also included in the experiment. These two soils are both typical of the tropics, being well-leached soils with their mineralogy dominated by iron oxides, so their results make an interesting contrast. Some field results for the Cerrado soil are described below (in the next subsection) and indicate that the residual value of added P is high. In contrast, the Kwale soil has a low phosphate sorption capacity, but no information on field residual effects is available. Phosphate sorption parameters are given in Table 6 (Section 3) and the direct and residual effects in the pot experiment are illustrated in Figure 7.

In year one, the response to fertilizer P was much better in the Kwale soil than the Cerrado soil; this can be attributed to its much lower phosphate sorption. In year two, the difference between soils in residual effect was not so obvious; for the same amount of fertilizer applied in the previous year, the P uptakes (and yields) were not dramatically different. Quantitative estimates of the effectiveness of the residual P were made by calculating the response per unit P using the slopes of the P uptake against fertilizer P lines, as illustrated in Figure 7. For year two, the slopes were calculated in two ways: (a) P uptake/mg P added and (b) P uptake/mg P remaining in the soil, allowing for P uptake in year one. The slopes were as follows:

			Slopes of response lines	
	Year		Kwale soil	Cerrado soil
Fertilizer P added	1	(a)	0.508	0.163
Fertilizer P added	2		0.139	0.091
Residual P	2	(b)	0.274	0.109
Ratio b/a			0.539	0.670

On average, the proportions of applied P taken up were 50.8 and 16.3% for Kwale and Cerrado soils respectively in year one, but were much closer in year two at 13.9 and 9.1% respectively. If the P uptake/mg of residual P (i.e. allowing for crop uptake) was calculated, it was clear that in Kwale soil, a greater proportion of residual fertilizer P was still available : 27.4% as against 10.9% in

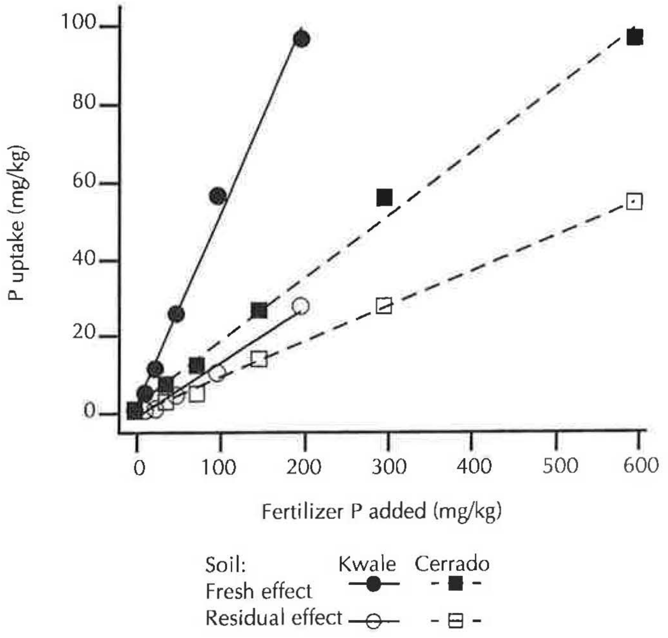


Figure 7 Fresh and residual effects in a pot experiment of fertilizer P in soils of contrasting phosphate sorption properties

Cerrado soil. It seemed that an important reason for the small residual effects in Kwale soil, especially from low rates of P application, was that a high proportion of the fertilizer P was recovered in the first year. A high enough rate of residual P fully restored the maximum dry matter yield. As the availability of fertilizer P was assessed in two consecutive crops, the decline in its availability over this period can be assessed by the change in the slope of the response lines. It is suggested that the ratio b/a estimates the residual value, the proportion of added P which stays effective. It was fairly similar in both soils. The decline was greater in Kwale soil, suggesting that, although the direct effect of P was better in Kwale, the residual value was similar or a little less than in Cerrado soil. This result is important because it suggests that the direct and residual effects of fertilizer P are not automatically closely associated.

RESIDUAL EFFECTS IN OTHER TROPICAL AND SUBTROPICAL SOILS

Residual effects have been of special interest in the Cerrado soils of Brazil which have high phosphate sorption and high fertilizer P requirements. Although much P is needed for reasonable yields, the residual value of it is still considerable; after application of the 580 kg/ha required initially on the dark red latosol at Planaltina, maize yields of 6250 kg/ha were maintained and 24.1 kg/ha P were taken up by the fifth crop (Yost *et al.*, 1981). On another site, 175 kg/ha P gave good yields four years later, although the increase in extractable P was small (Couto *et al.*, 1985). Thus high phosphate sorption in oxisols does not seem to be a bar to large residual effects in the field.

Useful comparisons can be made with assessments of P residual value in Australia because of widespread P deficiency in its soils, many of which, as in much of Africa, are old and strongly weathered. For clover at three locations in New South Wales, comparisons in the field were obtained by measuring the response per unit of fertilizer P (fresh or residual) in the linear relationship between relative response and fertilizer P. Residual effectiveness in terms of fresh P equivalent was 35-61% in the first year after application, 14-46% in the third year and 17% in the fourth year (Holford and Gleeson, 1976). Values of around 50% for the effectiveness of P after one year were found by Arndt and McIntyre (1963) in a lateritic soil and Fisher and Campbell (1972) in an alfisol. After seven years, superphosphate still had 8% of its initial value in the lateritic soil. Experiments with both pastures and legumes in Western Australia showed that the effect of superphosphate declined by about 50-70% in the first year in lateritic soils (Bolland *et al.*, 1984; Bolland and Bowden, 1984) and by about 50% in sandy soils (Bolland *et al.*, 1987a, 1987b). These results indicated that the availability of residual P is significant but reduced for the next one or two years after fertilizer application, and that after about four or five years, the effects become small. This agrees reasonably well with results from the African sites when the variations in control yield were small.

The Australian work seems to have benefited from lower variability, and principles developed there can be drawn upon as they are relevant to the soils of Africa. The experimental data of Arndt and McIntyre (1963) and Fisher and Campbell (1972) were later fitted to models by Janssen *et al.* (1987) and Probert (1985) respectively. The models predicted the effects well and the use of a model makes it possible to express the residual value in a single parameter, avoiding the need to make a specific comparison at specified rates of fertilization. Hence it is easier to compare soils and it is considered that the best way to investigate differences in residual value (between soils) is through modelling of data, as will be discussed in the Section 6.

RESIDUAL EFFECTS OF SLOW-RELEASE P FERTILIZERS

Both phosphate rock and organic manure, when directly applied as fertilizer, release phosphate slowly but the mechanisms of release are different: phosphate is released from rock by chemical dissolution; organic manure decomposes as a result of microbial action. The slow release of nutrient P can be a disadvantage in that P may not be available at the critical early stages of crop growth, and an advantage in that the slow release may improve overall availability by limiting the extent of the reaction of mineralized P with soil.

Phosphate rock

Phosphate rock (PR) is often less soluble and hence less effective initially than soluble fertilizer P but, because it does not dissolve so quickly, the effects of PR persist for a long time. Over seven years, the effect of PR in an Australian lateritic soil declined only to 60-70% of the initial effect on sorghum, whereas the effect of superphosphate declined to 8% of its initial effect (Arndt and McIntyre, 1963); the direct effect, however, was much greater for superphosphate. Bolland and Bowden (1984) found that two types of PR (Christmas Island and Queensland apatite) had similar effects on pasture year by year over six years, while the effect of superphosphate declined substantially. These results suggest that after a variable period in the soil, PR could become more effective than soluble fertilizer because of this slower decline. Thus, in their review of PR use, Khasawneh and Doll (1978) observed that it was commonly assumed that residual effects were greater for PR than for soluble fertilizer P, but the results then available did not in general conform to that assumption. They concluded that with equal amounts of applied P, superphosphates were always superior in the first three or four years. These conclusions were based mainly on American results and, since then, further experimentation including more tropical and subtropical soils has taken place.

Where availability of P in the PR is low, it remains that way: Christmas Island C-grade rock remained only 2-9% as effective as superphosphate over five years in an Australian lateritic soil (Bolland *et al.*, 1984). Where the PR is highly soluble and soil conditions are such that it is effective, direct effects near or equal to those given by superphosphate are found. The effects then decline over subsequent years in the same way as for the superphosphate. This conclusion is suggested by results in a selection of soils known or likely to have a high phosphate sorption capacity, such as a Philippines andept and an Indonesian ultisol (Harris, 1985), an Ethiopian andept (Nnadi and Haque, 1988) and some New Zealand soils (Mackay *et al.*, 1984). The high phosphate sorption would ensure that P concentration was always low and therefore conducive to rock dissolution. (It must be remembered that at the same time, high sorption diminishes the ability of plants to take up P released.) An extensive comparison of 10 kinds of partially soluble fertilizer including PRs of differing availabilities was carried out over eight years on the highly sorbing Brazilian Cerrado soil (Goedert and Lobato, 1984). At the first crop, differences in agronomic efficiency were large but from the fifth crop onwards the efficiency was similar for all sources. This agrees with an earlier result of Anderson (1965) that for Minjingu rock (an effective one) applied to pastures on Tanzanian red soils, superphosphate was more effective over a short period but, after three years, superphosphate was not significantly better than Minjingu rock. Similarly, for groundnuts at Sambwa, Tanzania, Anderson (1970b) found that Minjingu PR was less effective than double superphosphate in the first year, but was just as good by the third year after application.

In low-sorbing soils of the savanna zone of Nigeria, and Togo, PR gave residual effects as good as those of superphosphate (Mokwunye, 1979). In other alfisols, Bationo *et al.* (1986) found that a sufficient basal dose of PR was capable of maintaining yields over the next two years, and comparisons of an agronomic efficiency index indicated that it was better to apply PR as a large basal dose than split it between the years.

On balance it would seem that phosphate rocks of intermediate to low solubility do not, initially, give such good yields as those obtainable with soluble phosphate but, after three to five years in the soil, this difference, and also differences between rocks, becomes less. This applies equally to strongly and weakly sorbing soils.

Organic manure

Manures, particularly those based on animal dung, should be an ideal source of P because other nutrients are also provided. The lower initial availability of P may be a particular limitation, until mineralization has progressed sufficiently, and crops may not fully recover from early P deficiency. In the long term, the increase in soil organic matter substantially increases sustainability (Section 1). Based on his work in West African work, Watts-Padwick (1983) concluded that although organic manures might give smaller initial response, they had a large residual effect. Direct assessment of the residual value of an organic manure along the lines of the experiments reviewed and suggested for soluble fertilizers has not been done, and does not seem appropriate. The general practice is to apply organic manures on a continuous, annual basis to try to build up soil organic matter and soil fertility. Hence the concept of the residual effect of a single application has limited usefulness.

CONCLUSIONS

Results of field experiments concerning P residual value in Africa indicate the following points.

- Fertilizer P normally gives significant yield increases in the first one or two years after application.
- The residual effect can last up to at least nine years or ten successive crops, as shown in more than one experiment. When experiments are extended and no additional P is applied in the subsequent years, the sum of the residual responses in crop yields is likely to exceed the direct response.
- Numerical assessment of the residual value is difficult because the size of the crop response which depends on (a) control yield and (b) maximum response, both of which are likely to fluctuate widely between seasons, and (c) the rate of fertilizer application.
- Overall, the examples given suggest that a year after application, residues of moderate rates of fertilizer (less than about 50 kg/ha P) have a value of at least 50% of the value of an equivalent amount of fresh P. This is reflected in the residual effects, i.e. yield response, provided the control and maximum yields vary little between years. This could form an approximate guideline to the likely residual effect.
- The residual effect of a low rate of P fertilization lasts for a shorter time than a high rate as fertilizer P is depleted by crop uptake.
- There is some evidence that the residual value differs between soils in Africa. Residual effects can even be equal to the direct response but appear to be small in some soils. However, proper quantification of residual value under field conditions is needed to investigate this further.
- It does not seem possible to relate residual effect and value to soil properties at present, but strong sorption of phosphate and a consequent high fertilizer requirement is not incompatible with good residual effects, at least in soils rich in iron minerals.
- Data for residual value in Africa agree reasonably well with data for soils under similar conditions in Australia.

- Many crops can take advantage of residual P. Most work has used maize and groundnuts and although data in one report (Le Mare, 1959) suggest that groundnuts are better able than maize to take advantage of residual P, it has not been clearly demonstrated that there are significant differences between crops.
- Phosphate rock (PR) applied as a fertilizer gives residual effects similar to those given by ordinary soluble fertilizers if it has a high P availability. If the PR is of intermediate or low solubility, it is always less effective than soluble fertilizer, but the residual effects are long lasting. After three to five years in the soil, differences between different PRs, and between PR and soluble fertilizer, are much less.

In general, the properties of residual P in African soils agree with current approaches to the chemistry of P in tropical soils. In recent years, advances have been made in the modelling of the P turnover in soil and in the development of relatively simple yet adequately realistic and precise models for P residual value. The time has come to apply these to African conditions in order to quantify residual value and thereby investigate possible ways of taking full advantage of the P residual value to improve the efficiency of fertilization.

Section 6

Modelling of P residual value

PURPOSE

Results of a single field or pot experiment are specific to the soil, site and prevailing weather conditions and the conclusions are of limited use in other locations. The objective of constructing a model is to make a numerical rationalization of the results; the results can then be summarized in a few parameters which describe the influences of soil, climate and management on the crop yield. If successful, adjustment of the parameters will enable the model to describe a wide range of conditions. Results of appropriately documented experiments can then be extrapolated to other sites.

MECHANISTIC SIMULATION MODELS

The logical starting point for modelling residual value is the P cycle, since transfers of P to and from the available pool control the changes in effectiveness of fertilizer P. A full model of the P cycle will inevitably be complex since, in principle, there are many different fractions and transformations of soil P. The choice of component fractions in a model is likely to vary according to the soil and crop that the model is initially designed around. Cole *et al.* (1977) devised a simulation model based on permanent grassland in temperate semi-arid conditions in the USA, in which there were five component pools of P above ground and six pools below ground, each of the latter being replicated in four soil horizons. The transfers of P between pools were based on mathematical descriptions of each pathway, reproducing the effects of pool size, soil water content, temperature, relevant soil properties and plant growth stage. Ideally, these equations should be based on an understanding of the physiological mechanisms involved but in practice it is usually necessary to use empirical relationships. Preferably, a short interval, such as one day, between successive calculations of the model, is used to incorporate weather fluctuations that can substantially affect biological processes. This type of model can be tested only in a very intensively monitored experiment, i.e. with daily measurements of the driving variables and in as many pools as possible. It is therefore a research tool which helps to identify aspects of the P cycle that have the most influence and indicate where the needs for more research are greatest. Cole *et al.* (1977) found that information on the rates of mineralization of organic P, and on the activity and morphology of roots, was needed most.

A logical progression from a mechanistic model for P alone is a model which can be integrated into other models to describe the C cycle and turnover of other major nutrients, because the turnover of soil organic matter is fundamental to supplies of N, P and sulphur (S). Jones *et al.* (1984) devised a P model to fit the database of the US Soil Conservation Service. To reduce the model to a more manageable size, fewer soil P fractions were postulated, i.e. five, including both inorganic and organic fractions (Figure 5). Nevertheless, even in this 'simplified' model, in addition to the P pools, some 43 parameters and pools were involved, all of which had to be calculated daily. A problem with this database was that no soil P measurements were included. Although the model could be fitted satisfactorily, an independent assessment of soil labile P in particular seems desirable in so complex a model, especially since there is evidence that the mineralization of P and the soil C/P ratio are relatively independent of C and N mineralization (Duxbury *et al.*, 1989).

Further simplification of a model is necessary to enable its application to a wider range of datasets. This can be done by reducing the number of pools to be measured, increasing the time interval for calculations, and taking greater advantage of empirical relationships between desired model parameters and more readily measurable soil properties. The CENTURY model for soil organic matter dynamics (Parton *et al.*, 1988) retained nine soil P pools but had only a monthly time interval and a single soil horizon. To allow for variability in organic matter composition C/P ratios were allowed to fluctuate within limits. Like the two models previously referred to, it was developed for temperate permanent grassland: a relatively simple system. It was applied to tropical conditions (Parton *et al.*, 1989) using data for (a) maize at Yurimaguas, Peru, where a reasonable simulation of organic matter flux was found but where P data were not available and (b) grasslands at Serengeti, Tanzania, where discrepancies between predicted and actual grass production and soil C were in conflict with the original postulate that P was the major limitation on grass growth. In both cases, the amount and detail of information were inadequate to reformulate model relationships, and Parton *et al.* concluded that various adaptations were needed to make the model applicable to tropical conditions. Factors relating to the P cycle that would be needed were (a) the temperature and moisture relationships with metabolic rates (determining P transformations), which might be different in the tropics since biota are adapted to different climates, (b) the diverse mineralogy of tropical soils, which should be explicitly considered and (c) appropriate methods for characterizing the active and passive pools.

It may be concluded that, at present, mechanistic models are of no practical help in the agronomic assessment of the residual value and residual effects of fertilizer P or manure P in tropical soils, but they do indicate some research needs. Further determinations of the effects of soil mineralogy and soil organic matter on direct and residual effects of added P in tropical African soils, and studies of the decomposition rates of litter and other fresh organic material would provide information on the more easily assessed parts of the P cycle. Such studies would provide the information needed to turn the development of mechanistic modelling towards a better understanding of the processes occurring in the soils of Africa.

SIMPLIFIED EMPIRICAL MODELS

In contrast to the complexity of mechanistic models, empirical models postulate just two fractions of soil P. These pools are called different names by different authors, but are always conceptual pools, defined by being available or unavailable to plants. Neither pool is explicitly identified with a chemically characterized fraction of soil P. Simplification is also made by using a longer period, a month or a year, for the time interval of model calculations. No account is taken of soil water or temperature because, with a time interval of a month or more, they would have no relevance to the day-to-day variations that control microbial activity.

Russell (1977) proposed a two-compartment model with monthly calculations, and the size of the pools was determined by a balance of inputs and outputs: fertilizer applied and losses by erosion and crop removal. All processes were described by first-order rate equations, i.e. the rate of transfer was proportional to the originating pool size. The transformations considered were numbers 1, 2, 3 and 5 of Figure 8a (see 'Wolf Model' below), plus erosion losses. Barrow and Carter (1978) modified this concept because, in laboratory studies of P reactions with soil, first-order kinetics did not describe correctly the changes in extractable P. They proposed a model in which residual P availability was such that loss of P was proportionately greater at lower levels of applied P. Similarly, the offtake of P in crops was considered likely to be a higher proportion of the available P fraction at low P levels. This model could be applied successfully to field experiment data although the modification made little difference to the fit.

A relatively imprecise model is acceptable for field experiments even though it might not be suitable for laboratory incubation studies. Chemically extractable P could be measured at frequent intervals during a field experiment but to measure available P, as shown by plant uptake, at frequent intervals requires sequential harvesting, adding considerably to the scale of work. Furthermore, the most meaningful practical assessment of residual effect is by the yield of the desired crop, which is commonly the mature grain or fruit, and can therefore be assessed realistically only at the end of the experiment. Thus, assessment of residual P availability as that experienced by the plant is probably best done at annual intervals.

Wolf model

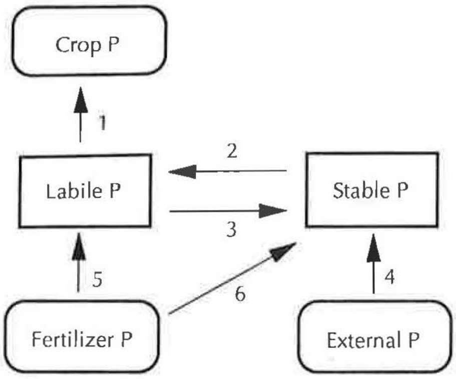
The model of Wolf *et al.* (1987, see Figure 8a) was based on essentially the same P cycle as that of Russell (1977), with a turnover of P between labile and stable components. An annual time interval for the calculations was adopted; the transfers of P being calculated at the end of each cropping season. This has the effect that P transferred to the stable pool in year one remains unavailable during year two, but may re-emerge for uptake in year three, which appears somewhat unrealistic. Transfers 1, 2 and 3 were first order while transfer 4 which accounts for P supplied by atmospheric deposition and weathering of minerals was constant. Estimation of transfer 4 and calculation of initial values for the labile and stable pools depended on the assumption that the nil fertilizer plot was at dynamic equilibrium and the net supply of P for crop uptake depended entirely on transfer 4. This is unlikely to hold for land brought into cultivation recently and made extra approximations necessary to initialize the model. The rate constants for transfers 2 and 3 were expressed in the form of time constants, defined as reciprocals of the fraction of pool P transferred each year, so that the longer the time constant, the slower the transfer rate.

In applying this model, Janssen *et al.* (1987) found that time constants of five and 30 years were suitable for the labile to stable and stable to labile transfers respectively, for three different tropical field experiments, provided fertilizer rates were not too high and seasonal variations not too strong. Probably the most important model parameter was the fraction of labile P taken up by the crop (called the 'uptake fraction of labile P') which was used to calculate transfer 1. It was estimated from the apparent recovery of fertilizer P by comparison with the control plot. In the application of this model, it was found that for most data the uptake fraction of labile P declined markedly as the rate of fertilizer increased. The field experiment results utilized include one of the experiments in Madagascar reported by Velly and Roche (1974), and examples in Brazil and Australia. The model was designed to be as simple as possible in concept and application to encourage its use. All calculations can be done by hand without computing facilities. However, because P uptake measurements are rarely made (as noted in Section 4), the model could be tried on only these few examples from the literature.

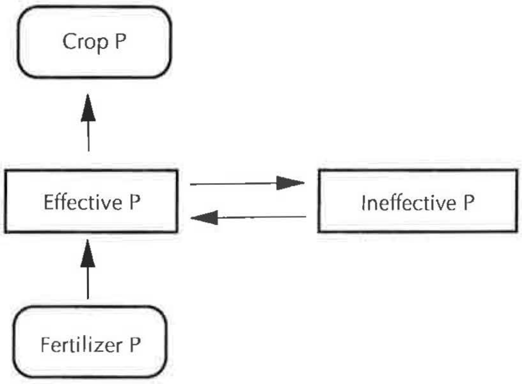
Probert model

The model of Probert (1985) employed the simplest concept (Figure 8b): transfer from effective to ineffective P was first order, while ineffective to effective was constant each year. Nevertheless, it gave a good description of yields and P uptakes by *Stylosanthes* pasture under semi-arid conditions in northern Australia over a three-year period. The change in effective P was described by the following equation, where PE = Effective P (potentially plant available), PU = P taken up and removed by the crop and subscript i refers to the year:

$$PE_{i+1} = (PE_i - PU_i).f + k$$



(a) Model of Wolf *et al* (1987)



(b) Model of Probert (1985)

Figure 8 Simple models for assessment of P residual value

Each year, the amount of effective P is diminished by the measured P uptake and then adjusted by the above equation to obtain PE for the next year. Parameter f can vary between 0 and 1 and equals the proportion of PE staying effective after one season. It is used to calculate the transfer of P from the effective to the ineffective pool. It thus strongly influences the P residual value: a high value of f implies a high residual value for P, while a low value indicates a low residual value. Parameter k represents the release of P from stable pools, plus outside additions by atmospheric deposition, and determines the lowest amount of effective P. One more parameter is required: p_o equals the initial value for PE before fertilizer addition in year one.

The relationship between PE and yield (Y) was assumed to follow a Mitscherlich equation:

$$Y_i = a_i(1 - \exp[-c.PE_i])$$

In order to fit the data for crop yield, P uptake and fertilizer P, the model equations must be written for each year and then fitted by iterative procedures using a computer. In principle this is a very flexible approach as the model equations can be adapted for plots which are given different amounts of P each year. A major advantage of this model over the model of Wolf *et al.* is that parameters f and k, which determine the transfers between effective and ineffective pools, are optimized for each soil and standard errors calculated, enabling numerical comparisons between soils. Important constraints are that (a) there must be enough data to give a full response curve, from nil fertilizer to the maximum attainable yield, otherwise the fitting of the exponential equation may not be possible and (b) some plots must achieve the maximum yield in each year or season. Probert found that it was necessary to allow parameter a_i (expressing the maximum potential yield) to vary between years, an important consideration under the variable rainfall of semi-arid climates. However, as there was no improvement in fit resulting from allowing parameter c (expressing response per unit fertilizer) to vary between years, this parameter can be regarded as a fixed characteristic of the soil and crop combination.

The model is based on the assumption that the Mitscherlich equation correctly describes the relationship between effective P and yield. This equation is based on the concept of a diminishing return from each additional increment of fertilizer P. Although it has been used for a long time, alternative relationships could be employed which might give different outcomes to the modelling process. The following quadratic equation is one example:

$$\text{Yield} = a \times (\text{PE})^2 + b \times \text{PE} + c$$

This equation is useful because it is more easily fitted to data by linear regression. It also fits the concept of progressive diminution of the yield response at higher fertilizer rates and should lead to similar outcomes as are given by the Mitscherlich equation. The use of a response model consisting of two intersecting straight lines has increased in popularity and is convenient for practical applications because it suits the objective of identifying clearly a point when further fertilizer application has no worthwhile effect. However, it has no obvious mechanistic base. In some pot experiments, and occasionally in field experiments, a sigmoidal curve is found, whereby the first increment of P gives a rather small yield increase and the response per unit of fertilizer then improves. Eventually, the response diminishes again in the usual way. It is rarely observed in the field but was identified by Le Mare (1968) in Uganda. If appropriate, a sigmoidal curve, such as the Gompertz curve in which four parameters a, b, c and m are optimized, could be incorporated into the model calculations:

$$\text{Yield} = a + b \times \exp(-\exp[c \times (\text{PE} - m)])$$

Comparison of Wolf and Probert models

Both the models of Probert (1985) and Wolf *et al.* (1987) are useful in characterizing direct and residual value through basic agronomic experiments extended for more than one year. Neither needs intensive site monitoring but annual measurements of P uptake are vital. Both the original papers give adequate detail for their application, and the main relative merits of the two models are compared in Table 11. An important advantage of the Probert model is that parameter f which determines the effective to ineffective transformation is optimized for each soil. After the direct recovery of P from the labile or effective pool, it has the most influence on the overall residual effect and could be used to assess residual value.

APPLICATION TO A POT EXPERIMENT

Both the Wolf and Probert models could be fitted to data of the P residual value in the pot experiment described in Section 5. The methods and results will be described in full in separate journal papers; the results showed an interesting contrast between the Kwale ferralsol and Cerrado dark red latosol.

Application of the model of Wolf *et al.* was simple for this experiment because the percentage recovery of fertilizer P was almost constant over all rates of application. The model application followed the equations given in Appendix 2 (Table A4). Monocalcium phosphate powder was used as fertilizer P and the labile fraction of fertilizer P was assumed to be equal to 1. The fraction of the labile P pool taken up (*uflp*) was calculated as the slope of the relationship between P uptake and fertilizer added (Figure 7 in Section 5). This parameter was therefore 0.508 and 0.163 for Kwale and Cerrado soils respectively (see Section 5 'Pot experiments at Reading') and these values were used to calculate transfer 1

Table 11 Comparison of the models of Probert (1985) and Wolf *et al.* (1987) relevant to their application to field experiments

Model of Wolf *et al.*	Model of Probert
Calculations can all be made by hand	Optimization of model by computer required
Transfer constants not optimized in original model although they could be adjusted by trial and error	Provides explicitly calculated parameters with standard errors for making numerical comparisons between soils
Deals only with P uptake data; these are needed for each year	Yield required each year; P uptake needed every year except the last. Should be more accurate as results are based on both yield and P uptake, and economic value of the fertilizer is reflected in the yield whereas P uptake is not in itself a measure of productivity
Can be applied to very simple datasets with only one plus a nil treatment fertilizer control	Requires multiple fertilizer applications to characterize the yield-effective P response curve
Difficulties if yield variations from year to year are large	Seasonal variability in potential yield catered for
Difficulties initializing model where soil P turnover is not at approximate equilibrium in nil fertilizer plots	

(Figure 8a) for each rate of fertilization. To calculate transfers 2 and 3, the constants recommended by Janssen *et al.* (1987) were used so that transfer 2 equalled 1/30 of the stable P and transfer 3 equalled 1/5 of labile P. This sequence of calculations is equivalent to the original model. The results are shown in Table 12 and it was found that the model tended to overestimate the P uptake from fertilized pots in the second year (1989). Discrepancies were greatest at low P fertilizer rates for Kwale soil and at the highest rate for Cerrado soil. Considering the simplicity of the model, which relies only on data available from a simple direct fertilizer response experiment, the outcome seems acceptable as a way of rationalizing the experimental results. It is therefore emphasized that correct assessment of the direct recovery of fertilizer P (the uptake fraction) from the labile pool is very important in the assessment of P turnover.

Table 12 Fitting the model of Wolf *et al.* (1987) to P uptake by grass on a pot experiment on two tropical soils

	P uptake (mg/kg)		
Fertilizer P (mg/kg)	Actual 1988	Actual 1989	Modelled 1989
Kwale soil, Kenya*			
0(Control)	1.08	0.93	1.08
12.5	5.43	1.09	2.93
25	11.73	1.39	4.79
50	26.02	4.90	8.50
100	56.86	10.60	15.91
200	96.86	27.97	30.75
Cerrado soil, Brazil#			
0(Control)	0.84	1.22	0.84
37.5	7.74	3.18	4.74
75	12.61	5.23	8.63
150	26.88	14.21	16.42
300	56.15	27.92	31.99
600	97.00	54.88	63.14

* Uptake fraction of labile P = 0.508

\# Uptake fraction of labile P = 0.163

Table 13 Fitting the model of Probert (1985) to grass dry matter yields (Y) in a pot experiment on two tropical soils

Fertilizer P (mg/kg)	Dry matter yield (g/kg) Actual 1988	Actual 1989	Modelled 1989
Kwale soil, Kenya			
0 (Control)	2.84	2.47	–0.40
12.5	13.13	2.85	4.09
25	21.27	3.83	7.06
50	24.11	10.04	11.43
100	24.51	20.56	14.32
200	24.43	26.67	26.40
Cerrado soil, Brazil			
0 (Control)	2.28	3.77	2.15
37.5	15.09	7.14	9.28
75	17.89	13.06	14.80
150	21.41	24.22	21.27
300	23.10	26.79	26.64
600	21.07	28.31	28.71

Table 14 Fitted parameters for the model of Probert (1985) applied to data from the pot experiment on six tropical soils

Soil	Parameter a_1	a_2	c	f	k	p_o
Manaus	23.08 ± 0.72	37.32 ± 0.77	0.0322 ± 0.0030	0.560 ± 0.069	0.57 ± 1.82	5.71 ± 1.27
Rengam	21.87 ± 0.47	31.17 ± 0.49	0.0677 ± 0.0073	0.300 ± 0.039	3.26 ± 0.59	8.32 ± 1.23
Cerrado	21.98 ± 0.45	28.88 ± 0.41	0.0241 ± 0.0016	0.420 ± 0.037	1.45 ± 1.31	5.02 ± 1.21
Segamat	25.15 ± 0.50	33.66 ± 0.48	0.0272 ± 0.0022	0.322 ± 0.171	0.45 ± 1.25	11.56 ± 1.72
Kwale	24.60 ± 0.60	30.61 ± 0.74	0.0644 ± 0.0054	0.297 ± 0.031	–0.46 ± 0.46	1.95 ± 0.54
Sitiung	22.86 ± 0.60	29.14 ± 0.65	0.0254 ± 0.0027	0.196 ± 0.026	3.43 ± 1.76	4.42 ± 1.69

a_1 = maximum potential yield in year 1
a_2 = maximum potential yield in year 2
c = response per unit fertilizer
f = proportion of P remaining in effective P pool after one season
k = transfer of P from ineffective to effective pool
p_o = initial value for effective P pool

Application of Probert's model followed the specified model equations* exactly. Results for actual and modelled dry matter yields of Kwale and Cerrado soils are given in Table 13. Modelled and actual yields in 1989 were in close agreement for Cerrado soil but not so close for Kwale soil. For both soils, yield was underestimated in unfertilized soils and overestimated at the two lowest fertilizer rates. Fitted parameters for all soils are given in Table 14. The direct response to effective P, expressed by the Mitscherlich parameter *c* (see 'Probert model' above), varied greatly between soils and was much larger for Kwale soil than Cerrado soil on account of the lower phosphate sorption and greater P uptake per mg fertilizer in the former soil. This is in agreement with the fitted model of Wolf *et al.* The parameter *f* was greater (although not significantly so) for Cerrado compared to Kwale soil, suggesting that in Cerrado soil a greater

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*The equations actually used are given in Appendix 2 (Table A5). This experiment lasted for two years and only the equations relating to years 1 and 2 are appropriate.

proportion of PE remains effective from one year to the next and less P is lost to the ineffective pool, i.e. the residual value was greater in Cerrado soil. This seems in line with the conclusion of Goedert (1983) that the residual value of P fertilizer in field trials was high in Cerrado soils although there is a large initial requirement. This difference between the two soils was not brought out using the model of Wolf *et al.*

Considering all six soils in the pot experiment, some significant differences between soils in parameter *f* were found, but these were not clearly related to phosphate sorption. As an example, for three soils, values of parameter *f* differed much less than their phosphate sorption values (Table 6). These soils were Kwale (Standard P Requirement = 35 mg/kg) Rengam (SPR = 107) and Segamat (SPR = 311). This suggested that residual value is not directly correlated with the direct effect. For the two oxisols from Brazil (Manaus and Cerrado) parameter *f* was rather larger than in the previous group and, within this pair of soils, phosphate sorption was higher and residual value lower in the second year in the Cerrado soil. The Sitiung soil containing volcanic ash showed a significantly lower value of parameter *f* than all the other soils, in agreement with literature on field experiments which suggests that residual value is low in andisols (Section 5). Parameter *k* did not seem to vary much between soils, only Rengam (and Sitiung) giving a higher value than the other soils. This is more in line with the assumption of the Wolf model that the transfer from stable to labile pools is constant in many soils.

APPLICATION TO SLOW-RELEASE P FERTILIZERS

Both the simple empirical models discussed above cater for the use of partially soluble P sources. In the Wolf model the proportion of fertilizer P, applied as phosphate rock, going to the labile pool is allowed for by an empirical fraction. This fraction was stated by Wolf *et al.* (1987) to be about 0.1 to 0.2 of the total P in the rock. It was pointed out that some of the PR going to the stable pool may in fact be almost completely unavailable if the rock is not very finely ground or treated in some way. In a similar manner, the Probert model for residual value can be extended to deal with a slowly or partially soluble P source by adding another parameter for optimization. It is asssumed that a fixed fraction (parameter *r*) of the applied rock becomes soluble each year and then the soluble P reacts with the soil in the same way as ordinary soluble fertilizer P and has the same residual value. Each year a further fraction of the applied PR dissolves. This model worked successfully for the description of yields up to three years after application of Christmas Island PR on an alfisol in N Australia (Probert, 1985) in conjunction with data for superphosphate. Assuming that the model is reasonable, the consequences on P availability in comparison with soluble P will be examined by model calculations in Section 8.

Manures could be treated in a similar way to PR for modelling purposes. Their more rapid initial decomposition which is always adequate to provide some direct fertilization effect would mean that the concept of a fixed fraction in one year, as used by the simple models, is less valid. A model with a time interval allowing calculations at least several times each year would be needed for prediction of organic P availability. It might be necessary to return to the simpler mechanistic models to account for the influences of water and temperature status on soil organic matter turnover.

CONCLUSIONS

- Quantitative information on P residual value in tropical African soils is very limited, although it is clear from the review that residual effects are frequently substantial. Work on simulation modelling of the P cycle in tropical soils in general (Parton *et al.*, 1989) shows that much more information on components, processes and simple P uptake data is needed. Quantitative assessments of residual value in more African soils would greatly assist fundamental studies and would provide data to relate residual effects to soil types and soil properties.

- Experiments testing P residual effects can be rationalized and the apparent transfers of P between available and unavailable soil P pools can be quantified using simple models. Applications of the simple models show that they give acceptable descriptions of the residual value, although they represent extreme simplifications of the P cycle. Because of the simplicity of their concept and application, they could readily be used to obtain quantitative assessments of P residual values in African soils by means of ordinary agronomic experiments and P uptake measurements. The model of Probert appears particularly appropriate for this purpose.
- There is some evidence that parameters describing the transfer of P between pools can vary between soils, but widely differing soils can have similar values for parameters which describe the loss of effective or labile P. To make use of this finding, parameters of the models could be correlated with other soil properties and soil classification. Sets of standard values for the parameters appropriate to the main soil types might then be devised for practical use.
- It seems that phosphate sorption is not an immediate guide to residual effects, and the properties which control the parameters are not yet revealed. It is necessary for more values of the residual value parameter (e.g. Probert's model parameter f) to be obtained first to develop this possibility.
- The measurement of P offtake from the soil in crops each year requires much practical work but this information is vital for the construction of a P balance sheet and the correct assessment of residual value. Care is required in experimental design, particularly for the Probert model, and in the following section appropriate experimental designs are outlined.
- Simple models can be modified to take account of the slow release of P by phosphate rock and manure used as fertilizers, but these modifications have been little tested.

Section 7

Experimental designs to assess P residual value

GENERAL

It has been established that it is necessary to compare direct and residual effects in the same season for quantitative assessment of residual value. The last year of an experiment is therefore particularly important because that is when the effects of fertilizer P of all ages are compared. Different experiment designs are required for pot experiments and field trials. In the pot experiment design, comparisons in the last season are emphasized for best precision in that season, and work is saved by (a) reducing the number of treatments in the earlier seasons and (b) storing soil without cropping for certain treatments. In the field it is impossible to store soil as such; fallowing, for example, is likely to change the fertility of the soil. Instead, it is desirable that the direct response should be assessed in all years as an insurance against major crop failure.

Although the residual effects can be very long lived (if enough P is added), the largest and most relevant residual effects are in the first and second years after applying fertilizer. Since fertilizer applications by farmers in developing countries are in, general, likely to be low and the large changes in the first few years will dominate the determination of model parameters, it is suggested that practical experimentation should be of three years' duration. The following designs are for this period.

In order to fit the yield response model of Probert (1985), there must be enough rates of P fertilization to reach the response plateau with some extra margin, because correct determination of the response parameters depends on having a wide range of crop yield and soil P data. Appropriate rates of P for the particular soil and crop combination in the experiment need to be determined beforehand through local experience or from a preliminary field or pot trial. Each year it is necessary to measure the crop yield (grain – if appropriate – and total dry matter) and total P offtake in each pot or plot: the latter analyses will form a major part of the whole experimental work involved.

FIELD EXPERIMENT

Highly variable experimental results are to be expected because of the extreme changes in environmental conditions prevalent in the tropics. It is therefore advisable to have some assessment of the direct response to P each year in the field as an insurance against some catastrophe spoiling results in the final year and reducing the value of the preceding work. Enough data should remain to fit the model.

Comparison between direct and residual effects of added fertilizer P in the same season and on the same soil can be achieved by splitting plots after a crop, so that part of a previously fertilized plot receives some fresh P and the other part receives none. The crop in the latter subplot then responds solely to the residual P. The principle can be extended to combining fresh and 'old' P in factorial combinations; in this way the value of residues is assessed in the presence of all rates of fresh P. Exact estimates of the residual value and the relative importance of fresh and 'old' P at each rate of fertilization can then be obtained. Results can be assessed by analysis of variance, with fresh and 'old' P as separate factors. In this method, however, the number of plots proliferates; with four rates of fertilizer (including nil P) and four replicate blocks there are 16 plots in the first year, 64 in the second and 256 in the third. The design is labour-intensive but it is comprehensive and easy to analyse statistically. It provides ample data to fit to a model. However, it is inefficient and unrealistic to apply the highest rates of P each year.

An alternative is to (a) assess the direct response most precisely in the first year with a full response curve, (b) assume that a fitted response parameter (e.g., Mitscherlich parameter *c* does not change much in subsequent years and (c) assess maximum response (e.g., Mitscherlich parameter *a* in the subsequent years by a very limited number of plots. Fisher and Campbell (1972) used an incomplete factorial design of only 11 treatments, with the direct response measured only in the first year. It was not possible to determine whether or not that direct response was atypical. Therefore, the new suggested design has a few treatments with fresh P in every year.

Suggested design

The suggested design is specified in Table 15. It is based on the following objectives.

- Where large initial rates of P are added (necessary to obtain a full response curve) subsequent applications are relatively small. This forms a test of the

Table 15 Suggested design of one block in a three-year field experiment to assess residual value of fertilizer P in conjunction with the model of Probert (1985)

Experimental schedule

Plot number	Treatment number*		
	Year 1	Year 2	Year 3
1	0	0	0
2	0	1	0
3	0	2	0
4	0	4	0
5	0	0	1
6	0	0	2
7	0	0	4
8	2	0	0
9	2	1	1
10	2	2	2
11	3	0	0
12	3	1	1
13	3	2	2
14	4	0	0
15	4	2	2
16	4	3	3
17	5	0	0
18	5	2	2
19	5	3	3

*Treatment number	Example fertilizer rate (kg/ha)#	Comments
0	nil	No fertilizer P
1	6	
2	12	
3	25	Ideally, 90% maximum yield reached between treatments 3 and 4
4	50	
5	100	More than enough P for maximum yield

\# Actual amounts to be adjusted for the soil and crop used: do not have to be the same throughout a multicentre experiment principle of giving a 'remedial' or 'investment' dose of fertilizer to raise soil fertility, followed by maintenance applications to offset crop uptake.

- In each year, about the same number of plots receive some fresh P (e.g. 12, 11 and 11 in years one, two and three respectively) so that each year is represented in the calibration of the direct response.
- In years two and three some plots receive fresh P for the first time (e.g. plots 2, 3 and 4 for year two; plots 5, 6 and 7 for year three) so that a simple direct response curve can be plotted for each year, if needed, to check the validity of the model.

The design has to be multiplied by the number of replicate blocks to be used: at least three are recommended. The plots are best laid out in completely randomized form within the block; the plot size depends on the crop used, and will be governed by local agronomic practice. The design has 19 plots; the 20th plot could be cropped without any fertilizer as a control to establish the N response (20 plots fit conveniently into a 4 x 5 plot block). It is suggested that the 20th plot is cropped as a nil P plot in year one and then used to improve the distribution of fertilizer rates if required. If the fertilizer P requirement was overestimated, plot 20 could be cropped without P in year two, and in year three, a new rate lower than rate number 1 could be applied to improve the direct response curve. If the P requirement was underestimated, a new, higher rate could be applied in years two and three to obtain the maximum yield.

The yield data that are used in fitting the model can be part (e.g. grain) or all of the crop. Since the grain or fruit usually constitutes the most desired part of the crop, residual value based on that yield seems the most suitable measure of residual effects.

It is assumed that other nutrients are not limiting within the maximum rate of fertilizer P used. Therefore, some fertilizer N will generally be required for this experiment.

Fitting the data to models

As concluded in Section 6, fitting field data to a simple model provides the best framework for interpretation of residual effects. This experimental design is intended to be analysed using the model of Probert, and the appropriate equations and a suitable computer program are given in Appendix 2A. The model of Wolf can also be fitted and very full details are given in the original paper (Wolf *et al.*, 1987). It was assumed by the authors that the uptake fraction of labile P could be different at varying rates of fertilization. However, in some cases, P uptake is directly proportional to P applied and an alternative method of applying the Wolf model is given in Appendix 2B, based on this assumption. The model is suitable when moderate or low rates of fertilizer P are used.

POT EXPERIMENT

The advantages of pot (glasshouse) experiments over field trials are that they are (a) more precise, (b) less affected by weather and pest problems and (c) smaller in scale and easier to conduct. Of particular relevance to residual value work is the ease of comparing different soils under standard conditions. Comparisons could also be made of the abilities of different crops to utilize residual P. However, the residual value and fitted parameters may well differ from those in field experiments for several reasons:

- the soil is more thoroughly explored by roots of the trial crop;
- water relationships in the soil are greatly different from those in the field;
- rates of immobilization into organic matter may differ because of different amounts of underground residues from present and past crops and weeds: microbial activity may also be different.

Because of a lack of comparability in conditions between field trials and pot experiments, the main value of a pot experiment is to compare one soil or crop with another. As with the field assessment of residual value, correct assessment of the direct response is essential since residual effects are compared with the response to fresh P.

In contrast to the field experiment, where large variations from year to year are likely and must be allowed for, work is saved in the pot experiment design by concentrating effort on the final year. The earlier years provide practice in the experimental work which can then be done more precisely in the important final year. However, more equations are needed to fit the Probert model.

Suggested design

The suggested design is detailed in Table 16. It is based on the principle that plants are grown in the first two years mainly to generate residues of fertilizer P, and so the main comparison of 'old' P with fresh P is made in the last year. The number of fresh P treatments is increased in the last year to improve precision of the yield response curve. Further economy in pot numbers is made by assessing

Table 16 Suggested design of a three-year pot experiment to assess the residual value of fertilizer P in conjunction with the model of Probert (1985)

Experimental schedule

Pot numbers	Treatment number* Year 1	Treatment number* Year 2	Treatment number* Year 3	Group number** (of data) Year 1	Group number** (of data) Year 2	Group number** (of data) Year 3
1-3	0	0	0	1	3	6
4-6	2	0	0	1	3	6
7-9	4	0	0	1	3	6
10-12	6	0	0	1	3	6
13-15	–	0	0	–	2	5
16-18	–	2	0	–	2	5
19-21	–	4	0	–	2	5
22-24	–	6	0	–	2	5
25-27	–	–	0	–	–	4
28-30	–	–	1	–	–	4
31-33	–	–	2	–	–	4
34-36	–	–	3	–	–	4
37-39	–	–	4	–	–	4
40-42	–	–	5	–	–	4
43-45	–	–	6	–	–	4

*Treatment number	Example fertilizer rate(mg/kg soil)#	Comment
0	nil	No fertilizer P
1	12	
2	25	
3	50	
4	100	
1	200	More than enough P for maximum yield

**Group number	Year	Fertilizer effect measured	Description
1	1	Direct	Fresh P added to soil
2	2	Direct	Fresh P added to more soil drawn from store
3	2	First residual	Group 1 pots recropped without more fertilizer
4	3	Direct	Fresh P in stored soil
5	3	First residiual	Group 2 pots recropped without more fertilizer
6	3	Second residiual	Group 3 pots recropped without more fertilizer

Actual amounts to be adjusted to soil and crop

the direct response in stored soil, thereby avoiding the need for many pots giving minimal yields up to the last year. In order to rationalize the structure, the data are divided into six groups of results, according to the year of cropping and whether the effect tested is direct or residual, as shown in Table 16. Each group has a particular model equation (see Appendix 2, Table A5). If triplicate pots are used, the number of treatments and pots per soil each year will be:

Year	1	2	3
Treatments	4	8	15
Pots	12	24	45

Three replicate pots are suggested for each treatment and the whole design has to be multiplied by the number of soils to be compared. Grass is suggested as a test crop, because the main objective of a pot experiment is to characterize the soil rather than the crop. Grass is relatively quick and easy to grow, small pots are possible and varieties tolerant of many different soil types are available.

Certain alternative experimental details will affect the results, e.g. (a) either the herbage may be cut at the soil surface and the soil left undisturbed until the next season or (b) the soil and roots may be separated by sieving after the growth of each crop. Yield and P uptake by both herbage and roots are measured. The latter procedure enables measurement of the total P taken up from the soil. Values for model parameters should then relate more closely to the reactions of P with the minerals in the soil. However, if roots are left intact in the soil, this will be closer to the field situation.

In the pots, root growth and exploration will be much more intensive than in the field and the larger amounts of root residues left behind would recycle more P than in the field. Difficulties might arise through the discouragement of germination and growth of the subsequent crops in soil with large amounts of decaying organic matter. The pots would need watering or incubation treatment to simulate field conditions during the uncropped period. In the more artificial situation with separation of roots, the soils can be dried (air dried or only partially) and stored in bags until the next suitable season or occasion in the greenhouse.

It is therefore important to specify the actual procedure used and maintain it in any series of experiments, because comparability of parameter values should be the aim. The author considers that as the pot experiment is an artificial soil characterization, the procedure of root separation should be followed as a standard procedure. As part of the soil has to be stored during the experiment, enough soil to last for the experiment must be sampled initially. Air drying and sieving are the most practicable methods of sample pre-treatment. Adequate supplies of other nutrients such as N and K must be ensured.

Fitting data to the Probert model

Since the purpose of a pot experiment is to characterize soil, the fitting of data only to the Probert model (1985) is recommended because it optimizes the model parameters for each soil. The model equations required and a suitable program are given in Appendix 2C.

Section 8

Modelling of some alternative P fertilization strategies

TESTING AND ADAPTING THE MODELS

Deficiency of P is a major constraint on the productivity of subsistence agriculture (Section 1), yet it seems that the use of fertilizer P is often difficult to justify at present on grounds of cost. From the review of field data it is clear that fertilizer P has substantial residual value almost everywhere that it has been investigated in tropical Africa (Section 5). It is therefore necessary to take account of this continuing effect to assess more accurately the full benefits of fertilizer P application. More precise identification of the benefits of fertilizer P, whether conventional or phosphate rock, may help in two ways: (a) it would provide a stronger incentive to find ways of supplying and fitting fertilizer into improved farming systems and (b) by classifying soils according to direct and residual P availability, it would focus work on appropriate systems for each soil category.

A major problem in carrying out this objective is that results of field experiments are site specific, but it is now possible to fit these data to simple models (Section 6), which provide a rational framework for interpretation. In these models, the short-term and long-term effects of fertilizer are simulated using a few model parameters to express soil properties that affect the yields over time. The advantage of presenting results in model form is that different fertilization strategies can be investigated without the immediate need for a field experiment. Fertilizer strategies that can be tested are (a) the effect on yields if fertilizer P is omitted for some years or (b) the subsequent effects of applying a large initial dose to remedy P deficiency. The simple models each take account of three main factors:

- uptake of P from a labile or effective pool in the soil;
- rate of transfer of P from the effective pool to a stable or ineffective pool;
- return transfer from stable to labile form.

If the parameter for each factor could be estimated, either directly or by association with some easily measured property or formal soil classification, model calculations would enable practical predictions of the long-term effects of P fertilization.

Uptake of P from the labile pool is particularly important and can be assessed from the direct response to soluble fertilizer. It is well established that phosphate sorption by soil, as measured in the laboratory, is in general inversely related to fertilizer P availability. As reviewed in Section 3, phosphate sorption can vary widely between African soils and differences in residual effects are to be expected from this factor alone; phosphate sorption is useful as a method of predicting the immediate fertilizer P needs of a soil in a high-input, high-yield system. So far, however, the results of sorption measurements have not been directly helpful in making fertilizer P recommendations for subsistence farming systems, which need to be improved more modestly by a low-input approach. The usual output of phosphate sorption measurements is a standard P requirement (SPR). This is the amount of P that would be needed for a high yield and is appropriate to a high-input system aiming for near-maximum yields. The problem of making recommendations appropriate to a low-input, modest-output system is more difficult: it is relatively easy to estimate more than enough for the best crop; it is less easy to prescribe just enough for a particular yield. For predictive purposes in the residual value models, it would be useful if phosphate sorption could be related numerically to parameters describing the yield response or P uptake caused by the labile fraction (e.g. Mitscherlich parameter *c*, or Wolf's uptake fraction of labile P, *uflp*). As yet there are no such established relationships. The main problem is that while phosphate sorption depends solely on the soil, the effect of fertilizer P or labile P depends also on the crop and the two would not have a general relationship.

Evidence so far is limited on the extent to which the residual value of fertilizer depends on soil properties. Also, there is no evidence to suggest that the return of P from the ineffective or stable pool differs much between soils, either from the original applications of the models, or from the pot experiment comparisons of the NRI projects reported here (see Section 5). Direct comparison of soils in the pot experiment showed that the transfer from effective to ineffective P could differ between soils, and laboratory incubation experiments also show that the decline in P availability can vary. The use of these parameters to describe the transfer of P between pools has been only recently established and there are no data to relate them to other soil properties: this is an area where research is needed.

The three factors controlling residual availability (P uptake from the labile pool; transfer from labile to stable; transfer from stable to labile) appear not to be closely related to one another, so the length and magnitude of residual effects could vary in a complex way between soils, as determined by the model structure. In order to examine the influences of these parameters on the overall utilization of fertilizer P, differing fertilization strategies will be modelled for four contrasting situations. These situations are represented as hypothetical soils with all combinations of high and low values for the direct and residual value (see Table 17). The model of Probert (1985) was found to be most useful and the calculations will be based on this model (the appropriate equations are given in Section 6 and Appendix 2). The parameters *c* and *f* are used to represent the direct effect and residual value respectively.

The Mitscherlich equation is used throughout. Other equations could be used, such as a sigmoidal curve as discussed in Section 6. The implications of its use will not be followed through here as it appears unusual in the field but would probably make large early additions of fertilizer more favourable.

HYPOTHETICAL FIELD EXPERIMENTS

A hypothetical field experiment with maize with a potential grain yield of 6000 kg/ha was considered; parameter *a* (the maximum potential yield) was set equal to 6000 for all years and seasonal variations were not taken into account. For all the soils parameter *k* (the annual release of P from the ineffective pool) was made equal to 2 kg/ha. It is rather less than the fitted values of about 5 kg/ha found in the Australian situation but more than the 0.3 kg/ha found for Brazilian Cerrado soil in the alternative model of Wolf *et al.*, and it roughly agrees with the values around 1 mg/kg found in the pot experiment described in Section 5.

Uptakes of P are required each year, and a constant P concentration of 0.2% in the crop yield (grain) was assumed, although it is recognized that this is an oversimplification; some luxury uptake of P occurs at higher fertilization rates and the concentration will normally be less than the 0.2% in P-deficient maize. If available, a more realistic equation relating P uptake to either yield or effective P could readily be incorporated into the model. However, as the offtake of P is not usually the largest single destination of P in each year, it is thought that the inaccuracy is not large enough to invalidate the model.

Variable model parameters

High and low values of the direct effect of P were represented by high and low values respectively of parameter *c*, and high and low values of the residual value for P were represented by high and low values respectively of parameter *f*. The principal variable parameters are given in Table 17.

Table 17 Variable model parameters

Soil	A	B	C	D
Direct effect	high	high	low	low
Residual value	high	low	high	low
Model parameters				
c	0.07	0.07	0.02	0.02
f	0.7	0.2	0.7	0.2
p_o	2.38	2.09	4.34	2.36
Unfertilized yield (kg/ha)	920	817	499	277

The values of p_o were obtained by trial and error so that the unfertilized soil would be at a steady state and the effective P and, hence, yield were the same each year if no fertilizer P was applied. Yield, effective P and p_o differ between soils because, for a steady state, the amounts of P transferred to the ineffective pool must be the same each year for all soils, as k is constant, although the percentage of effective P transferred is different.

First, the basic effects of varying the model parameters were illustrated by considering a standard P application of 80 kg/ha in each soil (Figure 9). This amount is over generous for soils A and B, as a near maximum yield was found. As expected, the yields declined more quickly in soils B and D, with low residual value, and yield response was minimal by year four. Considering only year two,

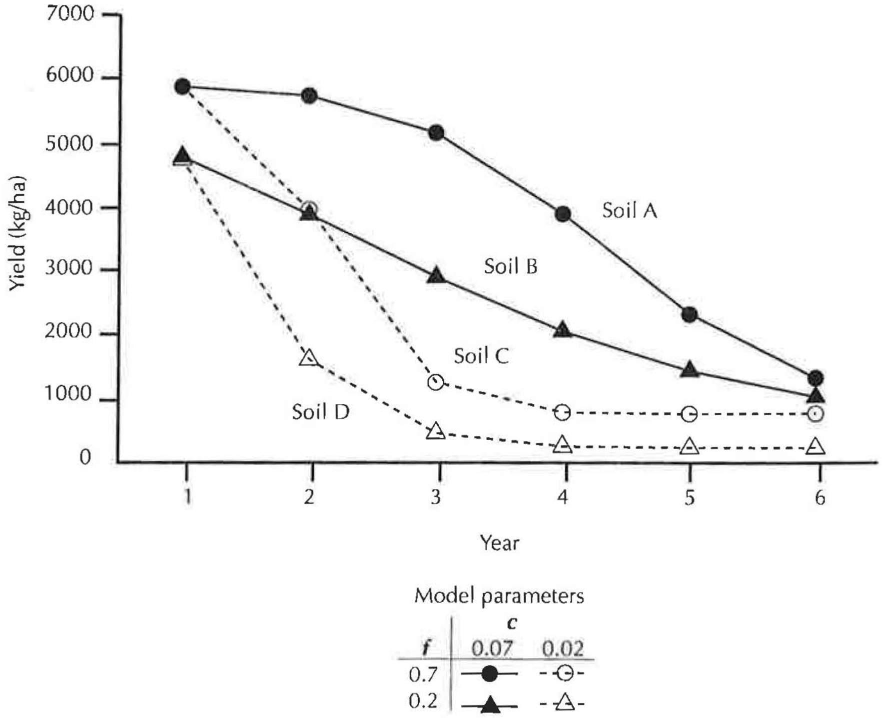

Figure 9 Effects of high (c = 0.07) and low (c = 0.02) direct effect and high (f = 0.7) and low (f = 0.2) residual value on modelled yields after a single application of 80 kg/ha P

the yield in soil B still seems reasonable, about 4000 kg/ha, two-thirds the maximum. The large excess of P applied in year one still gives plenty of effective P after transfer of P to the ineffective pool. If the yields in year two only are considered, there is little difference between soils B and C, of contrasting properties suggesting that field residual value experiments need to be run for several years for the full effects to be expressed. In soil D, where both direct and residual value are low, all yields after the first year are poor.

FERTILIZATION STRATEGIES

Different fertilization strategies were tested to illustrate the use of a model to explore the relative efficiency of various plans for fertilization.

Constant yield strategies

Using the model, the amounts of fertilizer required to maintain a particular yield were calculated. In year one, the amount of fertilizer required to correct the P deficiency of the soil is relatively large. After that, only a maintenance dressing is needed to offset crop uptake and net immobilization of P into the ineffective pool. Modelled results for a high-input strategy and four alternative low-input strategies are compared in Tables 18-20.

As the prime objective of a high-yield strategy is to sustain a high yield throughout, a yield of 90% maximum yield (5400 kg/ha) was specified, and the amount of fertilizer needed to achieve this each year was found by reversing the order of the model calculations. First, the effective P needed to give the 5400 kg/ha yield was calculated from the Mitscherlich equation, then the difference between effective P and the initial plus residual P was calculated. For the first low-input strategy (strategy 1), the distribution of fertilizer P was based on the high-input approach, comprising a remedial dose followed by lower maintenance applications. The same method of calculation was used but a lower yield (2000 kg/ha) was specified. This is one third of the maximum yield and represents between two and seven times the yield without fertilizer, depending on soil type. The modelled fertilizer requirements each year for the specified sustainable yields are given in Table 18.

For soils A and C, with high residual value, P requirement is much more in year one (than in subsequent years) in accordance with the concept of an initial remedial dose. However, for soils B and D, where residual value is low (only 20% of the effective P not taken by the crop remains in the labile pool), the

Table 18 Modelled P fertilizer requirements for constant yields in high- and low-input systems as influenced by direct and residual values

	Fertilizer required (kg/ha)							Total yield response	Yield response/kg P
Soil	Year 1	2	3	4	5	6	Total	(kg/ha)	(kg yield/kg fert.)
High-input system									
target yield 5400 kg/ha each year									
A	30.5	15.43	15.43	15.43	15.43	15.43	107.7	26 880	250
B	30.8	26.48	26.48	26.48	26.48	26.48	163.2	27 498	168
C	110.8	40.1	40.1	40.1	40.1	40.1	311.3	29 406	94.5
D	112.8	92.3	92.3	92.3	92.3	92.3	574.3	30 738	53.5
Low-input system (Strategy 1)									
target yield 2000 kg/ha each year									
A	3.41	2.54	2.54	2.54	2.54	2.54	16.1	6 480	402
B	3.70	3.43	3.43	3.43	3.43	3.43	20.9	7 098	340
C	15.93	6.88	6.88	6.88	6.88	6.88	50.3	9 006	179
D	17.91	15.02	15.02	15.02	15.02	15.02	93.0	10 338	111

fertilizer requirements remain relatively high each year, whether a low-input or high-input strategy is adopted. The yield response/kg fertilizer P was calculated over the six-year period considered to indicate the efficiency of fertilizer use. For all soils, fertilizer efficiency was better in the low-input system. This follows from the situation that, for high yields, effective P must be maintained at a high level, which also increases the amount of P transferred to the ineffective pool. Soils C and D, with low direct effect of P, always gave much lower fertilizer efficiencies than soils A and B. The lower uptake of P from the effective pool leaves behind more effective P potentially available for transfer to the ineffective pool.

It therefore appears that if a soil has a high phosphate sorption ability, leading to low fertilizer availability, a lower efficiency of fertilizer use is an inevitable consequence of requiring a greater P offtake in the crop. The model used assumes that the return of P from ineffective to effective form is constant each year. Eventually, of course, continued fertilization will increase the total P and the P deficit will be ameliorated more permanently; the model parameter *k* would have to be checked if the model is to remain accurate.

Alternative fertilization strategies

In a low-input system, there are several alternative strategies. If fertilizer is not applied every year, the effective P pool continues to supply P to the crop and is progressively depleted by uptake and transfer to the ineffective pool.

In the alternative strategies, a cropping period of six years was considered using the same total amount of P as in strategy 1 (see Table 18) but distributed differently. In strategy 2, it was spread evenly over all six years, which would ease the cash outlay for the farmer in the first year. In strategy 3, the P was applied in two equal amounts, at the first and fourth years. In strategy 4, all the P was applied at the start of the cropping period: this was simply to test the effect of infrequent fertilizer application on the efficiency of fertilizer use, it is not intended to be especially convenient or realistic. The year-by-year yields and efficiencies are given in Table 19 and illustrated in Figure 10; the efficiencies are summarized in Table 20.

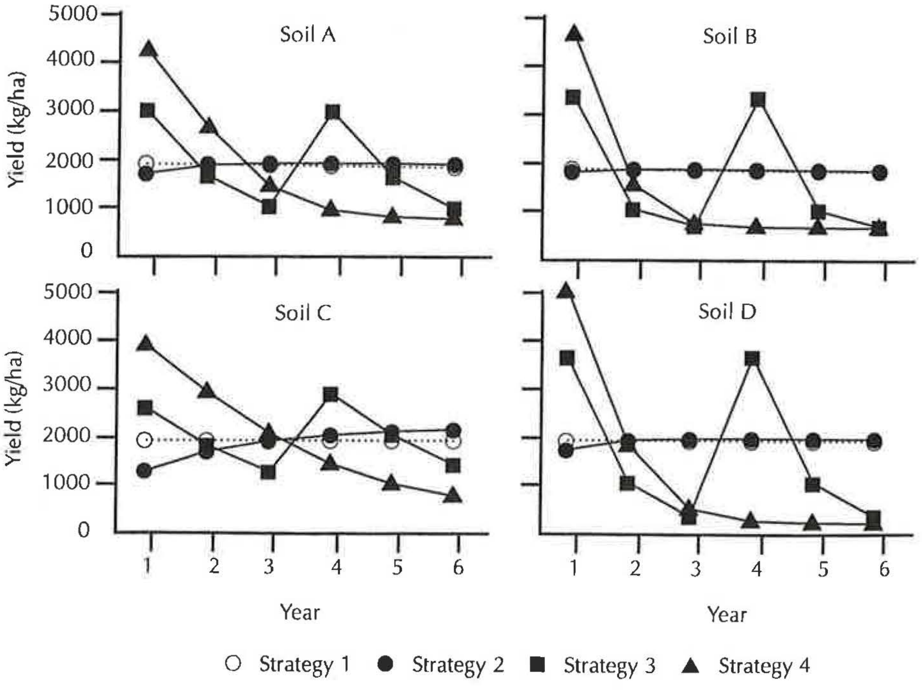

Figure 10 Modelled yields with different fertilization strategies

Table 19 Modelled yields with alternative fertilizer strategies for low-input systems as influenced by direct and residual values

Soil	Total fert. applied (kg/ha)	Year	*Yield (kg/ha)*						Total yield response (kg/ha)	Efficiency Response/ kg P
			1	2	3	4	5	6		
Strategy 2										
fertilizer distributed equally each year										
A	16.1		1 791	1 980	2 035	2 051	2 057	2 058	6 452	401
B	20.9		1 937	2 007	2 013	2 014	2 014	2 014	7 097	340
C	50.3		1 349	1 765	1 987	2 111	2 183	2 225	8 626	171
D	93.0		1 802	2 006	2 039	2 045	2 046	2 046	10 322	111
Strategy 3										
fertilizer applied in equal amounts in years 1 and 4										
A	16.1		3 109	1 757	1 138	3 135	1 773	1 143	6 535	406
B	20.9		3 503	1 172	839	3 504	1 172	839	6 127	294
C	50.3		2 675	1 890	1 336	2 967	2 115	1 488	9 477	188
D	93.0		3 742	1 115	418	3 751	1 118	419	8 901	95.7
Strategy 4										
all fertilizer applied at start of cropping										
A	16.1		4 354	2 768	1 563	1 078	953	926	6 122	380
B	20.9		4 797	1 674	880	821	817	817	4 904	235
C	50.3		3 990	3 002	2 142	1 507	1 089	834	9 570	190
D	93.0		5 109	1 899	576	324	284	277	6 807	73.2

Table 20 Modelled fertilizer efficiencies for alternative P fertilization stategies as influenced by direct and residual values

Fertilization strategy	Soil	Response/unit fertilizer applied (kg yield/kg P)			
		A	B	C	D
High input					
constant yield*		250	168	94.5	53.5
Low input					
Strategy 1					
constant yield*		402	340	179	111
Strategy 2					
contant fertilizer#		401	340	171	111
Strategy 3					
fertilizer every 3 years#		406	294	188	95.7
Strategy 4					
all fertilizer at start#		380	235	190	73.2

* From Table 18

\# From Table 19

With strategy 2, yields were lower in the first year and then built up, as expected. This strategy had little effect on the efficiency of fertilizer use (Table 20) compared to the constant yield option. Interestingly, the effects of infrequent fertilization varied markedly between soils. In soils B and D, with low residual value, the fertilizer efficiency declined with lower frequency of P application. This shows that if a low value for parameter *f* can be identified for a soil, frequent regular fertilizer applications give the best value. It is suggested that the larger applications made under strategies 3 and 4 increase the amounts of P transferred to the ineffective pool more than they increase the P uptake, whether or not the soil gives a good direct response.

By comparison, soils A and C, with high residual value, were less sensitive to infrequent fertilizer application. In soil A, strategy 4 reduced efficiency for the same reason as soils B and D. In soil C, less frequent application improved the fertilizer efficiency which was also improved for soil A in strategy 3. This may be due to fuller exploitation of the remaining effective P, which is not so rapidly depleted by transfer to the ineffective pool. This result would agree with field and pot experiments on the Cerrado dark red latosol. In field experiments, a high initial P requirement was followed by a good response to residues. In the pot experiment described in Section 5 this soil gave low value for direct response ($c = 0.0241$) and a relatively high residual value ($f = 0.420$).

FERTILIZATION USING PHOSPHATE ROCK

The main reason for direct application of phosphate rock (PR) as a fertilizer is to eliminate manufacturing costs but its lower P availability influences both direct and residual fertilization effects. The slow dissolution of the rock was incorporated by Probert in his model by assuming that a fixed proportion (parameter *r*) of the remaining rock dissolves each year. Thus, in the year of application, the effective P added by dissolution of the rock equals $r \times PR$, in the next year another $r \times (1 - r) \times PR$, and so on. To examine the interaction of this slow dissolution with the soil properties, further sets of model yields were calculated using this principle. Most long-term agronomic trials with PR start with a fairly high rate of P, and soluble P and phosphate rock are added at the same rate. For each model soil, P was applied only in year one and at the rates of soluble P required to give 5400 kg/ha (90% maximum yield). Two kinds of rock were modelled, a more soluble rock (rock 1) with $r = 0.5$ and a less soluble rock (rock 2) with $r = 0.1$. Comparisons of the effects of soluble P and the two rocks are shown in Figure 11. A longer time-scale was used because dissolution of rock is slow. Calculated fertilizer efficiencies are given in Table 21, although the potential efficiency for rocks would usually be greater if more time were allowed.

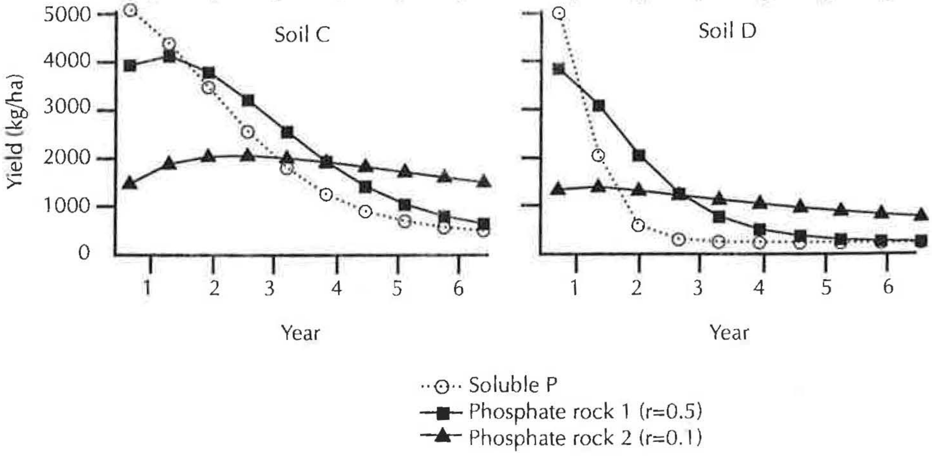

Figure 11 Modelled yields after a single phosphate rock application

Table 21 Modelled fertilizer efficiencies of P rocks with different solubilities as influenced by direct and residual values

Fertilizer form		Response/unit fertilizer applied (kg yield/kg P)			
	Soil	A	B	C	D
Soluble P		337	197	161	66.4
P rock 1 ($r = 0.5$)		384	290	182	97.8
P rock 2 ($r = 0.1$)		275	233	130	80.0

In year one, the yields from phosphate rock were always less than from soluble P as only a part of the P is available; this agrees with common findings. In all soils, the decline in yield was less steep for phosphate rock than for soluble P. This is because the supply of effective P is more closely matched to the plant requirement. The slow release of P from the rock preserves a part of the applied P from transfer to the ineffective pool. For the relatively soluble rock, the downward curve of the yield roughly followed that of the curve for soluble P, in approximate agreement with field results showing that the decline of effect of reactive PR is similar to that of soluble P (Section 6). For the relatively insoluble rock, there was a much slower reduction in fertilization effect. Indeed, in soils A, C and D, the yield was greater in the second year than the first, because the release of P to the effective pool was small and the latter was being built up while transfer to the ineffective pool was moderate. Although this modelled increase agrees with the hypothesis that the residual effects of phosphate rock fertilization may be greater than direct effects, it does not agree well with the conclusions of reviews (see Section 5). Similarly, for both rocks, the annual yield always overtook the soluble P yield; this is at variance with the review conclusions that the response to phosphate rock never exceeds the response to soluble fertilizers.

In all soils, fertilizer efficiency was greater for rock 1 than for soluble fertilizer. This improvement was greatest in the soils with low residual value ($f = 0.2$). For the less soluble rock 2, efficiency was not as high partly because a significant fraction of the applied P remained undissolved even after ten years.

CONCLUSIONS

The results of modelling indicate that for low-input systems, different fertilization strategies may be more suitable for different soil types.

- The efficiency of soluble fertilizer is insensitive to fertilizer distribution (over several years) in soils showing a good direct efficiency and high residual value. If fertilizer application is excessive, deficient or completely omitted in one year, the fertilizer will not be lost or wasted but will continue to be useful.
- If the soil residual value is low, it is important to supply P every year, otherwise the crop response to the fertilizer application is reduced.
- If the soil has a low direct efficiency for fertilizer P but high residual value, opportunities exist for improvement of the efficiency of fertilizer use by adjustment of the distribution of fertilizer P over the years of a cropping programme.
- Use of partially soluble fertilizer in the form of phosphate rock could raise efficiency; the effects are particularly beneficial in soils with a low residual value. The potential for improvement appears greater with rocks of intermediate solubility.

To take advantage of these possibilities, reliable identification of the soil direct and residual value is required. The direct effect can be identified by phosphate sorption. At present, it is not possible to identify definitively an appropriate value for the division between high- and low-phosphate sorption for this purpose. As a rough guideline, it is suggested that soils with SPR less than 200 mg/kg could be regarded as low sorbing for this purpose. Identification of the low residual value is necessary and at present this can only be done by field work. Eventually, if more data become available, it may be possible to estimate the residual value of soils in a simpler and quicker way.

The examples of model calculations given here show that the yield outcome depends on the balance of different effects. Inevitably, field results in the tropics tend to be very variable. But if results of many experiments can be fitted to a reliable model, it will become easier to establish the relative importance and quantitative effects of soil properties on direct and residual value of P fertilization.

Recommendations

- More work to relate phosphate sorption to crop growth is needed in the form of estimates of appropriate values for target solution-P concentration for different crops. It can be carried out in conjunction with agronomic experiments where several different rates of phosphate fertilizer are used. For measurements of phosphate sorption, the equilibration time must be around 24 h or more and a detailed experimental procedure is given in Appendix 1. The method of Fox and Kamprath (1970) can also be used. Data must be examined graphically and should be fitted to an equation; the Freundlich equation is almost always acceptable. Fitted parameters and figures should be published for all soils of such studies. At present, SPR based on 0.2 mg/l dissolved P is the best common ground for presentation of results as a single number.
- The hydrous sesquioxides of aluminium (Al) and iron (Fe) play an important part in determining phosphate sorption in tropical African soils and the disordered oxides, assessed by Fe and Al extracted by acid oxalate in dark conditions, are especially important. Therefore, it is recommended that Fe_{ox} and Al_{ox} should be measured in studies of phosphate sorption and residual availability. Measurements of Al_d and Fe_d, extracted by the dithionite/citrate/bicarbonate reagent are also useful.
- Quantification of residual value under field conditions is needed. Appropriate experimental designs for pot and field experiments are given in Section 7. Measurement of P offtake in the crops is required each year in order to construct a P balance. Pot experiments can be used to compare directly the residual values of different soils and relate fitted parameters to other soil properties. The designs are for use in conjunction with simple models to give a quantitative assessment of the P turnover and residual effects (see Appendix 2). Information is also needed on soil components, processes and P uptakes by crops to provide data to associate good or poor residual effects with soil types or properties.
- The model of Probert (1985) appears particularly useful for assessing P turnover and residual effects. This model and that of Wolf *et al.* (1987) are described in some detail along with their application to the suggested experimental designs. They will be useful in examining the likely outcome of different fertilization strategies before trials in the field. The most promising farming systems and ways of using fertilizer P can then be chosen.

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Appendices

APPENDIX 1 EXPERIMENTAL PROCEDURE FOR MAKING PHOSPHATE SORPTION ISOTHERMS OF SOILS

Basic Method

Reagents

Water is always distilled or demineralized.

Reagent 1 0.01M calcium chloride ($CaCl_2$) solution containing formaldehyde (1.6 ml of 40% HCHO solution/litre). This is used to make up all solutions which are added to the soil.

Reagent 2 Standard solution of 1000 mg/l P as potassium dihydrogen orthophosphate (KH_2PO_4); 4.394 g KH_2PO_4 (oven dried) is dissolved in water and made up to one litre with reagent 1. From this standard, phosphate-P solutions with a range of concentrations are prepared (a) for addition to the soil (see below for suggested concentrations) and (b) for the standards against which the final supernatants will be compared, about eight standards in the range 0.05 to 1.2 mg/l (plus 0.0 mg/l) are suggested initially.

Equipment

1 Glass tubes with tight fitting stoppers. Ideally, they should be suitable both for shaking the soil suspension and for centrifuging. Tubes of 30 ml nominal capacity are used in the present method; larger tubes could be used for suitably scaled up quantities. Up to about 100 samples can be handled conveniently at one experimental run after some practice.

2 Centrifuge.

3 UV spectrometer suitable for measurement at 882 nm.

4 Funnels and tubes or flasks to receive filtrate.

5 Pipettes, volumetric flasks and measuring cylinders to make up and dispense solutions. A variable volume dispenser (up to 50 ml) is useful to dispense reagent 1 into the soil and a variable volume pipette is useful for making up solutions and adding P solution to the soil suspension.

Procedure

1 Measure the dry matter content of the soil by drying overnight at 105°C. Results should be presented on an oven-dry soil basis; although an air-dry basis is acceptable for most soils if <5% of the air-dry weight is water.

2 Weigh soil accurately into the shaking/centrifuge tube. Soil can be air dry or field moist and should contain about 1.5 g oven-dry soil.

3 Add 27 ml of $CaCl_2$ solution (reagent 1) by dispenser.

4 Add 3 ml of phosphate-P solution by pipette; this must be as accurate as possible. See below for the range of concentrations.

5 Stopper tubes and shake according to the preferred method. The recommended method is by slow end-over-end shaking (one or two inversions/minute) for at least 22 hours (overnight).

6 Centrifuge the samples; 5 min at 2500 rpm is suitable for most soils. If the supernatant remains cloudy, centrifuge for a longer time or, if possible, at a higher speed.

7 Decant the supernatant. It is normally necessary to filter as well (Whatman No. 1 paper) to remove floating organic matter. Reject the first few millilitres of filtrate.

8 Measure P concentration of supernatant.

Measurement of P concentrations

Follow the method for P soluble in water, given by Olsen and Sommers (1982), or proceed as follows.

Reagent A Dilute 224 ml conc. H_2SO_4 (sulphuric acid) into 200 ml water.
Dissolve 0.44 g antimony potassium tartrate ($KSbO.C_4H_4O_6$) in 125 ml water.
Dissolve 19.2 g ammonium paramolybdate ($(NH_4)_6\ Mo_7O_{24}.4H_2O$) in 275 ml water.
Cool these solutions (preferably to refrigerator temperature) and mix.
Cool again (room temperature) and make up to 1 litre.
Store this reagent in cool (refrigerator) dark conditions.

Reagent B Dissolve 1.27 g ascorbic acid in 75 ml water. This must be prepared freshly each day.

Mixed reagent Add 75 ml of each of the reagents A and B to 750 ml water to give the dilute mixed reagent.

Pipette 5 ml of sample (or standard) into a vial. Add 6 ml dilute mixed reagent to each sample. Allow one hour for colour to develop. Measure absorbance at 882 nm. Adjust these quantities if 11 ml of solution is not enough or too much for the measuring cell in use, keeping the ratio of sample to reagent approximately the same.

Standards: Standard solutions of 0.0, 0.05, 0.1, 0.2, 0.4, 0.6, 0.8, 1.0 and 1.2 mg/l P are suggested initially, made up in 0.01M $CaCl_2$.

Plot the absorbance against standard concentration, which should be linear throughout, and use the fitted line to read sample concentration from sample absorbance. Alternatively, the standards data can be fitted to an equation by linear regression and sample concentrations calculated.

Experimental strategy

Trial run As phosphate sorption isotherms can vary considerably between soils, it is essential to make at least one trial run for each soil before starting on the main measurement. It is suggested that for the first trial, five soil samples are weighed out and phosphate-P additions of 20, 50, 200, 500 and 1000 mg/kg are made. For the method given here, solutions with 10, 25, 100, 250 and 500 mg/l P will need to be made up. The samples are taken through the basic procedure and analysed. This will then give an idea of the correct amount of P for a top final concentration of about 1.0 mg/l. If the soil is very strongly sorbing, a further trial will be necessary.

Main run The objective is to have a top concentration between 1.0 and 1.2 mg/l and a total of eight to ten different rates of added phosphate-P in order to fit an equation to the sorption curve. If for example an addition of 200 mg/kg gives about 1.0 mg/l final concentration, then the following rates of addition will be suitable: 0, 10, 20, 30, 50, 70, 100, 150, 200. There should be more points at the lower rates to give a more even distribution of points along the line of the sorption curve. The actual rates should be rounded off so that the phosphate-P concentrations are fairly easy to make up. Duplicates are made for each rate of P. A sample without added P may be included for interest; P will be desorbed from this sample and sometimes this point still fits well to the fitted equation.

Calculation of results

1 Calculate phosphate-P remaining dissolved for each sample. From the concentration of P in supernatant (C), calculate the total amount of P that remains dissolved in the sample tube:

P in solution = C [mg/l] × vol. of supernatant [l]

The volume of supernatant normally equals the sum of the volumes of solutions added (0.03 l in this case) but, if field moist soil is used, an allowance for the water added in soil is required.

2 Calculate the amount of P adsorbed:

P adsorbed = P added (vol. × conc. of added P soln.) – P remaining in soln. [mg]

Divide P adsorbed by the weight of dry soil used, to give results per kg soil [mg/kg]

3 Plot P adsorbed [mg/kg] against P concentration [mg/l] to give a graph like Figure2 and inspect the results to find any obviously outlying points.

4 The data should be fitted to an equation. As described in Section 3, the Freundlich equation is usually appropriate. The equation is fitted in its linearized form:

log(P adsorbed [mg/kg]) = log(*a*) + (1/*n*) × logC [mg/l]

The values of log P and log C are plotted (Figure A), a line of best fit drawn through the points, and the values of *a* and *n* obtained from the fitted line. The intercept (at log C = 0) equals *a* and the gradient equals (1/*n*). Alternatively, the data for log P and log C may be fitted by linear regression to the equation above. This is advantageous because it is then possible to calculate standard errors. It is still essential to plot and inspect the graph, looking for outlying points and any systematic lack of fit.

5 If required, the standard P requirement (SPR) can be calculated by inserting a value of C = 0.2 mg/l in the fitted equation.

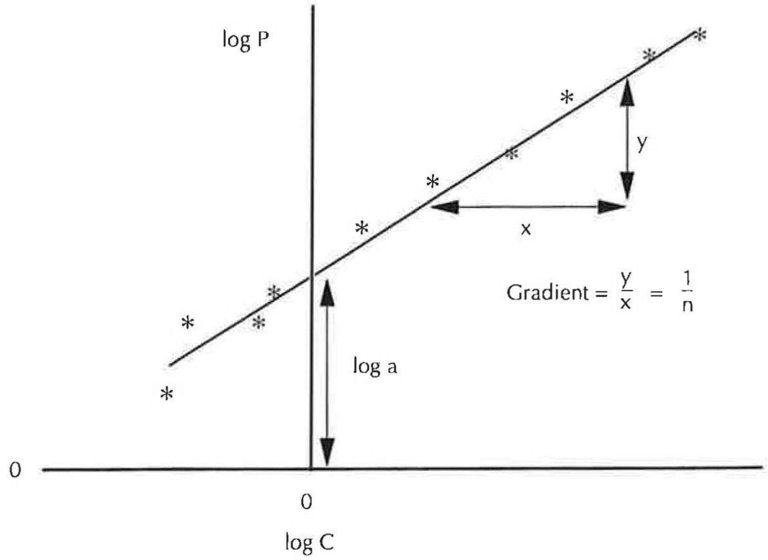

Figure A Fitting of phosphate data to the Freundlich equation

APPENDIX 2 FITTING DATA TO MODELS

A Fitting data to the model of Probert in the suggested field experiment

The data to be fitted are dry matter yield (Y), P uptake (PU) and fertilizer P (FP) for each year. The model equations are based on the equations formulated by Probert (1985). The change in effective P (PE) is described by the following equation, where subscript **i** refers to each year:

$$PE_{[i+1]} = (PE_i - PU_i).f + k$$

The relationship between PE and yield is assumed to follow a Mitscherlich equation:

$$Y = a_i(1 - \exp[-c.PE_i])$$

For further information on these equations refer to Section 6; parameters *a, c, f* and *k* are defined below. In order to fit the data, model equations must be written for each year. The derivation of the appropriate model equations for each of the years one to three is given in Table A1; these have to be fitted with the model parameters held constant over all three years. To fit the data by iterative procedures using a computer, a single model equation that caters for all years is needed, as given in Table A1. Multipliers x_2 and x_3 are used to define the correct terms needed for each yield. Thus, in year two:

$$a_2 = a_1 + \alpha_2 x_2$$

and in year three:

$$a_3 = a_1 + \alpha_2 x_2 + \alpha_3 x_3$$

Table A1 Derivation of a model equation to apply the model of Probert (1985) to a three-year field experiment to assess residual value of soluble fertilizer

Response equations for each year* #

Equation

$$\text{Year 1}\quad Y_1 = a_1(1 - \exp(-c[\underbrace{p_o+FP_1}_{\substack{PE_1\\ \downarrow}}])) \qquad (1)$$

$$\text{Year 2}\quad Y_2 = a_2(1 - \exp(-c[\underbrace{f(\overline{p_o+FP_1} - PU_1) + k + FP_2}_{\substack{PE_2\\ \downarrow}}])) \qquad (2)$$

$$\text{Year 3}\quad Y_3 = a_3(1 - \exp(-c[f\{\overline{\overline{f(p_o+FP_1 - PU_1) + k + FP_2 - PU_2\}}} + k + FP_3])) \qquad (3)$$

Fitted model equation suitable for data of all years#

$$Y = (a_1+\alpha_2x_2+\alpha_3x_3).(1-\exp(-c[(1+(f-1)x_3).\{\underbrace{(1+(f-1)x_2).(\overset{PE_1}{\overline{p_o+FP_1}}-PU_1)+kx_2+FP_2}_{PE_2}-PU_2\}+kx_3+FP_3])) \qquad (4)$$

Multipliers x_2 and x_3 are used to define model equations for years 1, 2 and 3 as follows:

	x_2	x_3
Year 1	0	0
Year 2	1	0
Year 3	1	1

Y is the dry matter yield

* Effective P for each year is contained within square brackets

\# PE_1 and PE_2 are indicated by single and double lines to indicate the derivation

Note: to reduce the number of times x_2 and x_3 are used and reduce inessential typing, the following shortcuts are made:

In year 1: PU_1, PU_2, FP_2 and FP_3 are always typed in as zero

In year 2: PU_2 and FP_3 are always typed in as zero

The parameters a_1, α_2 and α_3 are fitted by the program; a_2 and a_3 can be calculated from the above equations. The expression $(1+(f-1).x)$ reduces to 1 if $x = 0$ or f if $x = 1$ and effective P is multiplied by parameter f when appropriate in the model equation (1, 2 or 3). It must also be noted that, when using the equations given here, data are sometimes entered as zero instead of the correct values. This is solely a way of reducing the amount of typing when entering the data. A formally correct model equation would have additional multipliers to convert the unnecessary data to zero. These occasions are:

In year 1: PU_1, PU_2, FP_2 and FP_3 are typed in as zero
In year 2: PU_2 and FP_3 are typed in as zero.

A hypothetical set of results is given in Table A2 to show which data are needed and suggest a way of tabulating them. Any program or routine that can perform non-linear optimization could be used, but well-known statistical packages such

Table A2 Fitting of hypothetical data from a field experiment to the P residual value model of Probert (1985)*

Plot	Year	Yield (kg/ha)	FP_1 (kg/ha)	FP_2 (kg/ha)	FP_3 (kg/ha)	PU_1 (kg/ha)	PU_2 (kg/ha)	x_2	x_3	
1	1	51	0	0	0	0	0	0	0	Block 1
2	1	154	0	0	0	0	0	0	0	
3	1	7	0	0	0	0	0	0	0	
4	1	67	0	0	0	0	0	0	0	
5	1	106	0	0	0	0	0	0	0	
6	1	119	0	0	0	0	0	0	0	
7	1	228	0	0	0	0	0	0	0	
8	1	776	12	0	0	0	0	0	0	
9	1	655	12	0	0	0	0	0	0	
10	1	847	12	0	0	0	0	0	0	
11	1	2437	25	0	0	0	0	0	0	
etc.....										
19	1	3707	100	0	0	0	0	0	0	
20	1	45	0	0	0	0	0	0	0	Block 2
21	1	172	0	0	0	0	0	0	0	
22	1	75	0	0	0	0	0	0	0	
23	1	59	0	0	0	0	0	0	0	
24	1	49	0	0	0	0	0	0	0	
25	1	45	0	0	0	0	0	0	0	
26	1	44	0	0	0	0	0	0	0	
27	1	759	12	0	0	0	0	0	0	
etc.....										
38	1	3838	100	0	0	0	0	0	0	
etc.....										
Some year 2 data:										
1	2	53	0	0	0	1.19	0	1	0	
2	2	280	0	6	0	1.50	0	1	0	
3	2	712	0	12	0	0.70	0	1	0	
4	2	3068	0	50	0	1.76	0	1	0	
5	2	215	0	0	0	0.93	0	1	0	
etc.....										
19	2	3910	100	25	0	9.67	0	1	0	
and so on for each block and year:										
1	3	25	0	0	0	1.19	0.59	1	1	
2	3	272	0	6	0	1.50	2.19	1	1	
3	3	411	0	12	0	0.70	3.13	1	1	
4	3	3060	0	50	0	1.76	7.45	1	1	
5	3	532	0	0	12	0.93	1.22	1	1	
etc.....										
19	3	4112	100	25	25	9.67	7.73	1	1	

* Note that for each yield entry future FP is not entered nor are current and future PU

Table A3 Example program to optimize parameters of the residual value model of Probert (1985) applied as described in Table A1 and written for SAS

```
 1 /* SAS NLIN Program to optimize P residual value model */
 2 options linesize=80;
 3 data;
 4 input plot year yield FP1 FP2 FP3 PU1 PU2 x2 x3;
 5 cards;
 6 Data typed here as specified in Table A2
 7 ;
 8 proc print;
 9 run;
10 proc nlin method=dud outest=parms;
11 parms          a1 = 4000
12        alpha2 = –300
13        alpha3 = 200
14        c = 0.06
15        f = 0.5
16        po = 1.5
17        k = 1.5 ;
18 model yield = (a1+alpha2*x2+alpha3*x3)*(1–exp(–c*( (1+(f–1)*x3)*(
19        (1+(f–1)*x2)*( po+FP1–PU1 )+k*x2 + FP2 – PU2) +k*x3 +FP3)));
20 run;
21 data covb;
22 set parms;
23 if _TYPE_ = 'COVB';
24 drop _ITER_ _SSE_ _TYPE_;
25 run;
26 proc print data=covb;
27 run;
28 endsas;
```

Notes: The plot and year numbers are not needed in the calculations but they help to identify individual results for checking the data

Lines 11 to 17 contain the starting estimates of the fitted parameters

Variations to cater for the pot experiment design (see Table A5 for the derivation of the model equation) are as follows:

```
 4 input plot year yield FP PU1 PU2 x2 x3 z1 z2
18 model yield = (a1+alpha2*x2+alpha3*x3)*(1–exp(–c*( (1+(f–1)*z2)*(
19        (1+(f–1)*z1)*( po+FP1–PU1 )+k*z1 – PU2) +k*z2 )));
```

as GENSTAT* or SAS** make the work easier; an example written in SAS is given in Table A3.

All non-linear optimizations require initial estimates of the starting parameters. Trial and error may be the only way to obtain initial estimates that cause the optimization to run correctly. Prior inspection of the data is of considerable use in this model, since most parameters have a physical interpretation and many trial values can be estimated quickly from the raw data.

Parameter a_i This parameter represents the maximum yield each year and estimates can be made by inspection of the data or plotting the curve for yield against fresh fertilizer and extrapolating to the apparent potential yield. The value for a_1 equals the estimated maximum yield in year one, and estimates for α_2 and α_3 can then be calculated using the equations given above.

Parameter *c* This parameter expresses response per unit fertilizer and varies in the region of 0.01-0.1 irrespective of the units used for yield or fertilizer. A trial value of 0.03 is suggested if the soil is fairly strongly sorbing, i.e. SPR > about 200 mg/kg P, or more than about 200 kg/ha P is needed to reach 90% maximum yield. Otherwise, a trial value of 0.06 may be used.

Parameter *f* This parameter expresses the fraction of PE remaining effective after one year and should therefore lie between 0 and 1; an initial estimate of 0.5 is

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*GENSTAT 5 Reference Manual (1985) Statistics Department, Rothampstead Experimental Station, Oxford University Press.

**SAS Users'Guide 5th edn. (1985) SAS Institute Inc. of Cary N. C. USA.

suitable. Any optimized value <0 or >1 is a clear symptom that something is wrong: either (a) the model is not working correctly and cannot describe the data properly, i.e. the model is inappropriate, or (b) poor initial estimates of parameters have led to a set of optimized parameters that is self-consistent but not correct. An alternative set of starting estimates should be tried.

Parameters k and p_o These are not evident from the raw data. Parameter k is the transfer from ineffective to effective P. Parameter p_o equals the initial value of PE before fertilizer is added in year one. If the unfertilized soil is at a steady state (as assumed by Wolf *et al.*, 1987) k should exceed the P uptake in unfertilized soil. The mean P uptake for unfertilized soil seems to provide a reasonable initial estimate for both k and p_o.

B Fitting data to the model of Wolf *et al.* in the suggested field experiment

The model is suitable when moderate or low rates of fertilizer P are used. If yields are moderate and not limited by other nutrients, it may be possible to use a single value of the uptake fraction of labile P for all fertilizer rates. If this is the case and fertilized and unfertilized soils are treated the same arithmetically, then the calculations can be presented more concisely, as shown in Table A4. The fundamental model calculations are given in lines 13 to 21 and can be verified by reference to Figure 8a. In this case, the model can be applied as follows:

1 Assume a value for the labile fraction of fertilizer P (parameter *lffp*, see below).

Table A4 Structure and calculations of the model of Wolf *et al.* ((1987) as revised for application to data with multiple rates of P application and where P uptake is proportional to fertilizer P added

Line no.	Description	Symbol and calculation
Input data		
1	Fertilizer P in year subscript **i**	FP_i (field data)
2	External P	EP (see text)
3	P uptake in year subscript **i**	PU_i (field data)
Model parameters		
4	Time constant of transfer from labile to stable (years)	*rls* (Normal value = 5)
5	Time constant of transfer from stable to labile (years)	*rsl* (Normal value = 30)
6	Labile fraction of fertilizer P	*lffp* (see text)
7	Uptake fraction of labile P	*uflp* (From regression of PU_1 and FP_1)
Initial situation calculated from data of unfertilized soil only		
8	Size of labile pool: unfertilized soil only	$LP_{1,us} = PU_{1,us} \div uflp$
9	Size of labile pool	$LP_i = LP_{1,us}$
10	Transfer labile to stable:unfertilized soil	$TransLS_{1,us} = LP_{1,us} \div rls$
11	Transfer stable to labile:unfertilized soil	$TransSL_{1,us} = TransLS_{1,us} + EP$
12	Size of stable pool: fertilized and unfertilized soil	$SP_i = TransSL_{1,us} \times rsl$
Pool changes in year subscript i (first and subsequent years) for fertilized and unfertilized pots		
13	Size of labile pool: increased by fertilizer	$LP_i = LP_i + (lffp \times FP_i)$
14	Size of stable pool: increased by fertilizer	$SP_i = SP_i + ([1 - lffp] \times FP_i)$
15	P uptake	$PU_i = uflp \times LP_i$
16	Transfer labile to stable	$TransLS_i = LP_i \div rls$
17	Transfer stable to labile	$TransSL_i = SP_i \div rsl$
18	Change in labile pool	$\Delta L = - PU_i - TransLS_i + TransSL_i$
19	Change in stable pool	$\Delta S = EP + TransLS_i - TransSL_i$
20	Final size of labile pool	$LP_{i+1} = LP_i + \Delta L$
21	Final size of stable pool	$SP_{i+1} = SP_i+1 + \Delta S$

2 For the fertilizer (FP_1) and P uptake (PU_1) data for year 1, calculate the labile fraction of fertilizer P ($LFFP_1$ = *lffp* × FP_1) for each field plot. Plot a graph of PU_1 against $LFFP_1$, calculate the gradient and thus find the uptake fraction of labile P (parameter *uflp*) from the equation:

PU_1 = *uflp* × $LFFP_1$

If the relationship is not linear, individual values of parameter *uflp* for each rate of fertilizer must be used, as described by Wolf *et al.*

3 Assume values for EP (see Section 6), *rls* and *rsl* (see Table A4)) and calculate the size of initial labile and stable pools from P uptake in unfertilized soil (lines 8 to 12).

4 Calculate labile and stable pools and predicted P uptake each year using values of model parameters, initial pools and fertilizer applied.

5 Compare predicted and actual P uptakes by tabulation and graphs.

An initial estimate of external P (EP) depends on the assumption that unfertilized soil is at a steady state so that the P uptake in unfertilized soil equals EP (see Figure 8a). This will be reasonable if yield and P uptake in the nil fertilizer treatment does not decline greatly over the years. If there is a decline, the soil P is being run down; EP should be reduced and initial labile P (LP) and stable P (SP) increased somewhat. Suitable values have to be found by trial and error.

Values for the labile fraction of fertilizer P (parameter *lffp*) were given by Wolf *et al.*, depending on fertilizer type. Values of 1.0 for diammonium phosphate and 0.8 for triple superphosphate were proposed, while much lower fractions are applicable to rock phosphates. By this fraction, the lower availability of slowly soluble P sources is accounted for, although the actual values of the parameter appear nominal, rather than clearly derived from established principles. The required value for the uptake fraction of labile P (parameter *uflp*) is derived as shown above.

Initial values of the transfer constants, here symbolized as *rls* and *rsl*, should be taken to be five and 30 years respectively and, if these values give reasonable results, they support the conclusions of Janssen *et al.* (1987) that standard values are widely applicable.

C Fitting data to model (of Probert) in the suggested pot experiment

The model equations for each year and each group, and for all years and groups together are given in Table A5. Storage of soil allows the direct effect to be measured in each year, giving six groups of data each with its own model equation, requiring additional multipliers (z_1 and z_2); in Table 16 groups 1-6 are defined. The multipliers work in the same way as those described for the field experiment; again some economy of work in typing the data is made by entering values of PU_1 and PU_2 as zero for some groups, as specified in Table A5 In the computer program which is found at Table A3, the lines containing the model equation and describing the input data must be altered to suit the different model equations and data. As fertilizer is only added to soil when it is first potted up, only one data column for FP is required. The procedure of fitting the data by optimization is the same as for field experiment results and initial estimates of the various parameters are made in the same ways as given above.

Table A5 Derivation of a model equation to apply the model of Probert (1985) to a three-year pot experiment to assess residual value of soluble fertilizer

Response equations for each year and group*

			Group
Year 1	Direct effect	$Y_1 = a_1(1 - \exp(-c[\ p_o + FP\ ]))$	1
Year 2	Direct effect	$Y_2 = a_2(1 - \exp(-c[\ p_o + FP\ ]))$	2
	1st residual effect	$Y_2 = a_2(1 - \exp(-c[\ f(p_o + FP - PU_1) + k\ ]))$	3
Year 3	Direct effect	$Y_3 = a_3(1 - \exp(-c[\ p_o + FP\ ]))$	4
	1st residual effect	$Y_3 = a_3(1 - \exp(-c[\ f(p_o + FP - PU_1) + k\ ]))$	5
	2nd residual effect	$Y_3 = a_3(1 - \exp(-c[\ f\{\ f(p_o + FP - PU_1) + k - PU_2\} + k\ ]))$	6

Fitted model equation suitable for data of all years and groups

$$Y = (a_1 + \alpha_2 x_2 + \alpha_3 x_3).(1 - \exp(-c[\ (1+(f-1)z_2).\{\ (1+(f-1)z_1).(p_o + FP_1 - PU_1) + kz_1 - PU_2\ \} + kz_2\ ]))$$

Multipliers x_2 and x_3 are used to define model equations for years 1, 2 and 3 as follows:

	x_2	x_3
Year 1	0	0
Year 2	1	0
Year 3	1	1

Multipliers z_1 and z_2 are used to define direct effects and 1st and 2nd residual effects as follows:

	z_1	z_2
Direct effect	0	0
1st residual effect	1	0
2nd residual effect	1	1

Y is dry matter yield

* Effective P for each year is contained within square brackets

Notes: To reduce the number of times the multipliers are used and reduce inessential typing, the following shortcuts are made:

For direct effect pots (groups 1, 2 and 4): PU_1 and PU_2 are always typed in as zero

For first residual effect pots (groups 3 and 5): PU_2 is always typed in as zero and PU_1 refers to PU in the previous year

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