Phosphorus Requirements for Sustainable Agriculture in Asia and Oceania
Phosphorus Requirements for Sustainable Agriculture in Asia and Oceania

Proceedings of a Symposium
6-10 March 1989

SPONSORED BY
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ISBN 971-22-0002-7
Contents

Foreword v
Welcome remarks vii
Welcome address ix
Objectives of the symposium xiii

Recommendations 1
Introduction 19
Regional food security: demographic and geographic implications 21
  P. J. Stangel and H. R. Von Uexkull
Fertilizer policies for agricultural development 45
  L. M. Maene
Protection of the environment: sustained agriculture, sustained ecosystems 57
  K. Kyuma
Phosphorus for sustainable agricultural growth in Asia: an assessment of alternative sources and management 73
  G. M. Desai and V. Gandhi
Phosphorus fertilizer use in Asia and Oceania 85
  A. Belmehdi and K. F. Nyiri
The phosphorus resources of Asia and Oceania 97
  P. J. Cook, D. M. Banerjee, and P. N. Southgate
Recycling phosphorus from crop and animal wastes in China 115
  Zhu Zhao-liang and Xi Zhen-bang
New approaches to phosphorus fertilization 125
  M. J. Hedley, A. Hussin, and N. S. Bolan
Comparison of the effectiveness of phosphorus fertilizer products 143
Assessing fertilizer requirements 157
  I. S. Cornforth, A. K. Metherell, and Puntipa Sorn-srivichai
Phosphorus losses through transfer, runoff, and soil erosion 167
  J. C. Ward, K. F. O’Connor, and Gan Wei-bin
Utilization of phosphorus transported from uplands to lowlands and estuaries 183
  E. Miwa
Inorganic reactions influencing phosphorus cycling in soils 191
  J. K. Syers and Lu Ru-kun
Relating chemical processes to management systems 199
  N. J. Barrow
Phosphorus chemistry in relation to water regime 211
G. J. D. Kirk, Yu Tian-ren, and F. A. Choudhury

Chemistry of adverse flooded soils 225
H. U. Neue and Zhu Zhong-lin

Chemistry of adverse upland soils 243
K. Wada, Li Xue-yuan, and P. W. Moody

Effects of liming on soil phosphorus availability and utilization 255
D. C. Edmeades, D. M. Wheeler, and R. M. Pringle

Effect of sulfur, silicon, and trace metal interactions in determining the
dynamics of phosphorus in agricultural systems 269
G. J. Blair, J. R. Freney, and J. K. Park

Phosphorus as a factor limiting nitrogen fixation in flooded rice soils 281
I. Watanabe and Wisit Cholitkul

The role of phosphorus in nitrogen fixation in upland crops 295
M. J. McLaughlin, K. A. Malik, K. S. Memon, and M. Idris

Phosphorus requirements and management for lowland rice 307
S. K. De Datta, T. K. Biswas, and C. Charoenchamratcheep

Phosphorus management in lowland rice-based cropping systems 325
B. Palmer, M. Ismunadji, and Vo-tong Xuan

Phosphorus requirements and management in upland rice-based cropping systems 333
D. P. Garrity, C. P. Mamaril, and Goeswono Soepardi

Phosphorus requirements and management of maize, sorghum, and wheat 349
N. N. Goswami, M. B. Kamath, and Djoko Santoso

Phosphorus requirements and management of grain legumes 361
R. K. Pandey and J. L. McIntosh

Phosphorus requirements and management of oilseeds 371
K. L. Sahrawat and M. S. Islam

Phosphorus requirements and management of tea, coffee, and cacao 383
A. H. Ling, P. E. Harding, and V. Ranganathan

Phosphorus requirements and management of oil palm, coconut, and rubber 399
E. Pushparajah, F. Chan, and S. S. Magat

Phosphorus requirements and management of sugarcane, pineapple, and banana 409
R. L. Fox, R. P. Bosshart, D. Sompongse, and Lin Mu-lien

Phosphorus requirements and management of tropical root and tuber crops 427
R. H. Howeler

Phosphorus requirements of fiber crops—cotton, jute, and kenaf 445
Lin Bao and P. N. Takkar

Phosphorus management in intensive vegetable cultivation 453
S. L. Amarasiri

Management of fertility, variety, planting density, and irrigation for maximum yield 461
H. L. S. Tandon and D. K. Kundu

Participants 473
Over the years, IRRI has hosted many conferences, seminars, and workshops, but almost all of them have dealt predominantly with rice. A conference where a hundred or so participants from 23 countries from 5 continents meet at IRRI on a subject where rice is not central needs at least a short introduction.

Phosphorus has been known to mankind for 320 years. Its discoverer gave it the name Brand, meaning “fire,” which was the context of my first experience with that element, as the phosphorus bomb—and it was not a very comfortable one. I later learned that, as is so often the case, what we can use to kill we need to live. Life on our planet is hardly possible, hardly thinkable, without phosphorus.

Our goal of establishing sustainable agricultural production systems cannot be achieved by isolated disciplinary approaches. Holistic thinking and cybernetic methods are the keys to the doors we have to open. Each year we consume more than 13 million tons of phosphorus. Nobody knows how long this can go on. Nobody knows how the farmers, who cannot afford commercial fertilizer today, will be able to use fertilizer in the future to the extent needed to attain rice yields in excess of 10 t/ha.

Normally phosphorus removal by a crop does not exceed 15-20% of added phosphorus; the rest is retained in the soil. In IRRI’s five-year work plan we are committed to narrowing the basic knowledge gaps in phosphorus fertilizer and its dynamics, in rice nutrition, and in the management of soil and fertilizer phosphorus using a systems approach. More specifically, we shall undertake research on phosphorus nutrition and processes at the root-soil interface in relation to phosphorus uptake, and on the stimulation of biological nitrogen fixation in flooded soils by introducing highly efficient stem- and root-nodulating green manure species. We shall also evaluate less expensive phosphorus sources for sustainable production of rice and associated crops in irrigated, rainfed lowland, deepwater, and tidal wetland environments. A symposium like this one can be extremely helpful in our endeavors.

Phosphorus resources are concentrated in a few parts of the world, in a very few countries. Will phosphorus become an asset in the global struggle between have and have-not nations? It is a possibility. Our answer can be very easy to formulate but very difficult to put into practice. We have to be exceedingly careful in the use of phosphorus resources. And we have to make all efforts to avoid losses. Phosphorus fixation occurs in different soils under different conditions. We need more
knowledge of how to avoid and to overcome constraints, how to increase phosphorus availability to crops, and how to increase the efficiency of the plant root system. And we have to stop pollution of water, of soil, and of air, since we cannot afford to waste phosphorus, nor to use it in a way that makes our environment hostile. The carrying capacity of our globe, which should be 10-12 billion people, may be reduced if we make wrong decisions. Sustainability without nutrient recycling is an illusion. Economists must include not only short-term profits, but long-term liabilities in their calculations of gains and losses.

Specialization and modernization of farming systems, wherein human beings try to manipulate and exploit nature instead of being part of it, can lead to environmental degradation and the disintegration of agricultural production. Acid rain is the starting point of a disaster that mankind may not be able to control. Our problem is to find the way out of the dilemma without losing sight of our goal. Phosphorus requirements in agriculture seem to be a neglected topic, since we are thinking at best in decades. For me, this is very short-term. We must consider the generations to come. Let us share that responsibility and let us keep in mind that there is not much time left for new solutions and new attitudes. If the scientific community does not give the warning and provide direction for the way out at an early stage, we have to share with the politicians the responsibility for disaster.

This symposium was sponsored in one way or another by eight organizations, and we are grateful for the generosity of our partners: the Scientific Committee on Problems of the Environment (SCOPE)/United Nations Environment Programme (UNEP), World Phosphate Institute (IMPHOS), American Phosphate Foundation (APF), Potash and Phosphate Institute (PPI), Australian International Development Assistance Bureau, Food and Fertilizer Technology Center for the Asian and Pacific Region, and Fertilizer Advisory, Development and Information Network for Asia and the Pacific.

The Program Committee for this symposium was a particularly broad-based one. Chaired by J. R. Freney of the Commonwealth Scientific and Industrial Research Organization, it included A. Belmehdi and M. Debbi of IMPHOS, C.V. Cole of SCOPE/UNEP, H.W. Fogt, Jr. of APF, H.R. von Uexkull and R.P. Bosshart of PPI/IPI, H. Tiessen of SCOPE, and S.K. De Datta and S.J. Banta of IRRI. S.K. De Datta, J. Freney, and C.V. Cole arranged an excellent agenda, and S.K. De Datta handled the local arrangements at IRRI. H. Tiessen was the scientific editor and organized the papers into a logical sequence. S.J. Banta edited the proceedings with the assistance of G.S. Argosino.

The symposium was a very stimulating event and a successful one as well. Let me thank all who helped to finance, prepare, organize, and contribute to that endeavor: a joint effort towards a more future-conscious use of nonrenewable resources. In our world of uncontrolled consumption, we are in urgent need of more joint ventures of this caliber.

Klaus Lampe
Director General
International Rice Research Institute
Welcome remarks

The American Phosphate Foundation, like the other sponsors, is delighted to be a part of this common effort to explore phosphorus requirements for sustainable agriculture. I would like to thank personally several people who worked to bring us here today: Vernon Cole, who brought us SCOPE’s bright ideals for this conference; Helmut von Uexkull, who kept our feet on the ground and who focused our discussions on the realities of phosphorus requirements in the region; John Freney, who helped shape the diverse composition and objectives of the organizing committee into the program you see before you today; and S.K. De Datta, who with his staff worked tirelessly to bring this program to fruition. I thank all of them, and I thank you for coming.

Howard W. Fog, Jr.
American Phosphate Foundation
On behalf of the President of the Board of the World Phosphate Institute (IMPHOS), I deem it my privilege to address this audience of eminent scientists.

There are more than 100 participants from more than 20 countries here at the Symposium on Phosphorus Requirements for Sustainable Agriculture in Asia and Oceania, which makes it quite representative of the region. IMPHOS is proud to have contributed to the organization of this scientific event.

My appreciation goes to all those who have made this meeting possible and who have given valuable assistance to the Program Committee. The Committee has done an excellent job in the careful selection of the topics and speakers.

My particular appreciation is due to the International Rice Research Institute (IRRI) for making available the human and material resources needed for the organization of the conference, to the Scientific Committee on Problems of the Environment (SCOPE) for their scientific input, to the American Phosphate Foundation and the Potash and Phosphate Institute for their strong support, and to the Food and Fertilizer Technology Center for the Asian and Pacific Region and the Fertilizer Advisory, Development and Information Network for Asia and the Pacific for their contributions.

I have a special word of thanks for Dr. Klaus Lampe, Director General of IRRI, who straight away agreed to host the symposium here. My thanks go also to Dr. John Freney of SCOPE who, as Chairman of the Program Committee, has worked hard to make this conference a success, and to Dr. S.K. De Datta, Principal Scientist and Head of the Agronomy Department at IRRI, who has made a tremendous effort in preparing for the symposium, making arrangements for the travel and stay of the delegates, and looking after their comfort.

I offer a warm welcome to all of you who have come a long way to attend this international meeting, thereby demonstrating your keen interest in exploring the need for phosphorus for agricultural development in Asia and Oceania. I am confident that you will come up with practical recommendations for sustainable agriculture in the region.

Some of you present here know IMPHOS well, since you have previously attended its meetings. But for those of you who are encountering IMPHOS for the first time, please allow me to introduce the organization. Founded in 1973 in Tampa, Florida, by the major phosphorus fertilizer-producing companies, the World Phosphate Institute is a nonprofit association whose mandate excludes any activities of a commercial or political nature. Its main objective is to expand and promote
through research the various technical uses of phosphorus compounds, particularly as fertilizers and as supplements to livestock feed.

Among its objectives, greater food production to feed the growing world population, particularly in Asia and Africa, constitutes a permanent concern. Nobody knows better than you that increasing crop production requires proper fertilizer management, and that is the reason for IMPHOS programs and activities.

Since its creation, IMPHOS has encouraged the exchange of information among scientists, such as this gathering. It has conducted international congresses and regional seminars:

- Our first scientific congress, held in Rabat in 1977, was devoted to discussing nonfertilizer uses of phosphorus compounds. It covered human and animal nutrition, protection of metal against corrosion, fire-fighting, and pharmaceutical and medical uses of synthetic apatites.
- The second congress in Boston in 1980 reviewed existing methods for the identification, analysis, and recovery of impurities in phosphates and phosphoric acid. This congress covered three aspects:
  1. recovery of trace elements like fluorine, uranium, and rare earths for industrial use;
  2. elimination of undesirable products like cadmium and arsenic from phosphate rock and phosphorus fertilizers; techniques to ensure better environmental protection were discussed; and
  3. research on promising methods for processing low-grade phosphorus fertilizers with high impurity levels that could be very useful in developing local phosphorus deposits in Asia and Africa.
- The third congress took place in Brussels in 1983 and tackled the soil-plant-phosphorus relationship. Among the major subjects discussed were the mechanism of plant phosphorus uptake, plant and animal phosphorus requirements, and phosphorus fertilizer use efficiency.

Once the major industrial and agricultural applications of phosphorus were covered by international congresses, IMPHOS judged it appropriate to switch, starting in 1984, to seminars that discuss problems specific to a region. Prior to this one, two meetings have been held:

- The first regional seminar, held in Yamoussoukro, Ivory Coast, in 1984, was on the subject of soil fertility upkeep for better yield in the tropics. It brought together scientists, extension specialists, and decisionmakers from Africa to focus their attention on fertilizer as one of the most effective means of increasing crop yield.
- The second regional seminar in New Delhi in 1986 was an opportunity to look at the importance of fertilizer management in rainfed agriculture in South Asia, where a huge area with potential for yield increase remains dependent on rain. The seminar dealt with scientific, technical, and logistical aspects, as well as effective extension methods for rainfed agriculture in the 25 participating countries.

To encourage scientific research, we established in 1979 the IMPHOS award, to be conferred every two years on eminent individual scientists or groups of scientists.
who have accomplished during the previous five years fundamental research work contributing to the advancement of our knowledge of phosphorus fertilizer use.

- In 1979, the award went to Dr. Ralf Appel of the University of Bonn for his studies on phosphorus chemistry.
- In 1982, the first IMPHOS Agronomy Award went to a team of researchers from the University of Oxford, United Kingdom—Dr. Robert E. White, Dr. Peter H. Nye, and Dr. Michael J. Hedley—to recognize their endeavor to achieve a better understanding of the mechanisms involved in soil-plant-phosphorus interactions.
- A Junior Agronomy Award, intended to encourage young scientists, was conferred in 1982 on Mr. Philip Moody and Dr. John Standley of Australia for providing theoretical and practical guidelines for phosphorus requirements and management in tropical forage crops, especially for West Africa.
- The 1985-86 IMPHOS Agronomy Award went to Dr. N. J. Barrow for his attempts to find a theoretical basis for rational fertilizer use in the semiarid climates.
- Other studies recognized in 1988 were those of Dr. Robert L. Fox, Dr. M.E. Probert, Dr. J. Venkateswarlu, and Dr. R.P. Singh.

But our most significant and meaningful contribution has probably been the material and technical support we lend to agronomic research involving phosphorus use. The objective is to generate results that can readily be picked up by farmers to optimize their returns from fertilizer use and to minimize their risk of crop failure. Quite a few projects have been conducted with IMPHOS support in the Mediterranean area, sub-Saharan Africa, and Asia, for example:

- Comparative response of maize to fresh or residual phosphorus fertilizer in upland soils of Thailand.
- Phosphorus in tropical soils: assessing deficiency levels and phosphorus requirements. This study covered several countries in Asia, among others, and involved the characterization of phosphorus status, determination of suitable soil testing methods, and establishment of better criteria for phosphorus fertilizer recommendations.
- Balanced fertilization through phosphorus promotion at the farm level in Pakistan. The two-year project is intended to create awareness among farmers of the benefits of an improved N:P ratio in fertilizer use.
- Phosphorus fertilization of food crops on upland soils in Indonesia. The introduction of reactive phosphate rock as a substitute for triple superphosphate (TSP) in selected upland acid soils is expected to offer considerable savings at the national level.
- Evaluation of phosphate rock sources in comparison with partially acidulated phosphate rock and TSP for increasing rice yields on acid and acid sulfate soils. This project has been conducted under the overall leadership of Dr. S.K. De Datta in several countries of the region and is expected to last for another three years.
- Use of reactive phosphate rock for the rehabilitation of anthropic savannah in Indonesia. The objective of the five-year project is to demonstrate to policy
makers and international institutions such as the World Bank an economical and effective means of rehabilitating abandoned lands.

• Agronomic and economic evaluation of various phosphorus sources for direct application to Alfisols and Ultisols in Central and South China. This five-year project is designed to obtain practical information that would lead to rational use in China of phosphorus fertilizers, both phosphate rock and more soluble forms, for economically sustainable agricultural production.

Other interests that IMPHOS is pursuing concern the development of reliable statistical data on phosphorus capacities, prospects for phosphorus consumption, and future supply-and-demand balance on both world and regional scales.

The present symposium concerns Phosphorus Requirements for Sustainable Agriculture in Asia and Oceania. Most of the countries in the region have performed remarkably well in terms of food production and fertilizer use. However, large gains in food production have been obtained largely at the expense of soil fertility. Speaking about Asia, the Food and Agriculture 1987 Yearbook points out that the fertilizer consumption ratio for the three nutrients N-P₂O₅-K₂O is 2:1:0.1 in the Near East, 3:1:1:0.5 in the Far East, and 5:1:1:0.3 in China. These ratios clearly show how much emphasis has been put on nitrogen fertilizer use relative to other nutrients, to the point where China and the other socialist countries have the most unbalanced fertilizer consumption in the region. To improve crop yields, all growth factors must be at optimal economic levels. This is unfortunately not true in most cases. Farmers in Asia are reported to use nitrogen up to optimal levels where good irrigation is available, but they are far from applying adequate phosphorus and potassium.

One of the important themes of this symposium is to assess phosphorus requirements and management for major cropping systems. I hope that useful recommendations will emerge from your discussions of the subject.

The working groups on future research needs should attempt to identify technological and institutional constraints to rational and economical phosphorus fertilizer use in Asia. They should reflect on methods of applying available scientific research results at the farm level. They should also try to give serious thought to the kind of research we need to achieve higher efficiency in fertilizer use. Discussions of this sort may lead to the definition of agronomic and interdisciplinary research themes that would rank high in the funding priorities of international institutions. The considerable scientific work reflected in the program of this symposium would be of only limited value if it were not supported by an effective extension program that translates the scientific message into specific, usable, and affordable recommendations.

I wish you a successful exchange of views and hope that your debates and discussions will culminate in practical recommendations that will enable the participating countries to approach or consolidate the status of food self-sufficiency.

To all of you, I once again offer a warm welcome and many thanks.

Abdelwahed Benchekroun
Secretary-General
World Phosphate Institute
Phosphorus occupies a key place among the major nutrients because of its relative scarcity among the light elements and its essential role in energy transformations in all life forms. Human use of P reserves has produced both desirable and undesirable effects on the environment. Widespread fertilizer P applications have greatly increased food and fiber supplies for an expanding world population. On the other hand, P associated with eroded sediments from agricultural lands, and P discharges from urban and industrial areas as sewage effluents and other wastes are major causes of eutrophication of water bodies.

Scientific information is increasingly needed to guide the use of P to obtain maximum benefits without producing undesirable impacts on the environment. To this end, information on the P cycle needs to be summarized and then integrated with knowledge of other nutrient elements and their interactions. Phosphorus differs from C, N, and S, since it does not have a significant gaseous atmospheric transfer; however, it has significant indirect global effects on the environment through its effects on C, N, and S transfers. Extensive data are available in a number of regions of the world on a) mineral P deposits; b) fertilizer production and usage; c) detergents, pesticides, and other industrial production and usage; d) soils and plant communities in various ecosystems; e) river transport; and f) lake sediments. There have been few attempts to integrate this information.

Although on a global scale there is no shortage of phosphate rock (PR) for use in industry and fertilizers, reserves of high quality ores are being rapidly depleted. This will result in a need for new technology to utilize lower grade ores with high contents of silica and sesquioxides. High costs of production of soluble fertilizer products, together with indications of lower residual value, have stimulated the development of alternative approaches, including more direct application to the rooting zone of crops or the use of reactive PR and partially acidulated products. There is also an urgent need to develop improved methods for recycling P in wastes, particularly human and animal wastes. Research is under way to investigate these concerns in several countries.

Recent studies on P transformations focus on microbial activity and the importance of both inorganic and organic forms, as organic P forms are both a significant source and sink for biologically active P in ecosystems (Cole and Sanford 1989, Stewart and Tiessen 1987, Tate 1984). New methods have helped quantify levels of biologically active P and relatively inert physically and chemically occluded
forms in ecosystems. Key processes of P interactions with C, N, and S have been identified and incorporated into computer models to guide interpretation of P data (Parton et al 1988, Sanford et al 1989). These models need to be extended to a wider range of ecosystems so that, in addition to the database, they will provide a mechanism for the evaluation of the short- and long-term impact of man’s manipulation of P in the biosphere. A realistic understanding of elemental cycles is not possible in isolation from other nutrients, and a holistic approach to global biogeochemistry is needed.

SCOPE project

In response to these concerns, the Scientific Committee on Problems of the Environment (SCOPE) launched a major study aimed at better understanding the nature, sources, and fluxes of P in terrestrial and aquatic ecosystems, and at explaining the global environmental effects of P through interactions with cycles of other elements.

The objectives of the project are to
• critically assess knowledge of the nature, sources, sinks, and fluxes of P in the biosphere;
• identify mechanisms of supply of biologically active P in terrestrial and aquatic ecosystems;
• provide the information required to more effectively meet worldwide P requirements for sustainable food and fiber production while minimizing adverse effects on the environment;
• evaluate the environmental effects of current and projected use of P in relation to the biogeochemical cycles of C, N, S, and metals;
• evaluate the transfers of P from terrestrial to aquatic and marine environments and the relationship to the cycling of other elements; and
• assess current and likely future economic trends in P use.

The primary focus of this project is to integrate and synthesize information on P in diverse environments, with emphasis on its flows among terrestrial systems, groundwater, rivers, lakes, estuaries, and oceans. Both natural and anthropogenic fluxes in the P cycle will be assessed in a study of the biogeochemical processes. Particular attention will be paid to P interactions with other elements (C, N, S, and metals).

The project comprises three levels of activity:
• organization of regional workshops in Africa, Asia, Europe, and South America; these workshops will synthesize data on the P cycle in major ecosystems of each area;
• development of conceptual and simulation models of P cycling in major ecosystems of the world; these models will identify gaps in knowledge, and areas where careful management of P resources will be required to optimize food and fiber production and minimize hazards in various environments; and
• integration of the information from the four regional workshops and presentation of the results at a final international workshop to be held in India; every attempt will be made at this workshop to link these findings on a global
scale, including oceanic fluxes; it is expected that this will provide a global perspective on the economic and environmental consequences of the use of P resources.

This information is required to develop management strategies and policies for an important and potentially limiting resource. In addition, it will provide understanding of the interrelationship of nutrient elements in a changing world environment. It will develop insights into the mechanisms and processes involved in P cycling, in addition to addressing major agricultural and environmental issues. It is anticipated that the project will stimulate further investigations by the United Nations Environment Programme, SCOPE, and other scientific organizations.

The first meeting, held in May 1988 in Czerniejeowo, Poland, attempted to integrate and synthesize information on P in Central Europe, a densely populated area with intensive mixed farming systems and industrialization. The proceedings from this regional meeting (Tiessen 1989) attempt to point out the interconnectedness of the ecosystems. At a later meeting an attempt will be made to construct a framework of conceptual and mathematical models that will permit better integration of the data.

**Specific objectives of this meeting**

This, the second workshop in the series, will concentrate mainly on the P requirement to optimize food and fiber production in the main rice-growing areas of the world using Asian and Oceanic data in a regional case study. Specifically, a number of questions must be answered:

- What is the nature of P reserves in lowland and associated upland soils? From an understanding of the chemical and biological (i.e., biogeochemical cycles) reactions in aerobic and anaerobic soils, can we assess the nature of these reserves? How long will they last under present and predicted land use?
- What type of P transformations and translocations occur with rolling topography? How much P is transferred from upland to lowland soils annually? Can we stabilize upland soils while still maximizing food and fiber production?
- What sources of fertilizer P are available? How much is needed? What are the guidelines for efficient P use in flooded soils, upland soils, and intergrades between the two?
- How does the interaction of P with other major elements, such as C, N, and S, and trace elements affect land use and productivity?
- What do we know about the transfer of P from land to water bodies, to rivers, to estuaries? Can the amount of P in these transfers be reduced? Is eutrophication of lakes a problem in this area?
- What key policy and economic issues are important in determining P use?
- Can we identify important gaps in knowledge that should receive scientific attention?

Man), of these individual questions are addressed in the papers presented at this symposium. However, gaps in knowledge still exist in many areas. In particular, although data exist on P inputs and exports from ecosystems, even to the
documentation of P deposition in dust and rain, there is little concrete information on the extent to which the original parent material has been transformed, how much has been lost, or on the quantity left to be used. The question of the degree of weathering and transformation of P in parent material has received scant attention. Greater emphasis on documenting this question must follow, particularly as soils become excessively weathered and the important P reserves are used up (as has occurred in many tropical areas where crop production depends on strategies for minimizing loss of active P fractions and reserves). Recent methods such as the “pedogenic index” approach that have been used to quantify losses and transformations in temperate regions (St. Arnaud et al 1988) should be extended to other regions.

The challenge of the symposium is integration of the data for a complete region through discussion and analysis among experts to see if the complete picture can be understood.

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Notes
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Recommendations

The last day of the Symposium on Phosphorus Requirements for Sustainable Agriculture in Asia and Oceania was devoted to identifying research gaps and research needs related to the topic. Five working groups discussed the following topics:

- Chemistry and fertility
- Sustainable agriculture for lowland soils
- Sustainable agriculture for upland soils
- Agricultural inputs to phosphorus transfers
- Future requirements and forms of phosphorus inputs

The reports of the working groups follow.

GROUP I

Chemistry and fertility

Discussion leader: J.K. SYERS
Rapporteur: A. HUSSIN

The overall objectives of Group I were to assess P reserves in lowland and upland soils and to determine the processes involved in the supply of plant-available P for sustainable agriculture. Five specific topics drawn from the overall objective are discussed.

Adequacy of methods for assessing soil phosphorus forms

The group was firmly of the opinion that both organic and inorganic forms of P should be considered. The rate of supply of P was seen to be particularly important, as was pool size. For the long-term supply of soil P, an amount of P intermediate between a soil test value and total P was considered appropriate; however, the difficulty of quantifying that was readily recognized. The empirical fractionation of inorganic P into chemically defined (e.g., Al-P, Fe-P, etc.) forms was thought to be of limited value.
Evaluation of the processes involved in phosphorus supply, including biological cycling

The group noted the progress made in recent years in studying the desorption of inorganic P from soils. Further information on the rates of P desorption from different soils is required.

The turnover rate of organic P is much less well understood, especially in highly weathered soils. Radioisotopes or simple modeling approaches could probably be used here. The importance of biomass P was recognized, and further efforts should be made to quantify pool size and turnover.

Root morphology, including proteoid roots, is important in relation to root surface area, which is particularly relevant to the acquisition of a diffusing anion such as phosphate. We need a better understanding of root development, structure, and function in different soil-plant systems to provide the necessary basis for manipulation. Plant molecular biology is an exciting new area that offers the potential for genetic manipulation of root morphology. Similarly, genetic modification of root biochemistry, particularly organic acid (e.g., citric, malic, polygalacturonic) production, has important implications for P desorption.

The importance of mycorrhizae to plants growing in soils of very low P status has been recognized. The body of knowledge in this area is quite large, but there is a need to identify and rectify the problem if mycorrhizae are ineffective or absent.

Assessment of extracellular phosphatase enzyme activity is a potentially attractive technique for predicting the mineralization of soil organic P, but it may give misleading information, because substrate supply can be the major limiting factor.

Interactions involving P and other nutrients, particularly Zn, Al, and Fe, were considered by the group. The mechanism of interaction (particularly that of Zn) and the determination of critical levels in plant tissue were seen to be a priority area.

Soil testing and plant analysis for phosphorus

The group was in general agreement that soil testing is useful for predicting whether or not responses to fertilizer P are obtainable and for monitoring the effect of P fertilizer use. However, expectations of what can be achieved by soil testing should be realistic.

Plant analysis for P was seen to be complementary to soil testing, and in both cases appropriate calibration is essential. Information on soil and crop management should be given due consideration in interpretation.

There was discussion as to how soil tests can be improved. It was recognized that, although a simple test is often desirable, particularly for assessing the deficiency or sufficiency of P, there is a need for further sophistication in quantifying the strategy of P fertilizer use and in developing P balance and economic models. Possible improvements in P soil tests include the use of intensity (water-extractable P), quantity (Olsen, Bray, Mehlich, etc.), and buffering capacity (single-point P sorption isotherm) factors.

The concept of including the organic P present in an extract in the soil test value has been advocated, but some work suggests that this gives little advantage.
The group recognized that soil testing interpretation is more difficult with flooded soils.

The selection of the most appropriate soil-testing procedure for a particular situation should be based on a synthesis of available information relating to Soil chemistry and mineralogy, and on the form of P fertilizer to be used.

**Alternative approaches for assessing soil phosphorus status for sustainable agriculture**

The group considered a simple P balance sheet approach as best for determining whether soil P reserves are being depleted or increased.

Biological extraction techniques, particularly exhaustive cropping, have been extensively used in the past and may find renewed favor.

Improved assessments of soil P status include those described in the preceding section and the use of resin extraction over extended times and at higher temperatures.

A simple modeling approach, including trends in extractable soil P values over time, has considerable promise.

**Technology transfer**

The group briefly considered technology transfer at two levels, namely researcher to adviser and adviser to farmer. Practitioners in the group felt that there is a need for better interaction between research and extension workers and teachers. Given the often poor library facilities for research and extension workers in developing countries, a need was seen for “secondary literature.” For example, a publication outlining the main findings and recommendations from this Conference could usefully be published, possibly with sponsorship from the World Phosphate Institute.

A workshop concerning methodologies for soil testing and plant analysis in developing fertilizer P recommendations in Southeast Asia would be useful.

**GROUP II**

**Sustainable agriculture for lowland soils**

**Discussion leader: S. AMARASIRI**

**Rapporteur: D.P. GARRITY**

The group proposed as a basis for its work the concept of a sustainable production system in which productivity is maintained at a high or increasing level without negatively affecting the environment. Thus, resources, including P, must be successfully managed to satisfy increasing human needs and to conserve natural resources. Lowland soils were defined as soils that are submerged or saturated for at least part of the growing season.

Knowledge gaps and researchable issues were seen as follows:
Organic phosphorus

- **Soil microbial biomass.** Data from upland soils indicate that the soil microbial biomass is a major source of available P for plants. The P dynamics in the microbial biomass in lowland rice soils is poorly understood. Definitive data are needed on P uptake and soil and rhizosphere turnover in the microbial biomass, and in the floodwater biomass.
- **Crop residues.** The contribution of P from recycled rice crop residues is modest, but substantial quantities of K are returned to the soil in residues. The value of residue recycling needs more research in light of its important implications for sustaining crop yields with least off-farm nutrient inputs and as a source of rapidly available P.
- **Green manure.** Green manure may make a substantial contribution to P cycling in lowland rice cropping systems. Nitrogen fixation can be limited by the P supply in the soil solution or floodwater. These aspects of green manuring need more attention.

Inorganic soil phosphorus dynamics

Inorganic P dynamics are determined largely by sorption and desorption reactions. It is necessary to gain a greater predictive understanding of the P sorption and release characteristics of lowland rice soils from a range of environments to improve the predictive understanding of the processes, and to contribute to future P management tactics.

The phosphorus balance

There is a great need throughout the tropics for better understanding and documentation of the P balance of lowland rice soils. Balance sheets are needed for P input-output dynamics for major cropping systems in representative environments. More comprehensive data are needed on P removal for various target rice yield levels on different soils.

- **Residual phosphorus.** Phosphorus stocks in the labile and stable pools build up in a soil with continued application of fertilizer P. There is very little information on the long-term trends in P requirements as P fertilizers are applied at reasonable levels over many years. The residual effects of these buildups need to be studied with a view to long-term P management.
- **Phosphorus models as tools.** Practical models of P dynamics are needed as tools to study trends in P requirements over time in lowland rice-based cropping systems. There are numerous gaps in our conceptual and empirical understanding of the processes that control the P cycle (Fig. 1, 2). With understanding of these processes, we can proceed from conceptual to mathematical models. Summary models also need to be developed as management tools for use by field workers to understand trends and to refine P management recommendations.
- **Model validation.** The validation of models of cropping system P dynamics will require data sets of medium–or long-term fertility trials in a number of environments. Very few such data sets exist for tropical rice. More coordinated
1. Conceptual P cycle for a lowland rice soil.
efforts are needed to fill this gap. The value of these long-term trials will be greatly enhanced by use of such data in modeling work.

- **Upland losses.** Upland areas may contribute substantial P to lowland ricefields in the catchment areas below through soil erosion and leaching or runoff. Documentation is needed of the magnitude of these contributions.

**Phosphorus management practices**

- **Placement methods.** The apparent recovery of fertilizer P is generally less than 20%, even in flooded rice culture in the season of application. There appears to be substantial scope to increase P fertilizer uptake efficiency through improved application methods. More attention should be given to placement methods to economize on P application, including the use of starter fertilizer.

- **Plant uptake efficiency.** Species, and cultivars within species, may differ substantially in their ability to utilize the less soluble P fractions in the soil. Work to improve the cultivar P uptake efficiency in rice and in crops in rotation with rice should be pursued.

- **Improved soil tests.** The basis for developing P fertilizer recommendations is inadequate. We need to know much more clearly the levels of soil available P as related to specific yield targets. Soil tests for making P recommendations that are utilized currently in Asian countries are reasonably efficient in the majority of cases; but efficiency must be further improved in two areas: (1) Analytical methods must be carefully assessed and further standardized (e.g., use of wet vs dry soil, choice of extractant). (2) Interpretation of fertilizer response data is inadequate. Environmental factors that influence fertilizer response must be better understood and incorporated into P response models.

- **Phosphorus sources.** Sparingly soluble P sources are effective in some conditions. More research is needed on the exploitation of these sources.
• *Phosphorus management relationships in adverse soils.* The management of P in adverse rice-growing soils has many gaps in both knowledge and application. Improved P management is crucial to sustained yield increases in many major adverse rice soils, notably acid sulfate soils, peat soils, saline soils, Fe-toxic soils, and tide-influenced soils. Phosphorus kinetics in these soils often differ from those in nonadverse soils and need to be much better understood. This work must be integrated closely with intensive practical management research. How to manage P and other nutrients when the field water regime cannot be controlled needs more creative work.

• *Yield decline.* Serious declines in the productivity of lowland rice-based cropping systems are being observed in a number of locations in South and Southeast Asia. At many of these sites, the causes of decline are not known. Phosphorus may be a contributing factor in some cases and should be given serious research attention in future work to diagnose and correct the problem before it reaches alarming proportions.

• *Extrapolation.* A better characterization of soils and cropping systems is needed for the efficient extrapolation of knowledge and recommendations concerning P.

**Phosphorus in farming systems**

• *Phosphorus management on a cropping systems basis.* Phosphorus recommendations should be considered, preferably on the basis of the cropping system as a whole instead of on the basis of each separate crop in the sequence. This is particularly significant for lowland rice-based systems that include upland crops in rotation with a flooded rice crop, wherein soil P dynamics vary radically between successive crops. In most cases, fertilizer P is most efficiently applied to the upland crop rather than to the rice crop, but there are exceptions (e.g., acid sulfate soils in Vietnam), indicating that generalizations should be qualified; more research is needed on the cases where it does not apply.

• *Phosphorus in integrated systems.* More diversified farming systems may be the only way for small-scale rice farming families to raise their incomes and achieve prosperity. Therefore, more attention must be directed to P management for systems integrating rice with fish, legumes, or animals.

**GROUP III**

**Sustainable agriculture for upland soils**

Discussion leader: E. PUSHPARAJAH
Rapporteur: I.S. CORNFORTH

The group felt that there was a need to define the two key words “sustainable” and “upland.” These definitions are proposed:
• **Sustainable** — economically and environmentally appropriate long-term land use able to provide the food, social, and economic requirements of a changing population. This implies a dynamic situation.

- **Upland** — areas that are cropped without the use of impounded water, i.e., under aerobic soil conditions.

**Problems**

In the context of this symposium, the group felt that there was an implied emphasis on soils in the tropics and subtropics, with less reference to the temperate regions. In the tropics, the soils covered will normally include Ultisols, Oxisols, Alfisols, Andepts, and Entisols, many of which have variable charge. Furthermore, the theme of the symposium dictated that we were to consider the role of P in sustainable management systems. The group felt, however, that P cannot be considered in isolation from other constraints. Therefore, it identified the constraints under two major groupings—technical and socioeconomic. Those identified as very serious limitations are given under each group:

- **Technical**
  - Soil erosion
  - Depletion of organic matter and nutrients, particularly N, P, Ca, Mg, and K (the order of importance will vary)
  - Poor soil physical conditions
  - Soil acidity and toxicities
  - Pests and diseases
  - Inadequate water supply and retention
  - Steep topography
  - Inadequate technology packages

- **Socioeconomic**
  - Inappropriate government policies
  - Farmers’ lack of experience in upland agriculture
  - Inadequate finance
  - Population pressure

**What needs to be done**

Two scenarios were considered: 1) development of new land, or management of land already under cultivation but still reasonably productive; and 2) development of land already degraded either physically, chemically, or both. The former would need proper clearing and maintenance or both, while the latter would require regeneration. The actions required include the following:

- Compile an inventory of resources including
  - Soil properties
  - Climate
  - Topography
  - Growth-limiting factors
  - Production potentials
  - Inputs required for sustainable production
  - Input/production functions
• Develop appropriate management packages for the two scenarios:

1. *New land development strategies must*
   — manage land clearing appropriately (avoid burning, heavy machinery, and excessive disturbance);
   — keep soil surface covered;
   — match development to soil, topography, climate, vegetation, and proposed land use;
   — match tillage to topography; and
   — use crops and varieties appropriate to the environment and the people’s needs.

2. *Regeneration includes*
   — selecting appropriate species and varieties either for existing or ameliorated conditions;
   — minimizing further erosion;
   — correcting nutrient deficiencies, imbalances, and toxicities; and
   — developing appropriate water conservation and irrigation/drainage systems.

**Research needs in order of priority**

Within the context of the subject of this symposium, the following research areas need attention:

• continued development of crops and varieties to suit adverse soil conditions, including pioneer crops;
• soil conservation and improvement, including erosion control, tillage, and residue management;
• nutrient requirements and management, including economy of P and cost-effective P sources; fertilizer placement, application frequency, and timing; interaction and balance with other nutrients; use of rhizobia and mycorrhizae specifically adapted to degraded soils and their reclamation, maintenance, and improvement;
• water management; and
• cropping and farming systems, including low-cost pest, disease, and weed control, and the integration of livestock in cropping systems.

With these areas in mind, there is a need to develop alternative site-specific management packages and to compare them in a series of verification trials. At the same time, there is a need to do strategic research to fill gaps in current technology and ultimately incorporate these new findings into the management packages. Much of the required research is of a long-term nature. The management packages must be technically, socially, and economically acceptable. They should emphasize systems requiring low to medium cash inputs, but not inadequate nutrients.

To ensure that the limited trials will have the maximum impact, there is a need for detailed socioeconomic, physical, and climatic characterization of the sites. The development and validation of the trials should preferably be done on a network basis, with emphasis on the development of a national and international network system. At the national level, the network should integrate researchers, extension agents, social scientists, farmers, and policymakers. At the international level, there
should be close interactions between national agricultural research systems, international agricultural research centers, universities in developed countries, and the fertilizer industry.

An improved communication and information transfer system within and between networks is essential.

The second phase is developmental and involves demonstration of the most promising and farmer-acceptable systems, such demonstrations being done on a representative and well-characterized number of farms in collaboration with extension agents and farmer groups.

To achieve these objectives, there is a need to locate sources of funding for 1) resource inventory, 2) initial development of management packages, 3) development and demonstration activities, and 4) farmer loans for initial extension. This would also involve development of extension systems, possibly through farmer management groups. At the same time, there is a need to

- use the resource inventories to influence policymakers to make appropriate governmental decisions on land development strategies, investment in agriculture, population control, etc.;
- advise international agencies of the technology requirements for the development of sustainable systems;
- assure availability of appropriate and viable seed and planting material; and
- develop infrastructures for supplying inputs and marketing products.

GROUP IV

Agricultural inputs to phosphorus transfers

Discussion leader: J. WARD
Rapporteur: R. SANFORD

One of the objectives of the Scientific Committee on Problems of the Environment for this project is to provide the information required to more effectively meet worldwide P requirements for sustainable food and fiber production while minimizing adverse effects on the environment.

This report looks at P transfers from uplands to lowlands and from lowlands to estuaries, and identifies the data that are available and the gaps in them. We were also asked to identify in what form P moves from uplands to lowlands.

Phosphorus pools and transfers in soil, water, and air are determined for land-use categories and landscape units for Asia and Oceania. Land-use categories considered here are forests, tree-crop plantations, pastures, upland rice, lowland rice, other cereals, and vegetables, while landscape units considered are highlands (including slopes), upland valleys, streams and rivers, lowland nonflooded (= rainfed, nonirrigated), lowland flooded, groundwater, and estuaries. In addition, inputs (rain and other atmospheric deposition, fertilizer, and soil weathering) and outputs (product export, atmospheric loss, and loss to oceans) are examined for each of the land-use categories.


Pools

A matrix of landscape × land-use was developed to examine inputs, pool sizes, and outputs (Table 1). A flowchart diagram (Fig. 3) is used to identify transfers and evaluate data for transfer amounts and the mechanism of the transfer event. Figure 4 illustrates land-use categories.

Table 1. Phosphorus inputs, pools, and outputs in landscapes under different land use.a

<table>
<thead>
<tr>
<th>Item</th>
<th>Land-use category</th>
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<tbody>
<tr>
<td></td>
<td>Forests</td>
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<td>Inputs</td>
<td></td>
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<tr>
<td>R1a Rain</td>
<td>A</td>
</tr>
<tr>
<td>R1a Atmospheric deposition</td>
<td>B</td>
</tr>
<tr>
<td>R1b Soil weathering</td>
<td>B</td>
</tr>
<tr>
<td>R1c Fertilizer</td>
<td>A</td>
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<tr>
<td>Pools</td>
<td></td>
</tr>
<tr>
<td>R2 Highlands and slopes</td>
<td>A</td>
</tr>
<tr>
<td>R3 Upland valleys</td>
<td>A</td>
</tr>
<tr>
<td>R4 Streams and rivers</td>
<td>A</td>
</tr>
<tr>
<td>R7 Lowland flooded</td>
<td>B</td>
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<tr>
<td>R6 Lowland nonflooded</td>
<td>A</td>
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<tr>
<td>R5 Groundwater</td>
<td>A</td>
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<tr>
<td>R8 Estuaries and river deltas</td>
<td>A</td>
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<tr>
<td>Outputs</td>
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<tr>
<td>R9 Product export</td>
<td>A</td>
</tr>
<tr>
<td>R10 Loss to atmosphere</td>
<td>B</td>
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<tr>
<td>R11 Loss to ocean</td>
<td>–</td>
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</tbody>
</table>

aA = data available, B = data possibly available, C = no data, (–) = not applicable.

3. Directional transfer of P between landscape units in Asoa and Oceania.
Estimates of P pool sizes are available for most land-use categories across the landscape. Knowledge of the forms of P (organic vs inorganic, particulate vs dissolved) is unavailable for most systems. There are striking gaps in our knowledge of atmospheric P inputs and losses. Almost no information is available to estimate the variability of atmospheric P inputs (spatial or temporal). In the case of P losses to the atmosphere, the mechanisms and amounts are largely unknown.

Transfers
Altogether 35 transfer categories were identified among landscape units (Table 2). Whether data exist for these transfers was determined for each land-use category. Of the 210 transfers considered, data are available for 41, data are probably available for 76, and no data are available for 93 (Table 3). Important among the transfers

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4. Schematic diagram of landscape units considered for P pools and transfers in Asia and Oceania.

Table 2. Phosphorus transfer for landscape unit × land-use category interactions.

<table>
<thead>
<tr>
<th>Item</th>
<th>Land-use category</th>
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<tbody>
<tr>
<td></td>
<td>Forests</td>
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<tr>
<td>R2-R4</td>
<td>A</td>
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<tr>
<td>R2-R5</td>
<td>C?</td>
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<tr>
<td>R3-R5</td>
<td>C?</td>
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<tr>
<td>R3-R4</td>
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<tr>
<td>R3-R6</td>
<td>C?</td>
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<tr>
<td>R3-R7</td>
<td>C?</td>
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continued on opposite page
Table 2. continued

<table>
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<tr>
<th>Item</th>
<th>Land-use category</th>
<th>Forests</th>
<th>Tree-crop plantations</th>
<th>Pastures</th>
<th>Upland rice</th>
<th>Lowland rice</th>
<th>Other cereals</th>
<th>Vegetables</th>
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**Outputs**

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<th>Tree-crop plantations</th>
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<th>Lowland rice</th>
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</table>

a A = data available, B = data probably available, C = no data, (–) = not applicable.

Table 3. Summary of information on P transfers for landscape × land-use interactions (refer to Table 2). a

| Data availability | Land-use category | Forests | Tree-crop plantations | Pastures | Upland rice | Lowland rice | Other cereals | Vegetables | Total |
|-------------------|-------------------|---------|-----------------------|----------|-------------|--------------|---------------|------------|
| A (data available)|                   | 6       | 4                     | 11       | 7           | 3            | 5             | 5          | 41    |
|                   |                   | (19)    | (13)                  | (31)     | (26)        | (14)         | (16)          | (16)       | (20)  |
| B (data probably available)| | 11       | 11                    | 8         | 7           | 11           | 14            | 14          | 76    |
|                   |                   | (34)    | (35)                  | (23)     | (20)        | (50)         | (43)          | (43)       | (36)  |
| C (no data)       |                   | 15      | 16                    | 16        | 12          | 8            | 13            | 13          | 93    |
|                   |                   | (47)    | (52)                  | (46)     | (46)        | (36)         | (41)          | (41)       | (44)  |
| Total transfers considered | | 32       | 31                    | 35        | 26          | 22           | 32            | 32          |       |
|                   |                   | (100)   | (100)                 | (100)    | (100)       | (100)        | (100)         | (100)      | (100) |

Grand total | 210 (100)

a Numbers in parentheses are percent.
with no data are 1) lowland nonflooded to lowland flooded (overland erosion) for all land uses, and 2) subsurface and groundwater P to lowland flooded for all land uses. Many output transfers (Fig. 5) are also poorly understood, chief among them being 1) lowland nonflooded and highlands/slopes losses to the atmosphere (for all land uses); 2) lowland flooded and highlands/slopes losses to the oceans (for all land uses); 3) stream and river product P losses (fisheries); and 4) gaseous P losses from flooded lowland, estuaries, and deltas. Of the land-use categories, tree-dominated systems most frequently lack data for P transfers, while pasture systems seem to have been best studied. As is the case for P pools, information is generally lacking on P forms. Of the 20% of all P transfers for which there are data, only those for pastures and possibly forests are well documented with respect to P forms.

GROUP V

Future requirements and forms of phosphorus inputs

Discussion leader: N.J. Barrow
Rapporteur: K.L. Sahrawat

The group discussed the evaluation and selection of fertilizer sources, future approaches to evaluating sources, demand and requirements, phosphorus fertilizer and the environment, and several smaller topics.

5. P transfers from landscape to output categories.
Evaluation and selection of fertilizer sources

This symposium highlighted the problem of determining appropriate criteria to compare P fertilizer sources.

If the P response curves are curvilinear, and if they reach the same asymptotic yield, then the ratio of curvilinear coefficients of the Mitscherlich function is an appropriate single index of relative effectiveness (RE).

If the responses are curvilinear and do not reach the same asymptote, then a single agronomically meaningful index cannot be obtained over the whole response curve. The use of log/linear transformations is inappropriate to produce a single RE value, because they mask the curvilinear nature of the original data set. In this situation, comparisons between products can be made in terms of the amount of each fertilizer required for a target yield. By taking account of the relative costs of the fertilizers, a rational economic decision can be made. The appropriate costs are the costs of the fertilizer on the ground.

If the response curve can be broken into two parts (e.g., linear and curved), then the ratio of the slopes of the linear portion can be used to indicate RE within the application rate covered by the data.

The two paragraphs above on evaluation of sources of fertilizer were not adopted unanimously by the group. There are indications from many greenhouse and field trials that crop response to different phosphate rocks (PRs) can be described by a semilog function, and this approach for comparison of fertilizer sources merits further study. Some participants felt that a deeper evaluation of the various approaches to fertilizer sources by a group of qualified statisticians, mathematicians, economists, and agronomists should be undertaken to validate the suggestions made by Group V on comparisons of fertilizer sources. After a few years of further research, a conference to specifically address this issue would be merited.

Future approaches to evaluating sources

Sufficient and reliable short-term data sets of comparisons of P sources are available to allow greater attention to be given to incorporation of such data into mechanistic soil-plant models. These models should integrate climatic and management factors or variables such as crop type, soil chemistry, and fertilizer properties and placement. Such modeling exercises should aim to provide advice on a regional basis about appropriate management packages both to increase the efficiency of P utilization and to minimize environmental degradation. The model will also assist in highlighting areas where knowledge is lacking.

While short-term data sets are available, insufficient long-term trial data are available to properly assess residual values with a realistic (10-yr) time frame.

When P sources are evaluated in field trials, adequate measurements and soil and environmental characterizations should be made to enable testing of model predictions and extrapolation to other locations. The data required include rainfall, soil moisture, pH, pH buffering, organic matter, exchangeable cations, cation exchange capacity, P buffering, measures of P status, and Ca concentration in the soil solution.
Demand and requirements

Fertilizer P has a residual value, and successive applications should lead to P accumulation. However, this will occur only if the P supplied exceeds the P removed in the product. At present, this seems to be the case in areas where high fertilizer subsidies exist and in areas of high-value crop production. If the system is to be maintained, overall applications should increase. Farmers are unlikely to fertilize to restore P to the earlier higher levels but will likely continue to try to maximize output and minimize input. If the system is to be sustained, the question of who pays needs to be addressed.

In the context of the developing countries of Asia and Oceania, it is imperative for the future development of the food and agriculture sector on a sustainable basis that appropriate fertilizer materials in increasing quantities and at affordable prices be readily available to farmers. Both price as well as nonprice factors and policies need to be considered. In most cases, fertilizer distribution costs are high compared with the cost of production, and there is ample room for substantial savings through improving the distribution infrastructure. Problems relating to infrastructure are site-specific and should be addressed as such.

Assessing the P status of individual fields has always been a difficult problem. Field plots provide the ultimate criterion, but the number that can be undertaken is limited.

When field evaluations are undertaken, the results should be related to soil tests if possible. If reasonable calibrations can be established, the resources currently allocated to field evaluations could be redirected into more efficient and effective soil testing facilities and fertilizer advisory services. Where several organizations are involved in testing and evaluation, there is clearly a need for coordination.

A complementary approach to soil testing is the modeling approach followed in Australia and New Zealand. This attempts to assess current status by using appropriate discounts for the P applied in previous seasons. Perhaps this approach could be adopted by progressive farmers and would then diffuse to other farmers. Essential for this approach is information on the rates of reaction of P on the appropriate soils and knowledge whether this rate differs among local soils.

Phosphorus fertilizer and the environment

PR contains traces of U, its decay products, and heavy metals. The concentrations of U, Ra, and heavy metals can be decreased in the manufacture of phosphoric acid. However, this leads to increased costs as well as to additional disposal problems, with attendant environmental concerns. The increased costs may in turn affect consumption. Very little work appears to have been done on the fate of heavy metals or U and its decay products in acid soils. We should establish the consequences of using materials containing potentially environmentally damaging elements and evaluate the relative environmental effects of new P sources.

Other approaches

Seed treatment with high P levels has been shown to lead to increased yields and greater P uptake. This may be a strategy that can be used to decrease P requirements,
but attention should be paid to whether the long-term outcome may be more exploitative of the soil than standard fertilizer application practices.

**Role of mycorrhizae**
Mycorrhizae affect P uptake and utilization. Research has shown that differences exist between plant species in vesicular-arbuscular mycorrhizae (VAM) dependence and in the efficiency of VAM in assisting P uptake. Research is needed in Asia to explore the possibility of matching VAM and plant genotypes in a variable P environment in a similar way as was done with rhizobia and legumes. As in the research with seed treatment, the overall P input-output balance should be considered in the context of sustainability.

**Extension of existing knowledge to users**
Existing knowledge of the performance of PRs in different soils in Asia must be integrated. This should lead to a publication that would guide field researchers to the soil/climate/cropping system combinations where PRs could be worth testing.

Information on the effects of liming on P requirements (as influenced by nutrient interactions, species tolerance for Al, cost, etc.) needs to be summarized in publications written for field agronomists. Much knowledge on this subject circulates within the scientific community but is inaccessible to those who ultimately make recommendations to the farmers.

**Economic evaluation of agronomic research results**
Greater interaction should be encouraged between soil scientists and economists. Designs of regional programs that result in large data sets can be improved by input from economists at the early stages to ensure that sufficient information is collected for economic interpretation.

**Phosphorus deposits and reserves**
Substantial indigenous supplies of PR are presently lacking in Asia and Oceania. To address this problem, there needs to be a considerable increase in geological exploration aimed at discovering additional sedimentary PR deposits.
Introduction

The task of this symposium was to collect the expertise on P cycles in Southeast Asia and Oceania with the objective of addressing the topics outlined in the paper by J.W.B. Stewart. The complexity of this task meant that such different subjects as policy issues, environmental concerns, fertilizers and fertilization, chemical and physical processes in the P cycle, interactions with other elements, and agricultural management had to be addressed.

This volume is a compilation of the contributions to the symposium, which together cover all of the above topics; but no synthesis has been attempted. It will become clear to the reader that different authors have presented disparate interpretations of the present knowledge of the P cycle. Particularly, the topics of P fertilization, P fixation, and evaluation of fertilizer effects in different soils generated controversy. These topics are presented in this volume without any attempt to resolve the issues. It is hoped that this book will serve as a basis for discussion and synthesis of the P cycle at later stages of the SCOPE P program.

The first four contribution address policy issues and environmental concerns. They are followed by six papers on P fertilizers, resources, and fertilizer use. The next two contributions — by Ward and Wei-bin and by Miwa — deal with physical transfers of P in the landscape, a topic whose importance was identified at the previous workshop in Poland. The subsequent seven contributions deal with chemical processes and elemental interactions that affect P cycling. The interactions of P and N through the process of N₂ fixation are taken up separately by Watanabe and Cholitkul, and by McLaughlin et al because of the importance of N inputs into agricultural and other ecosystems. The remaining 13 papers deal with P fertilization and management of specific crops, but they also point to the importance of an integrated P management approach to entire cropping systems, rather than considering only individual crops and cropping seasons.

The recommendations were made by several panels at the symposium. Since the objective of this series of SCOPE workshops is the collection and integration of knowledge, these recommendations point to present gaps in our knowledge and understanding of the P cycle and highlight some of the controversial issues raised.

Holm Tiessen
University of Saskatchewan
Regional food security: demographic and geographic implications

P.J. STANGEL AND H.R. VON UEXKULL

Asia accounts for nearly 60% of the world’s population, approximately half of the global demand for food and fiber, and about 70% of all undernourished and poor people. Only one-fourth of the world’s arable land lies in Asia, nearly all of which (>92%) is now under cultivation. The productivity of Asian agriculture has more than kept pace with population growth, and between 1965 and 1984 increased by nearly 35% per capita supply of calories. This was made possible by the rapid increase in the supply and use of fertilizer (particularly N), rapid expansion of irrigated land areas, and the broad spread and adoption of fertilizer-responsive, high-yielding varieties of wheat and rice. Asian agriculture faces some major challenges in the immediate years ahead as well as over the longer term. Agricultural production of the basic commodities has slowed in the region since 1984, particularly in the dominant countries of China and India. Factors that may be contributing to this slowdown include low profitability of rice and wheat farming, lack of funds to maintain agricultural subsidies, large external debt, narrow agricultural base upon which past growth has been built, and the changing diets of the people. Over the longer term, national planners and researchers will need to a) find the technical means to continue to feed a major share of a population that will increase in number by 1.7 billion to 4.6 billion by 2020, and b) put into effect a broad set of policies to provide an agriculture with sufficient productivity to meet the basic food needs as well as satisfy a major portion of the food demand due to changing diets of its people and still serve as the platform upon which overall economic development can be based. This will require increased research on the fertilizer requirements of upland crops, increased efficiencies in the use of fertilizer and water, as well as new technologies that will improve the productivity of highly fertile soils, and allow the restoration of recently cleared infertile soils.

Close to 60% of the earth’s total surface is located in the tropics and subtropics. Tropical and subtropical Asia accounts for 29% of the land mass but is home to 58% of the world’s population.

According to recent United Nations (UN) projections (PRB 1988), world population will reach 6.2 billion by the year 2000 and may eventually stabilize at a level of approximately 10.5 billion sometime before 2100 (Fig. 1). By then 9.1 billion, or 87% of the world’s inhabitants, will be living in developing countries—most of them in Asia, which is already considered to be overpopulated (Fig. 2).

Between 1989 and the year 2000, Asia will have to provide food for an additional 615 million people—the equivalent of roughly three-quarters of the 1988 population...

2. World population by region (PRB 1988).

of India. Such increases will place huge pressures on national economies to produce the necessary food and fiber to feed and clothe the additional people.

Food production can be increased by

- increases in the area under arable land pastures and permanent crops,
- increases in cropping intensity, or
- increases in yields.

While the first option is still wide open for Latin America and many African countries, most of Asia, particularly the most densely populated countries of the region, will have to rely primarily on the last two options, because most land suitable
for agriculture is already under cultivation. Between 1961 and 1984, the land surface used in developing countries as arable land and for permanent crops increased by 102 million ha or 15%. The greatest expansion of agricultural land was in Latin America (35%), followed by Africa (18%). In the Far East, expansion was only 4%, and there was virtually no expansion in arable land in the centrally planned economies of Asia (Dudal 1988). In fact, in many Asian countries, most notably in China, substantially more good land is being lost to expansion of housing, industrial use, and road construction than is being added through reclamation and land clearing (Von Uexkull 1988).

Faced with population pressures and land constraints, many prophets of doom in the 1960s and early 1970s expressed serious doubts about the future ability of poor agrarian nations to feed themselves and about the capacity of other nations to cover their deficits. Massive famines were predicted for the developing world, especially for Asia (Myrdal 1967, Paddock and Paddock 1967, USDA 1966).

The fact is that over the past 25 yr, food production in Asia increased at a faster rate than in the rest of the world and surpassed the rate of population growth by a substantial margin (FAO 1987a). As remarkable as this accomplishment is, planners still have major concerns about the region’s ability to feed and clothe the future population. Growth in food production has stagnated globally since 1985 (FAO 1988a). Before charting the course of future growth into the 1990s and beyond, national planners feel several questions must be answered:

- What factors contributed to the outstanding performance of agriculture in Asia?
- Can the momentum be maintained?
- What new strategies should be adopted to maintain such momentum?
- What role will fertilizer, and more specifically P fertilizer, have to play in the future of Asia and in achieving a more regenerative and self-reliant food system?

Answers to these questions will be developed in this paper.

Factors affecting past performance of Asian agriculture

Twenty-five years ago national planners were divided as to the importance of agriculture to the overall economic development of a country. Some felt the overall economic growth of a nation must be based first on a financially sound and expanding agriculture; others felt the key was development of the industrial sector, with funds being extracted from agriculture to help finance this growth. Those who advocated a focus on agricultural development had a diverse set of goals ranging from strategies aimed at reaching the rural poor to those designed primarily to achieve self-sufficiency in the production of the basic food commodities.

The successful package

By the mid-1960s, researchers and national planners of international institutions and a number of Asian countries had begun to identify what has proved to be the successful combination of inputs necessary to provide a reasonable level of food security to the people of the region and also to provide a mechanism for income
distribution to the rural poor. This combination, which was also considered basic to agricultural as well as overall economic development, consisted of a package of inputs including 1) fertilizer-responsive, high-yielding varieties; 2) adequate water supplies (irrigation); 3) fertilizer; and 4) credit. This successful package of inputs created the phenomenon that is today popularly referred to as the Green Revolution. Fertilizer, the centerpiece of this package, provided the fuel to give the Green Revolution the necessary thrust to achieve its full production potential. To accelerate the realization of this potential, governments put into place a range of policies, regulations, and programs that had an immediate positive and powerful impact on both the agricultural and fertilizer sectors (Stangel 1988).

The major goals and policies employed by many Asian countries to achieve these included the following:

- Adequate domestic supplies of food were considered vital to the basic security as well as the key to future economic development of the nation. Both fertilizer and food were considered strategic items and central to the success of either goal.
- To maximize food security, the following approach was deemed necessary to reduce the nations’ dependence on imports of food and fertilizer:
  - Moving toward self-sufficiency through increased domestic production of basic foods (rice, wheat, and maize) and fertilizer (particularly N and, to a lesser extent, P).
  - Using, wherever technically feasible (but not always economically viable), indigenous resources and local production facilities to achieve these goals.

Government leaders felt these goals and policies could be met through strict controls on the agriculture and fertilizer sectors. Therefore, increased government intervention in the agricultural and fertilizer sectors was deemed justified. As a result, governments devised and put into place a series of policy instruments including

- price controls and subsidies, particularly on fertilizer and the basic food commodities;
- establishment of state-owned enterprises to control prices as well as take prime responsibility for the import, production, and distribution of fertilizers (this included nationalization of existing private companies and government ownership of all or nearly all future fertilizer production units);
- use of public funds to finance and/or underwrite (by the government) major costs to develop and operate the fertilizer sector; and
- focusing, for the majority of inputs, on a few basic food crops (rice, wheat, and, to a lesser extent, maize).

The food, fertilizer, and oil crisis of 1974 brought into sharp focus the importance of these commodities to national security. Food and fertilizer became strategic items considered vital to national security and were treated with the same rigor as if they were part of a system for national defense. Economic issues related to their production or storage became secondary considerations and in more than a few instances were treated as nonissues. Of particular significance was the fact that these policies offered very little place for capital formation and/or access to additional financing through active participation by companies from the private sector.
Impact on the fertilizer sector

The physical impact of these policies on the fertilizer sector in Asia, and for that matter in much of the world, has been truly remarkable. Fertilizer consumption in Asia during 1976-87 grew by 9.0%/yr, nearly 5 times the average rate for the rest of the world (Table 1). As a result, Asia’s share of world consumption of fertilizer rose from 18% in 1976 to nearly 30% in 1987. Similar increases in fertilizer production were also noted for the region: domestic output rose from 14.1 million t of nutrients (15% of world production) to 35.2 million t (25% of the world’s total). As a result of these shifts, Asia now leads all other regions of the world in the production and consumption of fertilizer. Six countries—China, India, Japan, Indonesia, Turkey, and Pakistan—are the dominant consumers of fertilizer in Asia. In 1987 they accounted for 87% of the fertilizer used in the entire region. China alone accounted for 43% of the region’s total consumption, followed by India (22%), Indonesia (6%), Japan (6%), Turkey (5%), and Pakistan (5%). The remaining 33 countries accounted for the remaining 13% of the total (FAO 1988b).

The growth in fertilizer consumption and production for Asia has been uneven with respect to the three basic nutrients. For example, Asia accounted for nearly 40% of the world’s N consumption and one-third of its production in 1987. In contrast, Asian farmers consumed only 26% of the world P fertilizers and even less (6%) of the world’s K. The region produces only 19% of the world’s P and 12% of the world’s K. This difference is due, to a large extent, to the scarcity in the region of raw materials (phosphate rock, S, and sylvite) needed to manufacture finished P and K fertilizers. On the other hand, many of the countries in the region have abundant supplies of natural gas—the basic feedstock used in the manufacture of N fertilizer—but lack the necessary raw materials to manufacture P and K fertilizers. This is a basic point when developing strategies for food security.

Impact on food production

The impact of food- and fertilizer-related policies on food production has been very substantial. Several countries that were major importers of rice, wheat, or maize in the mid-1970s are at least self-sufficient, and some are net exporters of their surpluses. A partial list of the countries and commodities in which self-sufficiency

Table 1. Share of fertilizer consumption in the world and Asia, by region, and annual growth rate during the past decade, 1976-77 and 1987-88 (FA 1988b).

<table>
<thead>
<tr>
<th>Area</th>
<th>1976-77 Nutrients (million t)</th>
<th>% of world</th>
<th>1987-88 Nutrients (million t)</th>
<th>% of world</th>
<th>Annual compound growth rate (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>North America</td>
<td>21.4</td>
<td>23</td>
<td>19.6</td>
<td>16</td>
<td>(0.9) b</td>
</tr>
<tr>
<td>Asia</td>
<td>17.5</td>
<td>23</td>
<td>41.0</td>
<td>29</td>
<td>9.0</td>
</tr>
<tr>
<td>Total world</td>
<td>94.5</td>
<td>100</td>
<td>139.9</td>
<td>100</td>
<td>3.6</td>
</tr>
<tr>
<td>Total excluding Asia</td>
<td>77.0</td>
<td>82</td>
<td>98.9</td>
<td>71</td>
<td>2.0</td>
</tr>
</tbody>
</table>

a Excludes ground phosphate rock. Calendar year data for 1986 would be included in 1986-87. Totals may not add because of rounding. Nutrients = N + P₂O₅+K₂O.

b Negative growth for the period.
has been reached includes Turkey, India, and Saudi Arabia (wheat); the Philippines and Indonesia (rice); Pakistan (rice and wheat); and China (rice and maize). Some of these countries have joined Thailand and Japan as rice exporters and are competing with them for shrinking and more distant markets. The most important impact of growth in these basic food commodities has been an increase in the amount of calories available per capita (Fig. 3). For example, Western Asia experienced a 38% real increase in the available calories per capita, while East and South Asia experienced 32 and 25% increases, respectively, during 1970-84 (FAO 1987a). In other words, most Asian countries have been able to produce the food needed to raise the caloric intake of their people provided they have the economic means to buy the commodities. Improved production per capita of cereals (mainly rice and wheat) has been the main contributor to this favorable situation. Asia has led all developing regions in this per capita improvement in supplies (Fig. 4). This increase in basic food supply is a necessary first step toward allowing governments to reevaluate their approach to food security and pursue more flexible policies of agricultural development, which include the eventual improvement in not only the quantity but also the quality of the diets for most of their people.

3. Per capita energy consumption.
Fertilizer has played the major role in improving the food situation in Asia. This has been well documented. In a recent study, the International Rice Research Institute reported that increased yield per unit area accounted for up to 66% of the increased rice production in select countries and, depending upon the country, fertilizer contributed up to 31% of this increase (IRRI 1986).

A more recent study by the International Fertilizer Development Center (IFDC) has confirmed that the recent increases in grain production for Africa, Asia, and Latin America are very closely related to increased fertilizer use (Baanante et al 1989). Using conservative estimates of 5, 10, and 7 as the units of food produced per unit of fertilizer nutrient applied, and taking into account the increase in total fertilizer used in these regions lead to estimates of an additional 475 million t of grain produced in 1985 as a direct result of fertilizer (Table 2). Asia accounted for 85% of this increase. Assuming full use by people, this was sufficient to feed more than 1.3 billion people.

Benefits versus costs of past policies

Past fertilizer- and food-related policies have resulted in substantial benefits to the national economies of many Asian countries. Achievement of self-sufficiency in one or more of the basic food commodities, rising per capita incomes, and more equitable income distribution are but a few of these benefits. However, as successful as these policies have been in the past, many countries that have moved agricultural production of the basic food grains a considerable distance closer to the yield potential, particularly for irrigated wheat and rice, are facing a new set of issues. It is
in this context that past and current policies need to be reviewed and, where appropriate, adjustments made; otherwise, future gains in agricultural productivity may be denied, and many of the gains made over the past two decades may be lost. The immediate major problem areas are 1) pressure on agricultural budgets, 2) cost of servicing the external debt, 3) the limit of funds for new agricultural development, and 4) the narrow focus on rice and wheat. As important as these issues may be, any policy changes must be undertaken with caution. World cereal production has declined since 1985-86 (FAO 1988a), reflecting the combined effect of planned cutbacks to reduce the global surplus and the droughts of 1988 in North America. As a result, ending stocks in the world for 1989 are at their lowest level since 1974 (USDA 1988).

Pressure on agricultural budgets
Fertilizer subsidies have been substantial and have placed major pressure on agricultural budgets. As examples, fertilizer subsidies in 1986-87 totaled US$359 million in Indonesia (World Bank 1987a), US$1,600 million in India, US$50 million in Bangladesh, and US$525 million in Pakistan (World Bank 1987b). These amounts reflect at least 30% and in some cases up to 80% of the nation's total agricultural budget. With the exception perhaps of oil-financed economies, these countries cannot continue such a high outlay of funds just to cover the operational component of the agricultural and fertilizer sectors and still expect agricultural growth of any significance.

High external debt
Although not critical at this time, a second and potentially very damaging cost to the national economy can be the cost of servicing the large foreign debt accrued during the past decade, much on very favorable terms, but which now is coming due. The World Bank estimates this bill to be over US$1.3 trillion for all developing countries (IFAR 1988).

Although world attention regarding high external debt has been focused on Latin American countries—notably Brazil, Mexico, and Argentina—Asian countries as a group borrowed at a rate comparable to that of the Latin American countries during 1980-88. Servicing this debt may not be a major difficulty under the
Regional food security

present booming economies for many countries within Asia; however, it could pose major problems if these countries continue to borrow at or above the 1980-88 rate and experience a slowing in economic growth. Indonesia, China, Turkey, and the Philippines would most likely be affected should this happen (Do Rosario 1989, Vatakrolis 1988). The debt service as a percent of exports in 1987 was as follows for the given Asian countries: Burma, 59.3%; Turkey, 27.8%; Indonesia, 27.9%; Philippines, 22.7%. These are in contrast to Argentina, 45.3%; Brazil, 26.7%; and Mexico, 30.1% (USAID 1989). Many national and international planners are suggesting that the external debt of many of these countries be serviced with foreign exchange generated through increased export of agricultural products. To do this, current national policies on agriculture will need to be refocused and their impact on food security assessed.

Narrow crop production base

For many countries in Asia, most of the growth in agricultural production can be traced to increased production of rice and/or wheat. Little growth has been recorded in the production of maize, oil crops, or vegetables. Many of the activities of the extension service, research organizations, and fertilizer sector reflect this narrow focus. As was explained earlier, this has resulted in a focus primarily on the production and use of N fertilizer. Only limited attention has been directed to the use of P and K fertilizer. This narrow focus on the production of food and fertilizer has limited the flexibility of Asian agriculture to broaden its production base.

Challenges facing Asian agriculture and the fertilizer sector

No doubt a strong case can be made to justify the fertilizer- and food-related strategies and policies implemented during the mid-1970s. Considering the gravity of the situation during that period, those may have been the most practical and prudent policies and programs for the time to raise food production and improve income distribution. However, those strategies had a long-term cost and may no longer be relevant as Asia enters the 1990s.

Furthermore, the agricultural and economic conditions within the region are substantially different from those that prevailed 25 yr ago. How national planners and government officials deal with this new situation will have a major bearing on the fertilizer sector overall, and specifically in the case of P use in the region.

Some conditions make the situation different:

• Population pressures are not the same throughout Asia.
• Considering the per capita purchasing power, current inventories, and projected levels of production, supplies of basic food commodities appear more than adequate to meet demand, at least over the near term.
• Because personal incomes are rising and individuals are striving for a better quality diet, there is increasing demand for meats, vegetables, and fruits as well as for rice and wheat.
• Government controls are beginning to cause major distortions in the agriculture and fertilizer sectors and, if continued, may do major damage to future growth of their national economies.
• For some newly industrialized countries (particularly those in the Pacific Rim), there is increased demand for labor in urban areas, thus providing an incentive for mechanizing agriculture to free rural labor and to reduce labor costs.

• Governments are finding it increasingly difficult to service their external debt and at the same time find sufficient local funds to finance agricultural and industrial development at levels required to sustain future agricultural growth.

• Asia is becoming increasingly dependent upon other regions of the world for procurement of some of its basic commodities as well as sale of its industrial output; thus, international trade is on the increase.

Other papers in this volume elaborate more fully on each of these areas. Only a few general comments will be made here on issues related to population, land, and water constraints, changing diet, and the future role of government.

Variable population growth
To date (1989), Asia has been able to produce food at a rate faster than has been the increase in the purchasing power of its people. One of the major concerns confronting national planners is whether or not the countries of the region will be able to maintain this relationship into the 21st century, considering the projected increase in population and the scarcity of new arable land and water supplies. Strategies developed toward ensuring secure food supplies will to a large extent take into account assumptions made about population growth, not only for Asia, but particularly in the food-surplus, developed regions of the world.

Global projections. Long-term projections (through the 21st century) of world population result in differing scenarios, largely dependent upon what is assumed about the future course of the birth rate. In the UN projections (Fig. 1), the middle series assumes that world fertility will decline to a total fertility rate of about 2 children per woman by 2035, with a resultant world population of 10.2 billion, exactly twice that of 1988. The lower series assumes the “two-child family” average would be reached by 2010, whereas the higher rate assumes this goal will be reached by 2065. Depending upon the set of assumptions used, these projections result in “ultimate stable” world populations of between 7.5 and 14.2 billion, respectively, as early as 2030 but no later than 2100.

Based on historical trends and previous forecasts, population growth has been slowing at a rate faster than most experts seem to anticipate (PRB 1975, Salas 1981). Therefore, it is highly probable that the world population will stabilize at levels below the medium range projection of 10.2 billion. Estimates discussed in the following subsection are based on the medium-range assumption.

Major growth centers. The vast majority of the world’s current population and its expected future growth can be found in developing countries. In 1988, 3.9 billion or 77% of the global population was in developing countries. If, as assumed, the current annual growth rate of 2.1% continues, this number is expected to reach 4.9 billion by 2000 and 6.7 billion by 2020. In that year, developing countries will account for 83% of the world’s population. This is up from the 76% recorded in 1988. Fully 93% of all future growth in population will occur in developing countries.
Because of its extremely high base, Asia will account for 58% of the global increase, followed by Africa with 25% and Latin America with 10% of the total (Fig. 2).

Because of a slower growth rate (0.6%/yr), developed countries will account for only 7% of the future growth in population between 1988 and 2020. As a result, their share of world population will drop from 23% in 1988 to approximately 17% by 2020 (Table 3). The majority of the developed countries will have reached zero growth and stable populations by 2020. These are important points in discussing food security, because most of the world’s food surpluses and most of its financial resources are currently in the developed countries, while high indebtedness and the need for food occur primarily in the developing countries.

Population increases in Asia are dominated by the growth patterns of China and the countries of the subcontinent, particularly India (Table 3). Although China is currently the most populated country in the world (1,089 million in 1988), it has made major strides in the last 10 yr toward reducing its birth rate (PRB 1988, 1975). As a result, population growth is currently increasing only at an average of 1.4%/annum and is dropping rapidly. This growth rate is nearly equal to the 1.3%/annum for other countries in East Asia and well below the 2.2%/annum average for South Asia, the 2.0%/annum rate for India, and the 1.8%/annum rate for overall Asia. As a result of these differential growth patterns, India is expected to equal China in total population (about 1.4 billion) by about 2030 and to assume the dominant position as the world’s most populated country by the middle of the 21st century.

The patterns of growth in India and China reflect the overall changes in population that are occurring in East Asia as compared with South Asia (Table 4). In general, population growth in East Asia (China, including Taiwan; both Korea; Japan; and Hong Kong) has slowed dramatically in recent years. In addition, as these countries have become more industrialized, the percentage of total population that is rural has dropped and personal incomes have risen.

<table>
<thead>
<tr>
<th>Region</th>
<th>Annual growth rate (%)</th>
<th>1988 Population (10^6)</th>
<th>% of total</th>
<th>2000 Population (10^6)</th>
<th>% of total</th>
<th>2020 Population (10^6)</th>
<th>% of total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Africa</td>
<td>2.9</td>
<td>623</td>
<td>12.1</td>
<td>886</td>
<td>14.4</td>
<td>1497</td>
<td>18.7</td>
</tr>
<tr>
<td>Asia</td>
<td>1.8</td>
<td>2995</td>
<td>58.4</td>
<td>3611</td>
<td>58.4</td>
<td>4629</td>
<td>57.5</td>
</tr>
<tr>
<td>Oceania</td>
<td>1.2</td>
<td>26</td>
<td>0.5</td>
<td>30</td>
<td>0.5</td>
<td>36</td>
<td>0.4</td>
</tr>
<tr>
<td>Latin America</td>
<td>2.2</td>
<td>429</td>
<td>8.4</td>
<td>537</td>
<td>8.8</td>
<td>711</td>
<td>8.9</td>
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<tr>
<td>North America</td>
<td>0.7</td>
<td>246</td>
<td>4.8</td>
<td>268</td>
<td>4.3</td>
<td>297</td>
<td>3.7</td>
</tr>
<tr>
<td>Europe</td>
<td>0.3</td>
<td>497</td>
<td>9.7</td>
<td>506</td>
<td>8.2</td>
<td>499</td>
<td>6.2</td>
</tr>
<tr>
<td>USSR</td>
<td>1.0</td>
<td>286</td>
<td>5.6</td>
<td>311</td>
<td>5.0</td>
<td>354</td>
<td>4.4</td>
</tr>
<tr>
<td>China</td>
<td>1.4</td>
<td>1087</td>
<td>21.2</td>
<td>1212</td>
<td>19.6</td>
<td>1404</td>
<td>17.4</td>
</tr>
<tr>
<td>India</td>
<td>2.0</td>
<td>817</td>
<td>15.9</td>
<td>1013</td>
<td>16.4</td>
<td>1309</td>
<td>16.3</td>
</tr>
<tr>
<td>Developing countries</td>
<td>2.1</td>
<td>3931</td>
<td>76.7</td>
<td>4811</td>
<td>79.5</td>
<td>6716</td>
<td>83.4</td>
</tr>
<tr>
<td>Developed countries</td>
<td>0.6</td>
<td>1198</td>
<td>23.4</td>
<td>1266</td>
<td>20.5</td>
<td>1335</td>
<td>16.6</td>
</tr>
<tr>
<td>World</td>
<td>1.7</td>
<td>5128</td>
<td>100.0</td>
<td>6178</td>
<td>100.0</td>
<td>8053</td>
<td>100.0</td>
</tr>
</tbody>
</table>
Table 4. Expected population growth for subregions of Asia between 1988 and 2020 (PRB 1988).

<table>
<thead>
<tr>
<th>Region</th>
<th>Annual growth rate (%)</th>
<th>1988 Population (10^6)</th>
<th>% of total</th>
<th>2000 Population (10^6)</th>
<th>% of total</th>
<th>2020 Population (10^6)</th>
<th>% of total</th>
</tr>
</thead>
<tbody>
<tr>
<td>West Asia</td>
<td>2.8</td>
<td>124</td>
<td>4.1</td>
<td>169</td>
<td>4.7</td>
<td>257</td>
<td>5.5</td>
</tr>
<tr>
<td>South Asia</td>
<td>2.2</td>
<td>1137</td>
<td>38.0</td>
<td>1448</td>
<td>40.1</td>
<td>1987</td>
<td>42.9</td>
</tr>
<tr>
<td>Southeast Asia</td>
<td>2.1</td>
<td>433</td>
<td>14.4</td>
<td>542</td>
<td>15.0</td>
<td>720</td>
<td>15.6</td>
</tr>
<tr>
<td>East Asia</td>
<td>1.3</td>
<td>1302</td>
<td>43.5</td>
<td>1451</td>
<td>40.2</td>
<td>1665</td>
<td>36.0</td>
</tr>
<tr>
<td>Total</td>
<td>1.8</td>
<td>2995</td>
<td>100.0</td>
<td>3611</td>
<td>100.0</td>
<td>4629</td>
<td>100.0</td>
</tr>
</tbody>
</table>

The changes occurring in East Asia are not yet apparent in South Asia (India, Iran, Afghanistan, Pakistan, Nepal, Bhutan, Bangladesh, Sri Lanka, and Burma). Not only does population growth in South Asia remain high (2.9-3.2%/yr in some countries; it will account for 50% of all growth in Asia), the percentage of total population in rural areas will also remain high while personal incomes will remain low. As a result, South Asia is likely to account for 43% of the total population and 90% of the estimated 700 million of the rural poor and undernourished by 2020 (Mellor 1988). In contrast, East Asia will account for only 36% of the region’s population and very few (less than 10 million) of the rural poor or undernourished. These trends will almost certainly influence the food policies that individual countries follow and the type and quantity of inputs used, including fertilizer produced and applied.

The remaining subregions of Southeast Asia (Thailand, Laos, Vietnam, Cambodia, Philippines, Malaysia, Singapore, and Indonesia) and West Asia (Turkey, Cyprus, Israel, Syria, Saudi Arabia, Iraq, Kuwait, Qatar, Arab Emirates, and both Yemens) account for about 19% of Asia’s population. Indonesia is the dominant country in Southeast Asia, and Turkey and Iraq are the most populous countries in West Asia. The population pressures for both subregions will be high. The greatest will be on Java, Indonesia, where 70% of that country’s population is concentrated, giving an overall density in excess of 900 people/km².

**Removal of land and water constraints**

Agricultural production has stagnated in a number of key Asian countries since 1984-85 (FAO 1988a,b). For example, cereal production in China peaked at 410 million t in 1984 and, despite major shifts in government policy, continued to hover near the 395 million t level since. Similar trends have developed in India, where annual cereal production has leveled near the 160 million t level, and in Bangladesh, where rice production has remained near the 16 million t level since 1984. Even in Indonesia, where agricultural growth has been upbeat since the early 1970s, there seem to be signs of stagnation in overall agricultural production. This stagnation may be temporary and due to the combined effects of poor weather and national markets readjusting themselves to overcome the impact of low prices caused by
temporary surpluses of basic food grains; however, the present trend may also be a glimpse of a more fundamental set of problems related to the growing scarcity of water and availability of good arable land.

New land development. Nearly all of the land in Asia suitable for agricultural production is already under cultivation (Dudal 1988). The acid, infertile, tropical soils (Oxisols and Ultisols) of East and Southeast Asia represent the largest single remaining block of untapped potentially arable land in Asia. This area, currently estimated at 333 million ha, is located primarily in Indonesia, Malaysia, Thailand, and tropical China (Table 5). Prior to the 1950s, most of these soils were under rain forest. Very little use could be made of them because it was difficult to clear them and, once cleared, it was nearly impossible to achieve economic cropping because of their low base saturation. The situation began to change in the 1960s as a result of a) rapidly rising demand for exotic tropical timber; b) development and introduction of more efficient methods of logging; c) need for foreign exchange; d) progress in breeding, selection, and agronomy of industrial as well as food crops that can thrive on these soils; e) sheer population pressures; and f) the anonymous nature of the tropical forests, rendering land ownership, hence individual responsibility for conservation, unknown.

Upwards of 2 million ha is cleared annually in Southeast Asia and tropical China, much with mixed success. For example, Von Uexkull (1988) estimates that in Indonesia alone about 700,000 ha of forest grown on acid, P-deficient soils has recently been cleared annually as part of the Government’s Transmigration Program to move people off the densely populated areas of Java. Of this land, about one-third ends up under tree crops (oil palm and rubber) and is usually highly productive; one-third ends up growing food crops, where sustainability is still uncertain; and one-third ends up as man-made savanna, of no value in food production. A similar fate seems to be the case for the cleared Oxisols and Ultisols of Thailand and Malaysia.

There is a growing debate as to the wisdom of clearing these and other new lands in Asia. Several researchers argue that the cost of developing these lands is too high, and these monies could be better spent improving the productivity of the more fertile high base soils already under cultivation (Arndt 1983, Hughes 1988, Mellor 1988).

Table 5. Estimates of the extent of acid tropical soils (Oxisols and Ultisols) in selected regions and countries (IBSRAM 1985).

<table>
<thead>
<tr>
<th>Region or country</th>
<th>Total land area of acid tropical soils</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Area (10^6) ha</td>
</tr>
<tr>
<td>Tropical America</td>
<td>852</td>
</tr>
<tr>
<td>Tropical Africa</td>
<td>490</td>
</tr>
<tr>
<td>Tropical Asia</td>
<td>333</td>
</tr>
<tr>
<td>Southeast Asia</td>
<td></td>
</tr>
<tr>
<td>Indonesia</td>
<td>82</td>
</tr>
<tr>
<td>Thailand</td>
<td>42</td>
</tr>
<tr>
<td>Malaysia</td>
<td>24</td>
</tr>
<tr>
<td>China (tropical)</td>
<td>16</td>
</tr>
</tbody>
</table>
They argue that modern technology has surpassed our ability to understand its impact on the environment and is already causing large-scale damage to the ecology and the environment. Other researchers concede the high-cost issue but conclude that sheer population pressures in Asia will force a continued movement of people to these marginal areas. Therefore, ways must be found to improve the productivity of these soils. Recent work by the World Resources Institute (Milliman and Meade 1983) dramatizes the urgency of addressing this issue. They have shown these and other types of mismanagement of soils have caused major levels of soil erosion and loss of soil productivity. This is particularly evident in South, Southeast, and tropical East Asia, where deposition of sediments to the sea is estimated to be nearly 8 billion t/yr (Fig. 5). This represents a huge loss in soil fertility, a loss that must be arrested and soon restored if Asia is to develop a regenerative agriculture. Increased use of P fertilizer will play a major role in this process.

*Curb reduction in good agricultural land.* Over the next decade, reduction in land area dedicated to food production will pose a major threat to the food security of an increasing number of countries in Asia. This threat will be the result of actions by governments of countries within the region as well as a few countries outside Asia. Within Asia, the sheer growth in overall numbers of people coupled with the rapid urbanization and industrialization of a number of countries will result in a

5. Annual discharge of suspended sediment from various drainage basins of the world (after Milliman and Meade 1983). Width of arrows corresponds to relative rate; of discharge of sediments. Numbers refer to average annual input of sediment in million t.
significant removal of land dedicated to food production. The impact of one or both of these factors will be most notable in the agricultural areas of Java, Indonesia; East and Southeast Asia; Japan; the Koreas; Dhaka District in Bangladesh; and similar areas in India.

Land use policies of governments outside of Asia will also affect the food security of the region. As an example, the recent actions by the United States Government are likely to be felt by the early 1990s and most noticeably by a number of countries in Asia. Historically, the US. has been a major supplier of agricultural produce moving in international trade (60% of world total in 1988). In addition, it has been willing to hold a major share of the food reserves and serve as a supplier of last resort to meet unexpected shortfalls in food supplies that occur elsewhere in the world, particularly in Asia and more recently in sub-Saharan Africa.

Recent policy shifts suggest that the U.S. is no longer willing to hold major uncommitted food reserves for the other countries of the world. This is because economic considerations and pressures from environmentalists are forcing the U.S. to withdraw major areas of land from agricultural production. This shift in policy began in earnest in 1985 when the U.S. Government put into effect the Conservation Reserve Program, designed to withdraw up to 20 million ha of land from agricultural production by 1990. By December 1988, it had already achieved 70% of this target, with 14 million ha taken out of production for a minimum of 10 yr (Doanes 1988).

This move has serious immediate as well as long-term implications on Asian food security, since the result of actions by a number of governments to reduce food surpluses coupled by the reduction in food production caused by the drought of 1988 has found world food reserves in 1989 at their lowest levels since 1974 (FAO 1988a). Researchers dealing with food security need to give this area immediate attention.

Untapped yield potential of high-yielding varieties. In many cultivated areas of Asia, wheat and rice yields as well as fertilizer use are already high and are nearing the maximum genetic yield potential. The most notable of these areas are Japan; the Koreas; Taiwan, China; East Central China; the Punjab of India; and Java, Indonesia. For these areas, increased food production will have to come primarily from improved cropping systems and added yield potential through genetic improvement. Nevertheless, in vast areas of Asia, rice and wheat yields are nowhere near the genetic potential that exists in currently available cultivars. By way of illustration, rice yields in eastern India are only a fraction of what they are in the Punjab, India, or Central Java, Indonesia (Cooke 1982). The same holds true for Bangladesh; the Outer Islands of Indonesia; much of Thailand, including the Central Plain; and major portions of the Philippines.

A number of research institutions (CGIAR 1988, IFPRI 1988) have identified a range of factors constraining rice and wheat yields in these areas. However, Hughes (1988) and Ahmed (1988) believe it is the uncertainty of water supplies and the lack of sufficient basic infrastructure that appear to be major causes of low yields. These factors in turn have a major impact on fertilizer use (Desai and Stone 1987, Stangel 1979). Policymakers have two options available to them: develop cultivars that have
a high degree of drought tolerance and minimal needs for inputs (including fertilizer), or make the investment in new irrigation and/or fertilizer facilities.

**Expansion and increased efficiency of irrigation.** The importance of irrigation and increased fertilizer use to increase productivity of Asian agriculture is well established. One-half of the food and fiber produced in the region comes from the 140 million ha of irrigated land—some 65% of the world’s total rainfall-independent land. In addition, fully 80% of all fertilizer used in 1985 was applied to irrigated crops (FAO 1988b). Relatively little fertilizer was applied to rainfed agriculture. Therefore, expansion of irrigated lands is central to future strategies to increase crop productivity in most Asian countries. This increase will come from a rise in cropping intensity as well as from higher yields. As important as irrigation is to future sustained growth of Asian agriculture, there are some major impediments to its future expansion: a) scarcity of good agricultural land that could be brought under irrigation; b) shortages of water and power; c) technical difficulties of converting, to upland crops, irrigated land currently dedicated to the production of lowland rice; and d) limitations of capital to finance irrigation projects. By way of illustration, the Asian Development Bank estimates the investment requirement in irrigation systems alone in Asia to be on the order of US$100 billion during the next 12 yr to sustain agricultural growth (ADB 1987). IFDC estimates that an additional US$30 billion will be required in new or refurbished fertilizer facilities during this period to meet additional demands. Nevertheless, demographic pressures and land constraints make it imperative that South Asia sharply increase its irrigated cropland.

Fortunately, much of South Asia has the potential to be one of the best irrigated regions on earth (Kaye 1989). For example, India’s yearly snow and rainfall of 1,150 mm is 10 times greater than what it can use. Unfortunately, three-quarters of this precipitation falls within 3 mo (June to August), making its agricultural economy hinge on the all-important annual monsoons and the nation’s ability to harness these waters.

Modern techniques of water and resource management have not been able to mitigate these vagaries of nature. Bangladesh, which has doubled its irrigated area since 1975, still has only 20% of the country’s arable land under good water control. Nepal has only 5% of its arable land under irrigation. Even India has realized only a fraction of its potential for irrigation. By 1985, it had tapped only 23% of the country’s groundwater potential and only 53% of the 113 million ha of land having irrigation potential.

Progress has been slow in developing this untapped potential in the subcontinent. Large- and medium-scale surface irrigation projects covered 25 million ha as of 1985, less than one-half of the total projected for this type of irrigation by the year 2010; however, the marginal cost of creating an additional hectare of irrigation potential has risen 22-fold since the early 1950s, raising questions about the cost-effectiveness of this approach. Clearly, there is a need for ways to reduce the costs of these systems or to develop alternate approaches that are substantially lower in cost. Use of tubewells, overhead low-volume sprinklers, and drip irrigation all show some promise. More research and development in this area are required. A breakthrough would be applicable to West Asia and East Asia, where water availability is limited.
Increased crop diversification

The cropping mix of Asian agriculture is in a state of transition. Because diets are changing in Asian countries, national planners are already taking steps to diversify the commodity base of their agricultural economies. Having for the most part achieved the production goals set for rice, wheat, and maize, policymakers have charted strategies to increase domestic production of oilseeds, fruits, and vegetables as well as specialty food crops, and they are also moving toward increasing numbers of livestock and poultry. The purpose of this action is not only to offset the already high import bills many countries have for these commodities (i.e., cooking oils, frozen beef, poultry, and pork), but also to meet the anticipated increased demand for an even wider range of foods as personal incomes rise and the demand for a more diversified diet increases (Govil and Rao 1988). The shift in diet in some of the Pacific Rim countries of Asia is already evident, not only in the increased consumption of meat but also in its diversified supplies (Table 6). For example, per capita consumption of pork has doubled in China and the Republic of Korea, while similar increases in poultry and beef consumption have been recorded during the last decade in Japan and China. These shifts have caused a sharp increase in the demand for feed grains. As the meat, vegetable, and dairy industries develop more fully, the fertilizer sector will have to provide a broader range of products and the knowledge necessary to target these to fit specific products and markets. Animal feed P, highly soluble P for use in irrigation systems, and feed-grade urea are but a few examples of new products that will be required. These shifts have major implications for the

<table>
<thead>
<tr>
<th>Country</th>
<th>Commodity (kg of meat/capita)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Pork</td>
</tr>
<tr>
<td>Japan</td>
<td></td>
</tr>
<tr>
<td>1978</td>
<td>12.5</td>
</tr>
<tr>
<td>1987</td>
<td>16.3</td>
</tr>
<tr>
<td>Republic of Korea</td>
<td></td>
</tr>
<tr>
<td>1978</td>
<td>4.8</td>
</tr>
<tr>
<td>1987</td>
<td>8.9</td>
</tr>
<tr>
<td>China, except Taiwan</td>
<td></td>
</tr>
<tr>
<td>1978</td>
<td>7.7</td>
</tr>
<tr>
<td>1987</td>
<td>17.1</td>
</tr>
<tr>
<td>Philippines</td>
<td></td>
</tr>
<tr>
<td>1978</td>
<td>7.0</td>
</tr>
<tr>
<td>1987</td>
<td>8.7</td>
</tr>
<tr>
<td>Taiwan, China</td>
<td></td>
</tr>
<tr>
<td>1978</td>
<td>23.4</td>
</tr>
<tr>
<td>1987</td>
<td>25.4</td>
</tr>
<tr>
<td>Singapore</td>
<td></td>
</tr>
<tr>
<td>1978</td>
<td>28.1</td>
</tr>
<tr>
<td>1987</td>
<td>29.3</td>
</tr>
</tbody>
</table>
research institutions as well as the overall makeup of the fertilizer sector. For example, except in India, most national research institutions have done relatively little to address the constraints to P use on upland crops. Furthermore, the fertilizer sector is poorly equipped to provide the diversity of P products that will be needed by the farmer.

**Asian agriculture in perspective**

As Asia charts its future development, it is important to keep its agriculture in perspective. First, Asian agriculture is unique. Despite the fact that Asia comprises nearly 60% of the world’s population and only 25% of the total arable land for food production, the region nevertheless has kept much better pace with the demands of growing population than has been the case for other continents (Fig. 4).

Compared with Latin America and Africa, Asia (without the Middle East and Soviet Asia) has
- the highest population,
- the smallest total land area,
- the smallest area of potentially arable land (424 million ha vs 894 million and 789 million for Latin America and Africa, respectively),
- the largest percentage of potentially arable land already under cultivation (>90% vs 18 and 19% for Latin America and Africa, respectively),
- the largest area under irrigation (43 million ha out of a total of 57 million ha in all developing countries),
- the highest levels of total fertilizer use and grain output (Tables 1 and 7),
- the highest rate of fertilizer use per hectare of arable land (Table 8), and
- the most “unbalanced” NPK ratio (100:12:8 in Asia vs 100:30:41 in Latin America) (Table 8).

Agriculture in most parts of Asia has several distinct features, the main factor responsible being rice. About 95% of the world’s rice is grown in Asia. Whenever agriculture centers on rice as the main crop, certain features become evident:
- concentration of agriculture primarily in the lowlands;
- high percentage of land under irrigation to thus minimize risk in using large quantities of inputs;
- predominance of smallholdings (0.5-3 ha);
- relatively low incidence of large farm animals, especially ruminants in the farm economy;
- widespread transfer of soil fertility from the uplands into the lowlands (particularly evident in China);
- relatively low fluctuations in year-to-year yields; and
- high population density.

As national planners struggle to reshape Asian agriculture, they must recognize that much of the present stability and overall food security in Asia is derived from its rice base. To change agriculture without causing an impact on this base and overall security of the region will not be easy.
Table 7. Grain output per person in developing countries.

<table>
<thead>
<tr>
<th></th>
<th>Latin America</th>
<th>Africa</th>
<th>Asia (excluding Near East)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Population (million)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1980\textsuperscript{a}</td>
<td>361</td>
<td>388</td>
<td>2314</td>
</tr>
<tr>
<td>1985\textsuperscript{a}</td>
<td>405</td>
<td>450</td>
<td>2523</td>
</tr>
<tr>
<td>1988\textsuperscript{a}</td>
<td>414</td>
<td>465</td>
<td>2563</td>
</tr>
<tr>
<td>Cultivated land (arable land + permanent crops in million ha)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1980\textsuperscript{a}</td>
<td>171.9</td>
<td>150.6</td>
<td>378.9</td>
</tr>
<tr>
<td>1985\textsuperscript{a}</td>
<td>178.3</td>
<td>154.6</td>
<td>383.6</td>
</tr>
<tr>
<td>Persons/ha cultivated land</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1980</td>
<td>2.1</td>
<td>2.6</td>
<td>6.1</td>
</tr>
<tr>
<td>1985</td>
<td>2.3</td>
<td>2.9</td>
<td>6.6</td>
</tr>
<tr>
<td>Grain production (million t)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1980\textsuperscript{b}</td>
<td>88.5</td>
<td>50.7</td>
<td>576.6</td>
</tr>
<tr>
<td>1985\textsuperscript{a}</td>
<td>109.9</td>
<td>58.9</td>
<td>696.3</td>
</tr>
<tr>
<td>1986\textsuperscript{a}</td>
<td>107.2</td>
<td>61.9</td>
<td>710.6</td>
</tr>
<tr>
<td>Grain production (kg/person)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1980</td>
<td>245.1</td>
<td>130.8</td>
<td>249.2</td>
</tr>
<tr>
<td>1985</td>
<td>271.4</td>
<td>131.0</td>
<td>276.0</td>
</tr>
<tr>
<td>1986</td>
<td>259.0</td>
<td>133.2</td>
<td>277.3</td>
</tr>
</tbody>
</table>

\textsuperscript{a}FAO 1987b. \textsuperscript{b}FAO 1986.

Table 8. Fertilizer use in developing countries (FAO 1985,1988b).\textsuperscript{a}

<table>
<thead>
<tr>
<th></th>
<th>Latin America</th>
<th>Africa</th>
<th>Asia (excluding Near East)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nutrient consumption kg nutrients/ha:</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1980</td>
<td>43.7</td>
<td>9.5</td>
<td>69.6</td>
</tr>
<tr>
<td>1985</td>
<td>41.4</td>
<td>11.8</td>
<td>86.4</td>
</tr>
<tr>
<td>Difference N:P:K ratio (1985-86)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>-2.3</td>
<td>+2.3</td>
<td>+15.3</td>
</tr>
</tbody>
</table>

\textsuperscript{a}Nutrients = N + P\textsubscript{2}O\textsubscript{5} + K\textsubscript{2}O.

Patterns of fertilizer use

Fertilizer use in Asia has followed a pattern distinctly different from that of the rest of the world. For example, before the mid-1950s agriculture in Europe and North America was largely centered on cattle. Soil fertility and soil productivity were largely maintained by the inclusion of leguminous forage crops in the rotation. Phosphorus and K were used to stimulate biological N\textsubscript{2} fixation by legumes and, thus, the growth of both the forage crops as well as the food crops that followed.
In rice-growing Asia, leguminous forage crops have been of only marginal importance and have been grown only in some regions (e.g., milk vetch in parts of China and Japan). There just has not been enough land available to make use of the effect of fertilizer P on biological N\textsubscript{2} fixation. Because of the scarcity of good agricultural land, the farmer has been preoccupied with producing maximum quantities of rice per unit area. Furthermore, national policies have been geared to push the farmer to grow maximum quantities of rice.

Fertilizer requirements for rice are different from those for most other crops. Flooding increases the availability of both P and K, making N the only universally needed nutrient. As stated, Asia’s success in increasing grain output over the past 25 yr has been based largely on the combination of modern rice varieties, irrigation, and N fertilizers that have been the cornerstone of the Green Revolution. Substantially lower quantities of P and very limited amounts of K were used to achieve these yields. But Asia’s share in world N consumption increased from 17% in 1964 to 40% in 1988.

Wherever irrigation was available, great yield responses could be obtained at very little risk by the application of N. Because of the large and highly predictable response, this technology was quickly accepted by rice farmers throughout Asia where good water control was available.

Nitrogen does not contribute to a buildup of soil fertility; therefore, most of the recent gains in food output in Asia have been obtained at low immediate cost but at the long-term expense of native soil fertility.

Because most rice farmers are already using N close to or even above the economic optimum on irrigated lands with good water control, there is very little room for a further increase in rice output through further increase in N use only.

**Strategies for the future**

As national planners struggle to reshape agriculture to meet new demands, they must not lose sight of the fact that much of the present stability and food security is derived from rice production. To change Asian agriculture without impacting this base will not be easy. In terms of increased food output, over the past 25 yr Asia has done better than the rest of the world. But there is concern about the very narrow base of those gains. Most are due just to the genetic improvement of two crops (rice in tropical and subtropical Asia, wheat in subtropical Asia) and to one plant nutrient—N.

**Broaden the food base.** While in the short term the focus on rice and wheat primarily with N fertilizer has yielded excellent results, such a strategy is inadequate for long-term stability in basic soil fertility. Furthermore, as the demand for cooking oils, plant proteins, vegetables, feed grains, and fruits increase, more attention will have to be dedicated to nutrition of the upland crops even if these are grown in rice-based systems. This shift will automatically require higher doses of P and other fertilizers compared with levels used of these fertilizers where rice was of primary concern.

There is also a worldwide concern that we are not making full use of other plants in a global resource pool of at least 20,000 species that have been identified as edible.
At present, 85% of all food consumed by humans comes from just 14 plants: wheat, rice, maize, sorghum, millet, barley, cassava, pulses, soybean, sugarcane, banana, pea, potato, and table bean (Freudenberger 1988).

In most of Asia, the food basis is much narrower, and for rice, the major cereal, most of the yield potential on irrigated lands has already been realized.

To maintain and improve adequate food security in the future, the food base must be broadened. More emphasis will have to be placed on a cropping system involving a wider spectrum of plant species and on better balanced fertility regimes than has been the case to this time.

*Increase the role of fertilizer phosphate.* Before the 1950s, P was the dominant fertilizer used worldwide. It lost this position in the 1960s through the combined effect of the introduction of a new ammonia technology that provided an abundance of cheap N, the release of stiff-strawed, N-responsive wheat and rice varieties, and the heavy focus on increasing food production in Asia.

It is expected that, in the future, food security can be sustained only if P regains some of the prominence it once had in agriculture. The current food system in Asia is heavily dependent on N fertilizer produced with energy from nonrenewable resources. Furthermore, N stimulates crop yields and thereby increases the demand for other nutrients. To ensure future, long-term food security, cropping systems must be considered not only in terms of short-term yields, but also in terms of sustaining and improving yields through proper management.

*From soil-mining agriculture to soil-building agriculture.* Soil is the basis for life on earth. Although it is a finite resource, man has often made very wasteful use of it. “Since permanent settlement of human species into villages, towns, city states, cities and now megalopolis, 50% of the original soil deposits of the earth have been eroded . . .” (Freudenberger 1988).

This book deals with phosphorus requirements for sustainable agriculture. With the increasing population and its food requirements growing while the area under arable crops has only limited and in some countries shrinking room to grow, “sustainable” agriculture is not enough. The word “sustainable,” when used in reference to agricultural futures, is often interpreted to mean that, given necessary resources, even a poor system can be sustained for a long time. To move beyond this ambiguity, Freudenberger (1988) suggested that the term “regenerative” replace “sustainable.” The idea of “regenerativeness” goes beyond conceptualizations of conservation, for this latter word usually conjures just the idea of being careful about using a resource to extend its time horizon as much as possible. In contrast, regeneration, particularly in terms of agriculture, refers not only to replacement of the essential resource but, hopefully, to its enhancement.

Over large parts of Europe and parts of North America and East Asia, a “regenerative” type of agriculture has been practiced for a long time. As a result, soils in those parts of the world are today far more productive than they were in their native state and are probably the most productive to date. In most cases, the buildup of soil P has been the decisive factor—a point that has become a major factor in affecting P use in free markets.

It is clear that to move from “soil-mining” agriculture to “soil-building”
agriculture or, to use Freudenberger’s term, to move to “regenerative” agriculture, inputs will be needed that are far beyond the financial means of the average Asian farmer who is living close to subsistence.

But what choices or alternatives are open? In the long run, it may be considerably more economical for individual nations as well as for humankind to establish policies and put into effect programs that limit agriculture as much as possible to the existing (cleared) land, and build soil productivity in these areas rather than continue to carve out a temporary living on marginal soils, whether these be savannas, or steep lands now covered by forests.

On a global basis, N is at present the most widely used fertilizer; however, in situations where biological N\textsubscript{2} fixation must supply most of the N, P is frequently the most limiting nutrient because unimpeded biological N\textsubscript{2} fixation is associated with adequate P nutrition (Fox 1988).

The potential for increased food production in Asia’s irrigated ricefields has largely been used up. The large untapped potential is now in the uplands, where lack of P is the greatest constraint.

Resources will have to be mobilized, both in terms of research and in terms of P inputs, to develop for the uplands cropping systems that go beyond sustainable agriculture and lead eventually to “regenerative agriculture,” thereby relieving pressure on what remains of the rain forest. Scientists, national planners, and the fertilizer sector must refocus their strategies, away from a single crop and single fertilizer nutrient orientation. Greater emphasis must be placed on overall agricultural development—an agriculture that provides a broad base of quality products demanded by the consumer and that is sufficiently regenerative to not only sustain but enhance the basic productivity of the soil resource.

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Notes

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Citation information: International Rice Research Institute (1990) Phosphorus requirements for sustainable agriculture in Asia and Oceania. P.O. Box 933, Manila, Philippines.
Fertilizer policies for agricultural development

L.M. Maene

The economic activity of most developing countries will continue to be dominated for a long time by agricultural production and by trade in agricultural commodities. Food production in these countries has to keep pace with high population and urban area growth rates. To achieve the target growth rate in agricultural production, fertilizer use together with the use of related inputs will have to increase substantially. Developing countries need a consistent and comprehensive fertilizer policy aimed at the efficient use of plant nutrients. This policy should cover aspects of fertilizer production and importation, pricing, marketing, credit, research, and extension. Of major importance is balanced nutrient application, which requires the availability of appropriate fertilizer grades in adequate quantities at the farm level. Developing countries must take that into consideration in deciding their sources of supply. Furthermore, major investment is needed in infrastructure, which in many cases has lagged behind tremendously. Since fertilizers must be made available at affordable prices at the right time and place, adequate price incentives and proper inventory levels are essential. Finally, extension services are an essential element of crop management strategies and deserve proper attention.

Agricultural production and the export trade in agricultural commodities are of vital importance to most developing countries, constituting an essential part of their total economic activity (Lecaillon et al. 1987). In 1985, the share of agriculture in total gross domestic product (GDP) was 20% in the developing world against 3% in industrial countries. This share was even higher than 25% in China, India, Nigeria, and Pakistan. In 1983-85, the share of agricultural exports in total exports was 14% in the developing world, 11% in industrial countries, and more than 25% in a large number of countries in sub-Saharan Africa and Latin America, as well as in certain Asian nations including India, Malaysia, Pakistan, the Philippines, and Thailand. Low-income developing countries are even more dependent on agricultural commodity production and trade. In those countries, excluding China and India, agriculture represented 45% of GDP in 1983-85 and provided employment for about 50% of the active labor force. For most developing Countries, self-sufficiency in the major cereal crops and an increase in the supply of noncereal foods and feed grains are important goals of domestic agriculture.

The poorest countries within the developing world are ill-equipped to face development constraints, and they are especially vulnerable to problems of food insecurity. The world food situation in the mid-1980s reflected a mixture of significant
achievements and continuing problems, many of them exacerbated by slow growth, if not stagnation, in economic activity and world trade during the first half of the decade. In the developing countries, the achievement of food self-sufficiency has been very uneven. In Africa, the declining per capita production of food and a series of poor harvests culminating in widespread famine have been of particular concern (Table 1). For the food-deficient, low-income countries, the failure to achieve food self-sufficiency has been generally attributed to shortcomings in national policies. These include relative prices, and inadequate or inappropriate research, extension, marketing and credit services, as well as inadequate provision of improved seeds, fertilizers, and other inputs.

The world food situation is rather volatile. In early 1988, it seemed that the situation was highly favorable, with very large supplies and low prices, and the outlook for 1987-88 was that this position would remain unchanged (OECD 1988). Since then, the situation has changed considerably, and the current food outlook is rather gloomy. According to the Food and Agriculture Organization’s (FAO) Global Information and Early Warning System on Food and Agriculture (FAO 1988), world cereal production in 1988 was forecast to be 4% lower than 1987’s below-normal harvest. For the first time in more than 4 decades, it declined for 2 yr in succession (Fig. 1, Table 2). Cereal stocks at the end of 1988-89 are projected to fall below the minimum level FAO considers necessary to safeguard global food security. This decline is due mostly to the reduced output of wheat and coarse grains in North America, which more than offset the expectation of an increased rice harvest in Asia and larger crops in West Europe.

With the safety margin provided by substantial global stocks now eroded, a large increase in cereal production is needed in 1989. To maintain global cereal consumption and to replenish stocks to the minimum level for world food security, cereal production in 1989 needs to increase by 13%—some 225 million t. However, for such a large increase to materialize, a significant increase in the area planted and normal weather conditions in the main producing countries are necessary. Prices of wheat and maize on international markets have increased sharply. With the cereal

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<td>0.36</td>
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<td>-1.10</td>
<td>-1.46</td>
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<td>2.59</td>
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<td>-0.46</td>
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<td>5.02</td>
<td>0.60</td>
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<td>2.31</td>
<td>2.50</td>
<td>0.60</td>
<td>0.39</td>
<td>0.86</td>
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Table 1. Annual changes in food production (FAO 1987b).
import needs of developing countries rising, these higher prices, together with the prospect of reduced food aid supplies, point to increased difficulties for a number of low-income food deficit countries.

The role of fertilizers in increasing food production

Many developing market economy countries have been successful in expanding food production from the uncertain base of the early 1960s. This progress has depended upon an interrelated package of policies and improved technologies, which has provided greater incentives to farmers through

• timely availability of improved inputs, such as seed, fertilizers, plant protection products, and irrigation;
• improved market access and terms;
• increased and better credit facilities; and
• improved extension services, supported by adequate research systems.

Without the enormous progress in plant nutrient consumption, the gains in food production would not have been possible. Fertilizers enabled both the potential of modern seed varieties to be tapped and substantial progress to be made with established cropping systems.

The future development of agriculture faces serious but surmountable challenges. This is true both for the developed countries, which have to slow down...
Table 2. World cereal situation (after FAO 1988).

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<td>World production&lt;sup&gt;a&lt;/sup&gt; (million t)</td>
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<td></td>
<td></td>
<td></td>
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<td></td>
</tr>
<tr>
<td>Rice (rough)</td>
<td>399</td>
<td>411</td>
<td>423</td>
<td>452</td>
<td>470</td>
<td>472</td>
<td>462</td>
<td>478</td>
<td></td>
</tr>
<tr>
<td>Wheat</td>
<td>446</td>
<td>454</td>
<td>483</td>
<td>494</td>
<td>518</td>
<td>506</td>
<td>538</td>
<td>511</td>
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<tr>
<td>Coarse grains</td>
<td>721</td>
<td>786</td>
<td>805</td>
<td>698</td>
<td>818</td>
<td>864</td>
<td>853</td>
<td>821</td>
<td>745</td>
</tr>
<tr>
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<td>1651</td>
<td>1711</td>
<td>1644</td>
<td>1806</td>
<td>1842</td>
<td>1863</td>
<td>1799</td>
<td>1734</td>
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<td>833</td>
<td>894</td>
<td>922</td>
<td>925</td>
<td>943</td>
<td>931</td>
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<td>838</td>
<td>878</td>
<td>750</td>
<td>884</td>
<td>917</td>
<td>920</td>
<td>868</td>
<td>772</td>
</tr>
<tr>
<td>World imports&lt;sup&gt;b&lt;/sup&gt; (million t)</td>
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<tr>
<td>Rice (milled)</td>
<td>13</td>
<td>11</td>
<td>11</td>
<td>12</td>
<td>12</td>
<td>12</td>
<td>12</td>
<td>12</td>
<td>12</td>
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<tr>
<td>Wheat</td>
<td>91</td>
<td>99</td>
<td>97</td>
<td>101</td>
<td>104</td>
<td>84</td>
<td>90</td>
<td>103</td>
<td>98</td>
</tr>
<tr>
<td>Coarse grains</td>
<td>102</td>
<td>102</td>
<td>88</td>
<td>90</td>
<td>103</td>
<td>85</td>
<td>87</td>
<td>83</td>
<td>89</td>
</tr>
<tr>
<td>World stocks&lt;sup&gt;c&lt;/sup&gt; (million t)</td>
<td></td>
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<td></td>
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<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Rice (milled)</td>
<td>43</td>
<td>43</td>
<td>43</td>
<td>49</td>
<td>54</td>
<td>55</td>
<td>51</td>
<td>40</td>
<td>36</td>
</tr>
<tr>
<td>Wheat</td>
<td>98</td>
<td>107</td>
<td>120</td>
<td>134</td>
<td>152</td>
<td>160</td>
<td>168</td>
<td>145</td>
<td>117</td>
</tr>
<tr>
<td>Coarse grains</td>
<td>96</td>
<td>135</td>
<td>174</td>
<td>99</td>
<td>128</td>
<td>204</td>
<td>229</td>
<td>211</td>
<td>122</td>
</tr>
<tr>
<td>Stocks as % of world cereal consumption&lt;sup&gt;d&lt;/sup&gt;</td>
<td>16</td>
<td>19</td>
<td>22</td>
<td>18</td>
<td>21</td>
<td>25</td>
<td>26</td>
<td>23</td>
<td>16</td>
</tr>
</tbody>
</table>

<sup>a</sup>Data refer to the calendar year of the first year shown, i.e., the last column of production figures relates to the 1988 harvest. <sup>b</sup>July/June except for rice, for which the data refer to the calendar year of the second year shown. <sup>c</sup>Stock data are based on an aggregate of national carryover levels at the end of national crop years. <sup>d</sup>FAO estimates that a carryover stock of 17-18% of consumption is required for world food security.
production growth without undermining the economic and social welfare of their rural communities, and for the developing countries, many of which will have to accelerate production substantially. In the developing countries, this requires foremost a conducive policy environment. It also necessitates substantial investment in infrastructure and manpower development. In addition, technologies and inputs should be used in the context of a strategy of conservation-based resource development.

According to the FAO (1987a), the overall sources of crop production growth in the developing countries over the next 12 yr will be very similar to those of the past. Nearly two-thirds should come from increases in average yields growing at an annual rate of 1.6%. More than one-fifth should result from increases in arable land, projected to grow at 0.6%/yr. The balance should be due to increases in cropping intensity (Fig. 2), which is projected to go from an average level of 78% in 1982-84 to 84% in 2000. Countries and regions differ substantially in the relative importance of these factors in their production growth. For example, the Near East, North Africa, and many countries in other regions, particularly in Asia, have reached the limits of land expansion, barring major investments or new technologies for marginal rainfall areas and soils (ESCAP 1985).

Fertilizers are essential for agricultural production in most developing countries. Estimates of the contribution of mineral fertilizers to crop production, given the necessary associated inputs, vary widely, but a relationship of around 10 t of grain for 1 t of plant nutrient is supported by experience. Since 1967, the share of the developing countries in global fertilizer use has more than doubled, from less than 10% to more than 20%, with very high growth rates in Asia. In some countries, however, particularly in Africa, growth has been insufficient to compensate for the nutrients removed by crops. The growth rate of fertilizer nutrient consumption in the developing countries is projected to be 4.7%/yr during 1982-84 to 2000 (Table 3). This declining growth rate reflects above all the higher levels already achieved, but also unfavorable overall economic conditions limiting the possibilities to import and to provide subsidies. However, the projected quantity of fertilizers used will more than double between 1982-84 and 2000 (Table 4). A small number of countries will
Table 3. Annual growth rate of fertilizer consumption (FAO 1987a).

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<td>7.1</td>
<td>5.7</td>
<td>4.7</td>
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<tr>
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<td>11.9</td>
<td>5.8</td>
<td>3.1</td>
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<tr>
<td>Near East</td>
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<td>7.8</td>
<td>6.8</td>
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<td>Asia</td>
<td>12.7</td>
<td>9.3</td>
<td>8.4</td>
<td>4.3</td>
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<tr>
<td>Latin America</td>
<td>12.1</td>
<td>3.2</td>
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<table>
<thead>
<tr>
<th>Region</th>
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<tbody>
<tr>
<td></td>
<td>million t</td>
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<tr>
<td></td>
<td>1982-84</td>
</tr>
<tr>
<td>Developing countries</td>
<td>25.8</td>
</tr>
<tr>
<td>Africa</td>
<td>1.0</td>
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<td>Near East</td>
<td>4.6</td>
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<tr>
<td>Asia</td>
<td>13.8</td>
</tr>
<tr>
<td>Latin America</td>
<td>6.5</td>
</tr>
</tbody>
</table>

continue to dominate fertilizer use in each developing region: Egypt in North Africa, Nigeria and Zimbabwe in sub-Saharan Africa, Turkey and Iran in the Near East, Mexico and Brazil in Latin America, and India and China in Asia.

The intensity of fertilizer use presents a different picture, with the Near East and North Africa currently having the highest average fertilizer application rates, followed by Latin America and Asia (Table 4). However, variations are large between countries within the same region, between sections of the same country, and between crops. Sub-Saharan Africa uses very low amounts of plant nutrients per hectare; this is partly a reflection of the small proportion of arable land that actually receives fertilizer. Average application rates in sub-Saharan Africa are projected to more than double by the year 2000.

Policies for expanding fertilizer use in developing countries

A rapid increase in basic food production almost always requires rapid growth in fertilizer use. To achieve food production goals and stimulate fertilizer use, a number of policy options that are available can be broadly categorized in three groups: price policies, marketing policies inclusive of credit aspects, and research and extension policies.

A major issue faced by developing countries is whether to produce locally or to import fertilizer. The importance of international trade in raw materials and finished fertilizer products is illustrated in Table 5. Important considerations in the trade in
Table 5. World fertilizer exports as percentage of world consumption (after FAO 1987b,c; International Fertilizer Industry Association, unpubl. data).

<table>
<thead>
<tr>
<th>Year</th>
<th>Nitrogen</th>
<th>Phosphorus</th>
<th>Potassium</th>
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<tr>
<td>1960-61</td>
<td>26</td>
<td>5.3</td>
<td>35.7</td>
</tr>
<tr>
<td>1965-66</td>
<td>21</td>
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<td>21</td>
<td>6.2</td>
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<td>1975-76</td>
<td>16</td>
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<td>1980-81</td>
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<tr>
<td>1986-87</td>
<td>24</td>
<td>11.9</td>
<td>55.6</td>
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<tr>
<td>1987-88</td>
<td>24</td>
<td>11.4</td>
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</table>

Fertilizers include differences in the availability and opportunity cost of raw materials, especially natural gas; the scope for expansion in major low-cost sources of phosphate rock and potash; the economies of scale in production by several units, supported by low-cost ocean bulk transport; and the lower capital cost of financing expensive projects in certain exporting countries compared with costs in the more heavily populated developing countries.

To maintain favorable prices for agricultural output and accelerate employment growth rates, a thinner spread of the capital resources of developing countries is necessary. In the recent past, industrialization projects have tended to concentrate capital sharply in large-scale industries. However, an accelerated growth rate of small- and medium-scale projects located in rural areas and major market towns may be preferable. During this stage of development, the economics of large fertilizer plants is not very attractive. Indeed, the return on investment in large fertilizer plants in developing countries has, in general, tended to be low because poor infrastructure has caused high capital and operating costs.

Fertilizer security through domestic production, developed because of occasional failures (albeit short-lived) of world markets to guarantee reasonably priced supplies, has also been a major consideration in some cases. In many of the poorer developing countries, complete dependence on imports has meant slower growth in fertilizer use than in a system complemented by some domestic production capacity, however inefficient. Rapid growth in fertilizer use is essential to agricultural growth and intensification which, in turn, are critical to overall economic development. Therefore, developing countries have to decide whether domestic production will best stimulate fertilizer use growth, or whether fertilizer import growth is possible with a rate of increase and security comparable to that of developing domestic production. One option may be to rely more on imported intermediates such as ammonia and phosphoric acid instead of producing them domestically.

If developing countries decide not to produce the major part of their fertilizer requirements locally, they must secure their supplies in a market in which prices are unstable and availability is sometimes uncertain. Moreover, they will require foreign exchange. Financing organizations, however, tend to favor providing foreign exchange for capital investment in plants, rather than for current expenditures for
imports. The question is whether developing countries should give priority to fertilizer imports or to domestic production. This is important not only at very low levels of aggregate fertilizer use, but also at relatively high levels, when balanced fertilization becomes essential for maintaining profitable growth in fertilizer use. Therefore, imports should be considered as complementary to, rather than competitive with, existing domestic production.

**Pricing**

An important issue facing developing countries is input pricing. Public revenue is a very scarce commodity in developing countries and should be allocated very carefully. Pricing policies have tended to increase fertilizer use on farms already using substantial quantities. Sometimes a greater response may be obtained in areas where present use is lower. Fertilizer use should therefore be expanded also in areas and on crops where the returns could be high on account of currently low use levels. Choosing between produce price incentives and input subsidies to stimulate the growth of agricultural production has been a long-standing issue. Most of the developing countries have made use of input subsidies. In a sample of 38 developing market economy countries, FAO reported that 68% used fertilizer subsidies (Couston 1988). Price information on N fertilizer for 25 countries showed that most developing countries prevented the 1974–75 explosion of international prices from being reflected in the domestic prices and prevented a deterioration in the cereals-fertilizer price ratio.

A review of fertilizer subsidies in developing market economy countries for 1980-86 revealed that the region with the largest number of countries without fertilizer subsidies was Latin America (Couston 1988). The Asian region had the largest number of countries with subsidies. Average growth rates of fertilizer consumption in those countries were twice as high as in those without subsidies. In the other regions, on the average, the countries with subsidies had positive growth rates, whereas fertilizer consumption declined in countries without subsidies. However, the difference in the average fertilizer consumption growth rates should not be attributed entirely to crop-fertilizer price relationships. Adequacy of supply, timely distribution of fertilizers, and the efficiency of the crop marketing system also influence the use of fertilizers.

The main argument against subsidies is that their use encourages wasteful and misdirected use of resources, since the prices no longer reflect real costs. Input subsidies, therefore, are generally considered less efficient than higher produce prices as a means of increasing output. However, fertilizer subsidies are more effective than produce price increases in raising the real incomes of small farmers with limited marketable surplus (Couston and Narayan 1987). Input subsidies have been widely used to maintain reasonable domestic price stability during periods of large increases in the prices of imported inputs. They have also been used to correct distortions in relative prices by providing incentive price-cost ratios.

It is generally accepted that once subsidies have achieved their objective, they should be phased out. The phaseout should be accompanied by public expenditure on infrastructure and research to improve the cost effectiveness of input distribution,
crop marketing systems, and agricultural productivity. A number of developed countries once used input subsidies, and some, such as Canada, Norway, Spain, Portugal, Greece, Australia, and New Zealand, still subsidized fertilizers in the 1980s. Norway phased out subsidies in 1984 and New Zealand in 1986.

While the difficulty in reconciling fiscal objectives and incentives for using fertilizers is widely recognized, it remains doubtful whether the full economic impact of reducing such incentives is appreciated or whether alternative policies are being adequately explored. Most of the work on crop supply elasticities in developing market economy countries shows good response to price changes. Price elasticities are high, particularly for commercial crops and irrigated crops. However, there is likely to be a greater price impact on crop mix than on aggregate agricultural production because when one crop price increases, farmers tend to switch to that crop. No doubt, price policy is important for agriculture in developing market economy countries, but there are constraints to a supply response other than price factors.

In general, the following price and nonprice factors should be taken into consideration in stimulating agricultural production (FAO 1987b):

- the effect of relative price changes of fertilizers and crops on the profitability of fertilizer use;
- the effect of fluctuations in farmers’ income on their ability to finance fertilizer purchases, on their confidence, and on their ability to obtain credit terms;
- the amount, cost, and availability of credit;
- increased fertilizer profitability resulting from improved technical opportunities, such as infrastructural support, irrigation, and improved varieties of seed and means of pest control;
- measures to reduce the risk of crop failure and of disappointing revenues from crops;
- the extent to which land tenure systems assure tenant farmers of an adequate return for their efforts, expense, and risk; and
- the development of farmers’ skills to manage more intensive production through increased fertilizer use.

A national fertilizer policy aimed at reconciling incentives for the increased use of plant nutrients with general economic and fiscal objectives must be based on these considerations. In the long and medium term, nonprice incentives are very important, as shown by the spread of high-yielding, fertilizer-responsive cereal varieties in the late 1960s and early 1970s (Desai 1986). Better cultivars, irrigation facilities, and improved soil, water, and crop management are important means of achieving efficient and increased fertilizer use.

**Marketing and distribution**

The establishment of effective marketing systems to ensure the promotion of efficient fertilizer use and to meet national goals of food self-sufficiency and export growth raises policy questions relating to the nature of the system used, import procurement, prices and margins, transport and storage, finance and credit, training, market development, and government support services.
If fertilizer use is to increase, rapidly growing supplies that are available to farmers must be assured. For this, two principal elements are required. First, stocks must be substantial because of inefficiencies in the marketing system and because errors are likely to be made with regard to the particular commodities concerned. The second requirement is a substantial and rapidly growing infrastructure. Mellor (1987) reported that in Bangladesh, villages with good infrastructure use 65% more fertilizer per unit area than villages with poor infrastructure. Infrastructure development is a critical causal variable for the expansion of fertilizer use. The effect of infrastructure on fertilizer use is much greater than can be explained by differences in the prices of fertilizers and crop output, in security of delivery, or in simple transportation costs. Infrastructure development is essential not only to strengthen the fertilizer supply, but also to support the entire process of market development and conversion of agronomic potential into effective demand for fertilizers (Desai and Stone 1987). A high level of investment is needed to ensure an adequate infrastructure. Developing countries, almost without exception, grossly underinvest in rural infrastructure in a number of areas, but especially in rural roads. In Taiwan, rural roads per unit area of arable land doubled between 1960 and 1970 (Mellor 1987); yet, even in 1960, Taiwan already enjoyed a substantial level of infrastructure development. In Bangladesh, on the other hand, probably one-third of the rural areas are suffering from poor infrastructure. Apart from rural roads, there is the whole gamut of infrastructure requirements for an efficient fertilizer distribution system, including adequate port and railhead facilities, internal transport, and storage facilities.

**Research and extension**

Economically as well as environmentally, fertilizers must be used efficiently, following scientifically based recommendations. The need for maintaining adequate returns to fertilizer use is generally well understood. This requires strengthening the agricultural research system, which must adapt agricultural technology to local conditions. National and international research efforts are required to make available sufficient basic technology to increase yields substantially on a sustainable basis. There is increasing recognition in many developing countries that fertilizer nutrient application is unbalanced and that N has been too strongly favored over the other major nutrients. However, there is still plenty of scope for increased fertilizer use in such countries, as illustrated in Table 6. In the long run, more efficient and balanced fertilization will be beneficial to all concerned and offers marketing opportunities for quality products and customer service.

Advice, demonstrations, and training on more efficient crop production techniques are essential components of policies for expanding agricultural production. The sophistication of the extension system needs to grow rapidly with increasing fertilizer use. Many developing countries have used stop-gap solutions, rather than pursued the long-term development of a technically competent extension service. The requirements of individual countries for extension services vary considerably. They reflect the technology level of the farming community and its experience with intensive agricultural production.
Fertilizer policies for development

Table 6. Fertilizer rates, crop yields, and areas (FAO 1987c, d; International Fertilizer industry Association, unpubl. data).

<table>
<thead>
<tr>
<th>Region</th>
<th>N, P, K fertilizer product use (kg/ha)</th>
<th>Mean yield (kg/ha) 1986-87</th>
<th>Arable land (million ha)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Maize</td>
<td>Wheat</td>
</tr>
<tr>
<td>Developed</td>
<td>115</td>
<td>6599</td>
<td>2699</td>
</tr>
<tr>
<td>Developing</td>
<td>46</td>
<td>1727</td>
<td>1733</td>
</tr>
<tr>
<td>Centrally planned</td>
<td>143</td>
<td>3826</td>
<td>2386</td>
</tr>
<tr>
<td>China</td>
<td>176</td>
<td>3694</td>
<td>2995</td>
</tr>
<tr>
<td>USSR</td>
<td>114</td>
<td>3129</td>
<td>1769</td>
</tr>
</tbody>
</table>

Mineral fertilizer use aims not exclusively at increasing yields, but also at increasing profitability at the farm level. Extension workers, therefore, need a basic understanding of the economics of fertilizer use and of cropping practices within the farming systems in which they work. It is important that the extension effort should fully appreciate the need for maintaining returns to fertilizer use despite a decrease in incremental returns with increasing fertilization levels. Access to and use of other inputs that are complementary to fertilizer are most important in this regard.

To provide adequate professional incentives, extension staff must be given well-defined tasks, adequate facilities, and the equipment to carry out their job. They should be properly trained and motivated, taking into account the difficult conditions under which they generally work. Unfortunately, in the majority of developing countries, limited finance and trained manpower result in either a thin spreading of the resources or a concentration in areas of high potential, which are generally more densely settled. In many countries, the introduction of fertilizers and their subsequent production have been spearheaded by commercial suppliers, who can be encouraged to play a continuing role.

In most developing countries, wide variations in fertilizer use exist between and even within farming communities. An effective fertilizer extension program must reflect the stage reached in the area concerned, as this affects not only the extension methodology adopted, but also the level of personnel required and the support services such as soil analysis.

Conclusions

Major aspects of fertilizer policy are the choice of plant nutrients, policies for their effective use, development of mining and manufacturing capacity, balance between domestic production and importation, price policies for fertilizers and crops, marketing and credit, and agricultural extension. These aspects need to be integrated into a comprehensive fertilizer policy that must be consistent with the overall economic objectives of a country and should aim for agronomic and economic efficiency in the use of plant nutrients to maximize agricultural output without neglecting social objectives. Formulating a well-integrated fertilizer policy requires a great deal of coordination, preferably on a national basis.
To achieve an adequate supply of fertilizers and the smooth realization of effective demand for them, including both buffer stock policy and infrastructure development, large public sector expenditures as well as a supportive policy and institutional environment are required.

In the past, developing countries benefited from the commodity surpluses of the developed market economy countries through access to cheaper commercial imports. However, such imports may depress a country’s agricultural and economic growth by undercutting domestic prices and removing any incentive for farmers to increase production. They may also create dependence on nontraditional foods that the country itself cannot produce. World economic instability, declining prices of agricultural export commodities, budgetary constraints, and balance of payments problems are of major concern to developing countries.

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FAO—Food and Agriculture Organization (1987d) Production yearbook. Rome, Italy.


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Citation information: International Rice Research Institute (1990) Phosphorus requirements for sustainable agriculture in Asia and Oceania. P.O. Box 933, Manila, Philippines.
Protection of the environment: sustained agriculture, sustained ecosystems

K. Kyuma

From its very nature—growing renewable plants—agriculture has long been considered unconditionally sustainable. Today this thesis must be reexamined, however, because of many instances in which agriculture is no longer sustainable or, even worse, has disrupted the balance of nature. Many of the environmental problems that are threatening the future of humankind are in one way or another related to agriculture. In this paper, some problems of global importance are taken up to examine the relevance of agriculture to them. The rapid rate of deforestation in the tropics is caused mainly by shifting cultivation. The implications of shifting cultivation are considered first from the viewpoints of CO₂ evolution, soil fertility degradation, and increased runoff and soil loss. Second, the impact of water and air pollution from agricultural sources is discussed, based mainly on Japanese experience. Third, the causes of the deterioration of soil productivity presently in evidence in both developed and developing countries are considered from the viewpoints of agricultural sustainability. Finally, a few points are raised as a possible approach to sustained agriculture and preservation of the ecosystem.

Global environmental problems, such as the accumulation of CO₂ in the atmosphere, the destruction of the ozone layer, deforestation, desertification, and acid rain, are becoming more and more serious each year in spite of wide recognition of their causes. It seems that knowing the cause is not necessarily enough to arrest such problems. In this paper some of the problems directly related to agriculture, including animal husbandry and forestry, are taken up to examine how and to what extent agriculture affects the sustainability of the ecosystem. Because it is impossible to review the literature exhaustively, mostly Japanese literature has been cited.

Deforestation and forest degradation

The rapid decrease of forested areas in recent years has aroused profound worldwide concern about increasing CO₂ in the atmosphere and the extinction of many plant and animal species. How and to what extent is agriculture responsible for this?
Deforestation in the world and in Asia

A recent study by Lanly (1982) under a Food and Agriculture Organization/United Nations Environment Programme project disclosed that, annually, large areas of forested land either totally disappear (deforestation) or are seriously degraded (degradation) as a result of agricultural activity. Figure 1, adapted from that study, describes the present world forest situation. About 11.3 million ha of forest is lost every year: two-thirds comes from closed forests (tree crowns covering a high proportion of the ground) and one-third from open forests (with crown coverage exceeding 10% of the ground area but less than in closed forests). Of the large deforested areas, 55% or 6.2 million ha is converted to nonforest and 45% or 5.1 million ha is changed by shifting cultivators to a mosaic of temporary croplands and secondary regrowth. As arable and grazing lands should have a large share of the area converted to nonforest, agriculture, including shifting cultivation, is definitely the most important cause of the recent drastic decrease in the world’s forested area, particularly in the tropics.

If we take only tropical Asia, the annual loss of forests amounts to 2 million ha, more than 90% occurring in closed forests. The main cause of the loss is again shifting cultivation, which explains about 49% of the deforested area (Lanly 1982). What is specific to tropical Asia is its considerable area of swamp forest, which occurs extensively on tropical peats in insular Southeast Asia.

Deforestation and carbon dioxide evolution

Kyuma and Pairintra (1983), together with other scientists, conducted an interdisciplinary study on various ecological aspects of the cropping phase of shifting

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1. Global deforestation (after Lanly 1982). Figures in boxes give the increase (+) or decrease (-) of area in million ha.
cultivation in northeast Thailand, clearing a primary semideciduous seasonal forest with a slash-and-burn technique and cropping maize for 2 yr. One of the important results of their study was a quantitative description of the C cycle in the forest and its disruption by deforestation. Tsutsumi et al (1983) measured the stock and flow of C in various compartments of the forest, while Tulaphitak et al (1983) studied the dynamics of soil respiration both in the forest and in cleared fields. Combining these two sources of data, the C cycle in the forest was depicted (Fig. 2) based on the model and assumptions of Kira (1976). An important datum obtained was an estimate of the amount of C evolved annually from soil organic matter: 6.5 t C/ha per yr. An estimate of the C evolved from a cleared field was 13 t/ha for the first year after clearing and another 8 t/ha for the second year, the 2 figures combined amounting to nearly 30% of the total C stock of the soil in the forest. This was thought to be due to a much higher soil temperature in the cleared field exposed to direct solar radiation.

Thus, burning a forest releases not only C stored in the vegetation, but also that stored in the soil, the latter representing a very large share of the C in the biosphere. Presumably, this source of CO₂ contributes significantly to the buildup of atmospheric CO₂ in recent years. Estimates of ecologists (e.g., Yoda 1985) of the CO₂ increase in the atmosphere due to deforestation amount to 1.3-1.5 × 10⁹ t C/yr, compared with that due to the combustion of fossil fuels: 5-5.5 × 10⁹ t C/yr. The CO₂ increase in the atmosphere is expected to cause a “greenhouse effect” and raise

2. Kira’s model of the C cycle in the forest soil ecosystem (a) and the measured C cycling in Nam Phrom, Thailand (b) (after Kira 1976, Kyuma and Pairintra 1983). Figures in boxes in (b) are in t C/ha, others in t C/ha per yr. # = figure based on the assumption that 40% of soil respiration comes from tree root respiration.
the temperature of the earth’s surface, eventually raising the sea level and submerging the most fertile coastal alluvial lands. The frequent recurrence of climatic anomalies in recent years could be a partial expression of the greenhouse effect.

**Deforestation and decline of soil fertility**

Another important result obtained in the experimental shifting cultivation was an estimate of nutrient balance (Tulaphitak et al 1983) in the cropping phase. By clearing and burning the forest, large quantities of plant nutrients, such as P and K, were released as ash (Fig. 3, time II). Even ammoniacal N increased in the surface soil because of burning. In addition to the nutrients inherited from the vegetation, those released from decomposing soil organic matter were also supplied to the soil.

A large proportion of the nutrients released was, however, lost in the first few rain showers (Fig. 3, time III), even before the first maize crop was planted. Under the monsoonal climate, burning is done toward the end of dry season and before the onset of rainy season to get maximum burn. Therefore, the cleared land is usually left nearly unprotected for at least a few weeks until the crop is established, causing large initial erosion losses.

![Graph showing changes in fertility characters of soil in the cropping phase of an experimental shifting cultivation in Nam Phrom, Thailand (after Tulaphitak et al 1983).](image)

3. Changes in fertility characters of soil in the cropping phase of an experimental shifting cultivation in Nam Phrom, Thailand (after Tulaphitak et al 1983). I = before clearing, II = immediately after burning, III = immediately after sowing the first maize crop, IV = immediately after harvesting the first maize crop, V = 1 yr after felling the trees, VI = immediately after sowing the second maize crop, VII = immediately after harvesting the second maize crop, VIII = about 2 yr after felling the trees.
Table 1. Nutrient balance during the 2-yr cropping phase of an experimental shifting cultivation in Nam Phrom, Thailand (Kyuma and Pairintra 1983).

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Nutrient (kg/ha)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>N</td>
</tr>
<tr>
<td>Available nutrient gain by the soil</td>
<td></td>
</tr>
<tr>
<td>From burning</td>
<td>54</td>
</tr>
<tr>
<td>From organic matter decomposition, 1980</td>
<td>240</td>
</tr>
<tr>
<td>1981</td>
<td>160</td>
</tr>
<tr>
<td>Total</td>
<td>454</td>
</tr>
<tr>
<td>Nutrient removal from the ecosystem</td>
<td></td>
</tr>
<tr>
<td>By initial erosion</td>
<td>−</td>
</tr>
<tr>
<td>By crop removal, 1980</td>
<td>68</td>
</tr>
<tr>
<td>1981</td>
<td>72</td>
</tr>
<tr>
<td>Total</td>
<td>140+</td>
</tr>
</tbody>
</table>

Neglecting the other sources of nutrient loss such as leaching and erosion during later stages, a nutrient balance was formulated (Table 1). Gains in the available nutrient pool consist of addition by burning and by organic matter decomposition in the first and second years. The greatest part of nutrient loss is due to initial erosion. Particularly for bases, crop removal is negligible. But the gains in Table 1 are a mere transformation within the total capital stock in the original soil-vegetation system, whereas the losses represent real removal from the system. If the losses at the later stages are counted, in one crop-fallow cycle considerable capital loss occurs; unless the loss is made good during the fallow period, the system will eventually be degraded.

Deforestation and subsequent agricultural use of land thus degrade soil quality because of erosion and nutrient removal. This is particularly true for P, which tends to accumulate more in the aboveground biomass than in the soil. At the Nam Phrom site, P was distributed in the vegetation-soil system as shown in Table 2.

The soil P is the fraction soluble in a 0.2 N HCl solution. Assuming that the soil to the depth of 50 cm had a mean bulk density of 1.3 g/cm³, the soil available P content was only about 17.5 ppm. Thus, one merit of burning in shifting

Table 2. Distribution of P in the forest ecosystem in Nam Phrom, Thailand (Tsutsumi et al 1983).

<table>
<thead>
<tr>
<th>Location</th>
<th>P (kg/ha)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aboveground part</td>
<td></td>
</tr>
<tr>
<td>Biomass</td>
<td>189.4</td>
</tr>
<tr>
<td>Forest floor</td>
<td>5.4</td>
</tr>
<tr>
<td>Subterranean part</td>
<td></td>
</tr>
<tr>
<td>Roots</td>
<td>9.3</td>
</tr>
<tr>
<td>Soil (0-50 cm)</td>
<td>113.5</td>
</tr>
</tbody>
</table>
cultivation is the quick release of critically needed nutrients like P. However, P thus released may not be conserved by crops that have a much smaller biomass than did the original forest; P tends to be lost by surface runoff and, to a lesser extent, by leaching, resulting in impoverishment of available P.

The P in the aboveground part of the forest, the forest floor, and the thin layer of the surface soil has accumulated over hundreds of years of plant succession. An ecological study that traced the course of development of plant and soil on newly deposited volcanic ejecta on Oshima Island (Tezuka 1961) revealed the sequence shown in Figure 4. The soil in stand A is devoid of the A horizon and carries only very sparse grasses. It is sandy, having developed from basaltic lava for 200 yr. As plant succession proceeds, the soil develops morphologically, accumulating organic matter in the A horizon and increasing depth and clay content, finally reaching the climax vegetation stage after 1200 yr (stand H). Soil fertility has also built up, as shown in Figure 5. Phosphorus in the top 30 cm of soil, both total and available, increases from a very low level to an amount enough to support a forest with aboveground biomass of 443 t/ha due to the pumping effect of tree roots. Thus, time is an important factor for the buildup of soil fertility under natural forest, while the careless felling of trees can destroy fertility even in 1 d.

**Deforestation and increase in runoff and soil loss**

Takahashi et al (1983) studied runoff and soil loss in the shifting cultivation experiment in Thailand. Their data for the first year of cropping show a profound effect of deforestation on soil and water conservation. The ratio of runoff to rainfall went up to 50% in the cleared plot when the crop was not well established, and the annual total runoff amounted to 5-9 times that under forest conditions.

4. Soil profile development on volcanic ejecta in Oshima, Japan, as a function of time and plant succession (after Tezuka 1961). A to H = sites in a time series ranging from 200 yr (A) to 1200 yr (H).
Nutrient buildup in the surface horizons of volcanic soils in Oshima, Japan, as a function of time and plant succession (after Tezuka 1961). A to H = sites in a time series ranging from 200 yr (A) to 1200 yr (H).

Soil loss for the first year in the cleared plot was as much as 70 t/ha, about 80% of which occurred during the first few months, whereas that in the control plot under forest was <4 t/ha. Thus, the influence of deforestation on the hydrological conditions and soil erosion of a watershed is very large. Both floods and drought are likely to increase in agricultural lands within the same watershed.

Environmental pollution

Agriculture has long suffered from industrial pollutants such as fumes and wastewater. At the same time, it has acted as a source of dust and sediments due to erosion. More recently, with the introduction of chemical fertilizers and pesticides, agriculture has become a source of chemical pollutants.

Water pollution

Water pollution can originate from both upland and lowland fields.  

Upland fields as pollutant source. Concern about the eutrophication of Japanese inland lakes such as Biwako and Kasumigaura has grown rapidly since...
1970, and the impact of agricultural sources of pollutants, particularly N and P fertilizers, has been studied intensively to address the concern.

Figure 6 (Tabuchi and Takamura 1985) is a summary of many studies on the relationship between the amount of fertilizer N applied and the loss of N leached from arable upland and grassland. The leaching loss from grassland is much smaller than that from arable uplands, probably because of a year-round uptake of N in the former. Even at zero application, a certain amount of leaching loss originates from organic matter decomposition, rainfall, irrigation water, etc. The ratio of leaching loss to the amount applied normally ranges from 10 to >50% for arable uplands and from 0 to 20% for grasslands, depending on the type of soil, particularly soil texture, and on the rainfall or the amount of water percolation. Most of the nitrate pollution of inland lakes originates from upland soil leaching.

In contrast, Kolenbrander (1973) found the leaching loss of P from upland fields and grasslands very small, ranging from 0.05 to 0.72 kg/ha for arable soils (mean 0.21 kg/ha) and from 0.2 to 0.3 kg/ha for grasslands (mean 0.23 kg/ha). Such losses may even be observed in a soil with no applied fertilizer, because a high level of geochemical release of P occurs in the process of weathering of parent materials (Koshino 1978). In one experiment conducted in Japan, 86 kg P/ha of fertilizer applied to an ordinary upland field and 183 kg P/ha applied to a vegetable field gave a leaching loss of only 0.5 and 1.5 kg P/ha (0.6 and 0.8%) of the applied P, respectively, indicating a high capacity of the soil to retain P (Yatazawa 1978). Thus, the environmental impact of P fertilizers is generally much smaller than that of sewage water or P-containing detergents.

The major P loss from upland fields occurs by erosion of P-retaining clay and organic matter. A loss of P due to soil erosion may easily amount to 100 times that due to leaching (Prochazkova 1975). However, there are some uncertainties about the fate of P thus entering water bodies. Most of the P retained by the eroded soil particles is deposited and does not act as a pollutant (Hillbricht-Ilkowska 1989).

6. Relationship between N applied and N lost through leaching for arable uplands and grasslands (after Tabuchi and Takamura 1985).
Low land fields as pollutant source. The inflow through irrigation and rainfall, and the outflow through surface runoff and leaching are the items to be considered in making a P or N balance sheet for a ricefield. The environmental impact must be evaluated based on the difference between the sum of fertilizer application plus inflow and the sum of plant uptake plus outflow. Figure 7 shows the results of some such calculations (Tabuchi and Takamura 1985). In the case of N, supply and loss are more or less balanced: four of the five cases showed relatively small net positive outflows, or were polluting the water; and one showed a net negative outflow, or was purifying the water. Cases of ricefields with a water-purifying effect have been frequently met among Japanese studies.

As shown in Figure 7, P addition as fertilizer was by far the larger input, the greater part of it being retained by the soil. Three cases had a net positive outflow, and the remaining two cases had a net negative outflow. But the absolute amount of P in the outflow, either positive or negative, was very small, causing relatively little impact on the environment.

Water pollution with herbicides and pesticides originating from arable lands has not so far become an important problem in Japan. Recently, however, pollution with herbicides used on golf courses has aroused public concern in some areas.

7. N and P balance sheets for ricefields in various regions of Japan (after Tabuchi and Takamura 1985). Balance is the difference between outflow and inflow. Minus sign means a purifying effect, and plus sign a polluting effect on water.
Air pollution
Aside from CO\textsubscript{2}, some gases that evolve from agricultural lands may have an environmental impact. Methane and H\textsubscript{2}S from ricefields affect the atmospheric composition through their roles in regulating O\textsubscript{2} concentration. Methane is also known to contribute to the greenhouse effect.

Evolution of N\textsubscript{2}O from the use of N fertilizers is now considered to have an environmental impact. The gas is produced in both nitrification and denitrification, the former being presently considered more important. Nitrous oxide affects the destruction of ozone (O\textsubscript{3}) to O\textsubscript{2}, acting as a catalyst after being converted to NO. Nitrous oxide gas in the atmosphere also acts as an absorbent of infrared heat rays re-radiated from the earth’s surface, contributing to the greenhouse effect. Nitrification inhibitors have been tested with some success to suppress the evolution of N\textsubscript{2}O (Minami 1988).

Ammonia volatilization from agricultural lands is of particular concern in relation to acid rain in northern Europe. Van Breemen and Jordens (1983) reported a large amount of (NH\textsubscript{4})\textsubscript{2}SO\textsubscript{4} entering the soil. The main source of NH\textsubscript{3} for the (NH\textsubscript{4})\textsubscript{2}SO\textsubscript{4} is manure spread on grasslands in areas of intensive animal husbandry. Sulfur dioxide evolved from industrial sources combines, after oxidation to SO\textsubscript{4}\textsuperscript{2-}, with NH\textsubscript{3} to produce (NH\textsubscript{4})\textsubscript{2}SO\textsubscript{4}. One measurement made by the authors gave a value of 64 kg N/ha per yr entering into the soil from the atmosphere in the Netherlands. Even more important is that dry deposits of (NH\textsubscript{4})\textsubscript{2}SO\textsubscript{4} on plant leaves and branches are dissolved by rainwater, and the salt solution enters into the soil either as stem flows or as throughfalls, resulting in direct contact of the concentrated salt solution with the tree roots. As the trees already have sufficient N, most of the ammoniacal N is nitrified as follows, causing strong acidification of the root zone:

\[
\text{(NH}_4\text{)}_2\text{SO}_4 + 4 \text{O}_2 \rightarrow 2 \text{HNO}_3 + \text{H}_2\text{SO}_4 + 2 \text{H}_2\text{O}
\]

This is at least one of the mechanisms of widely observed forest degradation in the acid rain-affected areas of Europe.

Deterioration of soil productivity
The plant is a renewable resource, and agriculture that relies on such a renewable resource is expected to be basically sustainable. However, this thesis does not hold true unconditionally and is valid only if soil productivity is sustained. In many cases, agriculture is apparently not sustainable. What is called desertification is not necessarily caused by climatic anomalies but is often induced by human impact. The loss of soil productivity due to salinization is clearly a result of our mismanagement of irrigation. Here we look into the sustainability of agriculture in both developed and developing countries.

Problems in agriculture in developing countries
The population explosion in developing countries in the tropics after World War II has no comparison in history. When population growth was slower, man could adapt to the
change by developing new farming techniques. In the postwar period, however, there was no time to adapt to the rapidly increasing population, and the only solution was expansion of cultivated land through deforestation. Even such expansion has a natural limitation set by national or tribal boundaries or by climate, and further population increase inevitably increases stresses on existing land use.

In subsistence farming systems, such as those practiced by hill tribes in Asia and by many African tribes, a reduced fallow period has been evident in recent years. Fresco (1986) surveyed cassava production in a shifting cultivation system in the Kwango-Kwilu region of Zaire. He found increasing output to meet the demand of the inhabitants in Kinshasa, the capital, but it was made possible only at the expense of soil quality. Because of a shorter fallow period, bush fallow was degrading into grass fallow, and even a very poor soil derived from the Kalahali sand deposits that had been left untouched was being cropped to cassava, resulting in accelerated erosion and total loss of soil productivity.

Suehara (1985) conducted a survey on the agriculture of the Bashi people in one village in Kivu, eastern Zaire, as a follow-up of a survey carried out in the 1950s in the same village by a group of Belgian scientists (Hecq et al. 1963). The village population had doubled and landholdings had been fractionalized during these 30 yr, while few technological innovations had occurred. A general reduction of the fallow period and an expansion of cultivated areas into traditionally unused swampy lowlands were observed. In the 1950s, 59% of the uplands and only 20% of the lowlands were being utilized; present land use covers 95 and 85% of the respective land categories. Such a tight land use situation compelled some households to use the same piece of land continuously without fallowing, with no replenishment of soil fertility. Such exploitative land use or overcultivation causes widespread soil erosion (Region du Kivu 1984).

Exploitation of soil resources is also evident in Asia. Degraded Imperata grasslands that do not readily revert to forest testify to overcultivation by shifting cultivators in insular Southeast Asia. Also, commercial cultivation of maize and cassava is producing barren scrubland in some upland areas. However, Asian countries have the great advantage of an ecologically sound system of staple food production, viz., lowland rice cultivation, that can be intensified as population pressure increases without severe environmental risks like soil erosion.

Under marginal environments such as the semiarid and arid climatic zones, land is particularly susceptible to mismanagement and is liable to deteriorate. Both overcultivation and overgrazing are apt to lead to a total loss of soil productivity, called desertification. According to Novikoff (1983), approximately 65 million ha of productive land in the southern portion of the Sahara alone are estimated to have become desert in the last 50 yr; in the Sudan, the desert is reported to have advanced southward 90-100 km in the 17 yr before 1975. Novikoff also quotes from a United Nations study saying that 173 million ha of rainfed cropland and 3,071 million ha of rangeland are affected by desertification in addition to 27 million ha of irrigated land that has lost productivity because of salinization.
Problems in agriculture in developed countries

Power and Follett (1987) warned that monoculture, which is widely practiced in the United States as an efficient means to attain high crop productivity, may not be compatible with the other goal of a good farming system, i.e., sustained production through protection of the environment. The main points of their discussion are quoted below.

Three technological factors pushed farmers toward monoculture. The first is mechanization, which enabled farmers to expand their farms. The average farm size in the corn belt expanded from 65 ha in 1907 to 200-300 ha in 1980. With a heavy investment in large, specialized machinery, the farmer has a strong incentive to grow only the crop for which the machinery was designed.

The improvement of crop varieties is the second force pushing farmers toward monoculture. Plant breeding techniques have led to improved crop varieties with desirable attributes, such as higher yield potential, better grain quality, higher water use efficiency, and higher resistance to diseases and insect pests. By concentrating on a single, improved crop, the farmer can exploit its traits to the utmost.

The third technological factor underlying the shift toward monoculture is the development of chemicals, i.e., fertilizers and pesticides, which have made it possible to grow a single crop year after year without apparent yield decline or without much trouble from weeds, pests, and diseases.

Over and above these technological factors, socioeconomic factors, such as governmental farm policy and availability of credit, have played very important roles in the shift to monoculture. Where monoculture becomes dominant, a supporting economic and material infrastructure usually develops, reinforcing the position of the dominant crop. In this way, monoculture usually promises high income to the farmer.

Then what is wrong with monoculture? In monoculture, the land is left vacant after harvesting the specialized crop. Thus the soil is not protected from the impact of rain and does not receive as much organic matter as in the case of a rotational system; eventually the soil structure weakens and erosion is enhanced. Furthermore, monoculture increases risks from pests and diseases. Increased use of chemicals to cope with such unfavorable elements of crop growth in the monocultural system would enhance the danger of environmental pollution.

In the long run, monoculture degrades the environment by accelerating soil erosion, increasing the potential for depleting or degrading groundwater resources, reducing the quality of surface water, and using up fossil energy resources. To avoid these drawbacks, Power and Follett (1987) advocate a return to rotation, multiple cropping, and intercropping along with no-tillage farming.

Although the farming scale is not comparable, a similar trend can be observed in Japan. According to Yamashita (1986), recent changes in Japanese farming, starting with the introduction of the power tiller, have led to a collapse of the traditional mixed farming system with draft animals as an integral part, and to heavy dependence on chemical fertilizers. The need for higher income has urged farmers to neglect traditional practices that maintain soil quality. The first concern of the Japanese farmer in the past was how to maintain or even promote soil productivity; to attain this goal,
he used to spend a lot of labor, time, and money in making farmyard manure, maintaining irrigation and drainage facilities, and so forth (Yamashita 1986). But the farmer's attitude has changed drastically, and his major concern is now to increase his income, paying little attention to conserving soil productivity for his children. Thus, the soil is exploited to the utmost, and sustainability of agriculture is jeopardized.

The same consideration would apply to the United States. The commercialism apparent in modern farming enterprises has changed the value system of the farmer and destroyed the concept that the soil is a limited resource to be passed from one generation to the next. The highest priority is always placed on maximizing today's benefit, but not on sustaining soil productivity. As this is a matter of our mental attitude, it appears very difficult to change and to reestablish a high value on the conservation of soil resources.

**Toward sustained agriculture**

Sustained agriculture can be established only on soil with sustained productivity. To sustain soil productivity, sound replenishing measures must exist. In shifting cultivation, for example, a sufficiently long fallow period must be provided, and in modern commercial farms a sufficient amount of organic matter and fertilizer must be applied to restore the physical and chemical properties of the soil. We do not know exactly, however, how long the fallow period should last or how much organic matter and fertilizer should be applied to sustain soil productivity. As a result, on the one hand, an overdose of chemicals may pollute the environment, and on the other, the soil resource may be overexploited as land and the economic situation become tight. Therefore, we must develop methodologies to estimate necessary measures to replenish soil productivity quantitatively at any given technological and economic level.

Even before such methods are developed, we should maximize the recycling of materials to maintain soil productivity. Human and animal wastes should be recycled as much as possible. One of the characteristics of Chinese and Japanese agriculture in the past was the use of night soil to replenish soil fertility. Public health considerations do not allow this any more, but sludges from sewage disposal plants could and should be recycled, provided that the problems of heavy metals can be avoided.

Long distance transport of food and feed eventually causes environmental hazards. The exporting area loses the chance to recycle the nutrient elements, leading to soil impoverishment. whereas the importing area suffers from eutrophication due to excess N and P. In Figure 8, Miwa and Iwamoto (1988) illustrates the P dynamics in the Japanese food supply system. Phosphorus in the imported food and feed exceeds that supplied by domestic produce. Every year, along with quite a large quantity of fertilizer P, this amount of P from the imported food and feed is added to the soil and water. Since Japanese agricultural soils already have a large stock of available P, an annual amount nearly equivalent to the newly added P is either immobilized by the soil or released to the environment. As a means to reduce environmental stresses, replacement of some of the fertilizer by waste should be seriously considered. But usually the location and timing of disposal do not coincide with those of fertilizer application, making replacement highly impractical. Thus, the
8. **P dynamics in the food supply system of Japan, 1982** (after Miwa and Iwamoto 1988). Numbers are t \( \times 10^3 \) yr. # = includes P immobilized in soil.

Greater part of the P released to the environment will eventually be loaded onto inland water bodies, only to aggravate eutrophication. A similar figure drawn for N shows an even more critical situation. Nitrogen nearly twice the amount of that applied as fertilizer (1,455,000 t N/yr) is being disposed of in the environment, with the clear danger of eutrophication of not only water but also arable soils, since excess soil N inhibits the normal growth of crops (Miwa and Ogawa 1988).

Japan is now importing a huge quantity of food and feed that is produced from an area twice as large as the present area of her domestic cultivated land. This may be justifiable from the viewpoint of Japan’s international trade balance, but not from an environmental standpoint, because such importation encourages overexploitation of soil productivity in other developed countries through monoculture, deprives the poor soils in the exporting developing countries of their nutrients, and eventually pollutes Japan’s own soil and water. In principle, therefore, every nation should attempt to produce as much food and feed as possible on its own land to nourish its own people, with due consideration to the recycling of nutrients and the avoidance of excessive use of chemicals.

**References cited**


Notes

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Acknowledgment: The author is deeply indebted to the following people who provided him with useful information materials: Mr. K. Kotari (Japan International Cooperation Agency), Drs. E. Miwa and M. Koshino (National Institute of Agro-Environmental Sciences), Drs. T. Tabuchi and Y. Takamura (Ibaraki University), and Dr. H. Watanabe (Kyoto University).

Citation information: International Rice Research Institute (1990) Phosphorus requirements for sustainable agriculture in Asia and Oceania. P.O. Box 933, Manila, Philippines.
Sustainable agricultural growth in most of the developing countries of Asia implies sustainability of growth in yields through intensive cultivation of land. Two necessary conditions for such growth are improvements in crop varieties and high soil fertility. This paper highlights evidence on the P constraint. It also reviews the experience of growth in fertilizer use to overcome soil fertility constraints. The three most important problem areas are identified: 1) low use of organic manure outside East Asia, 2) persistent geographical concentration of fertilizer use within countries, and 3) much less use of P than of N fertilizers. To sustain yield-based agricultural growth in the developing countries of Asia, effective mechanisms are urgently required to deal with soil fertility constraints in a dynamic context. A reorientation in policies is necessary to develop such mechanisms.

Sustainable agricultural growth in most of the developing countries of Asia implies sustainability of growth in yields through intensive land cultivation. The experience of the last 25 yr reveals that this requires developing crop varieties with high yield potential as well as effectively tackling soil fertility constraints.

An overview of the experience leads to three broad conclusions: 1) Well-coordinated efforts in both the above directions are critical for developing sustainable intensive cultivation of land. 2) Although fertilizers are becoming more important in supplying plant nutrients, there are major deficiencies in the policies and efforts designed to tackle soil fertility constraints through fertilizers. 3) It is urgent to remove those deficiencies because intensive cultivation is increasingly constrained, both in technical and economic terms, by the fertility status of soils.

Dynamics of soil fertility constraints in Asia

It has been known for a long time that Asian soils are remarkably deficient in N, but the severity of other nutrient deficiencies has not been as commonly recognized. According to Ignatieff and Page (1958), the manifestation of other nutrient deficiencies was only a matter of time. During the last two decades, this has indeed proved correct.
In the case of P, the deficiency occurred despite substantial growth in the use of P fertilizers.

In Asia it is especially necessary to examine soil fertility constraints in a dynamic context. The unprecedented yield-based growth in production has stepped up nutrient removal from limited arable land, which in most countries has not been matched by commensurate and balanced growth in the supply of nutrients through organic sources and fertilizers. In India, for instance, N, P, and K removed by crops increased by 70% between 1961 and 1984, reaching the equivalent of 17 million t of aggregate N + P\textsubscript{2}O\textsubscript{5} + K\textsubscript{2}O by 1984. Although estimates of net supply of nutrients through organic matter (OM) and chemical fertilizers vary widely, they fall short of nutrients removed through crop production. Thus, together with loss of nutrients due to soil erosion, grazing, etc., soil fertility has decreased.

That the fertility constraints have not been overcome is suggested by the smaller than expected effects on yields of increasing fertilizer use and even a decline in the efficiency of fertilizer use before the full genetic potential of available varieties is fully realized (Ahmed 1985; Pakistan 1988; Randhawa and Meelu 1975; Sarma and Gandhi, unpubl. data; Stone 1986). A wide variety of factors are responsible for this, but the importance of fertility constraints cannot be denied. Regional variations in levels and growth of yields at comparable levels of irrigation, diffusion of modern varieties (MVs), and N use, as well as farm-level evidence in research on yield-gap analysis, point in this direction. On land planted to MVs but not receiving fertilizer, fertility constraints seem to have become more severe, as indicated by declines in average wheat yields in about 7,500 trials conducted in farmers’ fields in India between 1967 and 1982 (Tandon 1987).

Soil fertility problems are not confined to P, as the evidence from a growing number of locations indicates for deficiencies of S and micronutrients. But P deserves special attention for four reasons: first, next to that of N, deficiency in available P is most widespread in many Asian countries. For instance, the commonly used soil test methods show that 46% of the districts in India were classified as “low” in available P, 50% as “medium,” and only 4% as “high” (Tandon 1987). Furthermore, the proportion of districts with severe P deficiency has increased over time. In China, too, a similar pattern is indicated. During the 1930s, about 30% of China’s farmland was considered P deficient. Estimates for the 1950s varied between 40 and 55% (Stone 1986). Recently, the Chinese Academy of Agricultural Sciences estimated that 74% of farmland is P deficient (Zhu and Xi 1990). Second, despite improvements in the P-N ratio in aggregate fertilizer consumption in many countries, not all is well with respect to P fertilizer use, as shown in the next section. Third, in unirrigated regions, where even N fertilizer use has remained low, correction of P deficiency may be crucial to raise returns on the seed, fertilizer, and other dryland technologies. Finally, these reasons gain further strength once we note the role of P at various stages in crop growth and relate it to the historical experiences of countries with sustained growth in yields. In this context, the P constraint seems to have already begun to emerge in a major way in the developing countries of Asia.
Phosphorus constraints and growth of fertilizer use

Since the early 1960s, the developing countries of Asia have raised their fertilizer consumption impressively. Between 1961-65 and 1983-85, total world fertilizer consumption (as aggregate N + P$_2$O$_5$ + K$_2$O) increased from 38 to 128 million t at an average annual rate of 6%. During the same period, total consumption in the developing countries increased from 5 million t to 46 million t at an average annual rate of 10.9% (FAO 1975, 1986). Within the developing world, Asia had the highest growth rate (12%), and its consumption increased from 3 to 37 million t. Thus, in less than three decades, the developing countries of Asia raised their fertilizer consumption to about the same level as total world consumption in the early 1960s—some 120 yr after the use of chemical fertilizers began in the 1840s. About 80% of fertilizer consumption in the developing world in the mid-1980s was in Asia.

Between 1961-65 and 1983-85, the P-N ratio in world fertilizer consumption dropped from 0.85 to 0.48. It declined in both developed and developing countries, from 0.95 to 0.58 in the former and from 0.46 to 0.36 in the latter. Incidentally, the decline in the ratio in the developed world was a correction of the historical trend, since its fertilizer use was dominated by P fertilizers until the 1940s. Within the developing world, the P-N ratio declined from 0.42 to 0.31 in Asia but improved in both Africa and Latin America. Asia, however, had the highest growth rate of P consumption. Thus, the decline in its P-N ratio was due to marginally higher growth rate of N as compared with P consumption (11.5 and 10.1%, respectively).

**Asian developing countries**

Total fertilizer consumption grew at 13%/annum in both China and India from 1961-65 to 1983-85, although from different base levels (13 kg/ha in China and 3 kg/ha in India). In most other countries, fertilizer consumption grew at an annual rate of more than 10%. Only where the early 1960s levels were relatively high—Sri Lanka, Republic of Korea (ROK), Democratic People’s Republic of Korea (DPRK), Vietnam, and the Philippines—did consumption grow at less than 10%/annum.

There were, however, important differences in the relative rates of growth of N and P consumption, and hence in the direction of changes in the P-N ratio. In many countries, P consumption grew more rapidly than that of N, raising the P-N ratio. The improvement in the ratio was modest in India and Indonesia, where it was already above 0.25 in the early 1960s. In other countries like Pakistan, Bangladesh, Burma, Malaysia, and Sri Lanka, where the ratio was relatively low, the improvement was dramatic. On the other hand, in four East Asian countries (China, DPRK, Vietnam, and ROK) and two Southeast Asian countries (Philippines and Thailand), consumption of N grew faster than that of P, and the P-N ratio declined. Thus, the decline in the P-N ratio in developing Asia as a whole was due to the decline in the ratios in these six countries.
This pattern raises an important question: How could the East Asian countries (especially China) continuously raise N consumption, and up to very high levels, without commensurate growth in the use of P fertilizers despite widespread P deficiency? The answer seems to lie in their meticulous management of soil fertility through recycling of OM. Even in the late 1970s, at least 65%, and perhaps as much as 75%, of the substantial quantities of total applied nutrients in China came from organic sources (Stone 1979). Although the contribution of P through OM was relatively low (Zhu and Xi 1990), its massive and meticulous use relaxed the constraints on raising the application of N fertilizers to high levels through effects on soil properties that improve P availability. Thus, the Chinese experience provides a success story in managing alternative P sources and tackling the P constraint in the course of very rapid growth in N fertilizer use (Desai and Stone 1987a).

Thus far, countries outside East Asia have relied mainly on improving the P-N ratio in fertilizer use to manage the P constraint to intensive agriculture. But can this trend continue without adverse impact on both the technical and economic efficiency of fertilizer use? The question is pertinent because most Asian soils are poor in OM content. That recycling of OM is important in sustainable intensive agriculture with high rates of fertilizer use is also clear from the experience of the developed countries (Weber and Gebauer 1986).

It would be naive to assume that the traditions developed over centuries in East Asia could be readily transplanted to other Asian countries. Furthermore, given the high labor requirements of mobilizing, processing, transporting, and applying OM, and also the alternative uses of some forms, the scale of the East Asian experience may not be practicable in the developing market economies of Asia. In fact, because of the same reasons, the relative importance of P will most likely increase in the future growth of fertilizer consumption in China and DPRK. Nonetheless, the experiences of the developed world and East Asia stress the complementarity between OM and chemical fertilizers in overcoming soil fertility constraints to sustainable growth in yields.

Three South Asian countries
This section, based mainly on ongoing research at the International Food Policy Research Institute, focuses on the growth of fertilizer use in India, Pakistan, and Bangladesh to highlight certain issues in tackling P and other soil fertility constraints to sustainable yield-based growth.

Fertilizer consumption in each of the 3 countries was 3-4 kg/ha in the early 1960s. By 1985-86 it had increased to about 50 kg/ha in India, 60 kg/ha in Bangladesh, and 75 kg/ha in Pakistan. Although the diffusion of MVs played a key role in all three countries, growth of fertilizer consumption occurred under quite dissimilar conditions (Desai 1988a). For instance, among the three, real prices of both N and P fertilizers (that is, ratios of fertilizer to crop prices) were highest in India and lowest in Bangladesh throughout the period. On the other hand, Pakistan had the highest level of irrigation, and India had relatively better developed physical and institutional infrastructure than Pakistan and Bangladesh. Despite these differences, the growth of fertilizer consumption had similar strengths and weaknesses.
Strengths. First, fertilizer use in all three countries grew on farms of all sizes and under all types of tenurial conditions, although the application rates were often higher on small farms. Second, use was not confined to irrigated areas. Among the three, use on nonirrigated areas was most common in Bangladesh and least common in Pakistan; in India, the pace of fertilizer diffusion under nonirrigated conditions varied widely across locations. Third, the bulk of the growth in use in all countries was for the production of foodgrains (mainly rice and wheat) rather than for high-value commercial crops. Finally, the trends in fertilizer consumption in all three countries were robust and resilient enough to sustain growth despite the shock to the economy of the oil crisis and upward pressures on fertilizer prices.

Weaknesses. Three weaknesses are highlighted: low and infrequent application of OM, persistent geographical concentration of fertilizer use, and slower adoption of P than of N fertilizers.

OM use in South Asia is nowhere near as high and sophisticated as in East Asia. There is insufficient recognition of the fact that, for soils poor in OM, OM use may be too low to sustain growth in yields through fertilizer use alone. Surely, a high proportion of farmers use OM every year, but the quality of OM is generally poor, rates of application are low, and only a small proportion of land receives it.

According to a nationwide survey conducted in India, no more than 38% of the total cropped area received OM in 1976-77 (Table 1). The situation in Pakistan was even worse, with only 22% of the cropped area receiving OM in 1980 (Table 2). In Bangladesh, too, the plots receiving OM typically varied between 25 and 50% for all major crops except aus rice in the late 1970s to early 1980s (BARC-IFDC findings reported by Navin and Khalil 1988). All these findings suggest that a very high proportion of cultivated land receives moderate quantities of OM only once in 3-5 yr. They also suggest that no more than 20-25% of the cropped area in India and 15-20% in Pakistan receive application of both OM and fertilizers in any year. This is unlikely to improve dramatically in the near future, because low

<table>
<thead>
<tr>
<th>Supplement</th>
<th>Cropped area (%)</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Irrigated</td>
<td>Nonirrigated</td>
<td>Average^a</td>
</tr>
<tr>
<td>Organic manures</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Farmyard manure</td>
<td>42.03</td>
<td>33.48</td>
<td>35.7</td>
</tr>
<tr>
<td>Oilcake</td>
<td>0.94</td>
<td>0.38</td>
<td>0.5</td>
</tr>
<tr>
<td>Others</td>
<td>2.37</td>
<td>1.83</td>
<td>2.0</td>
</tr>
<tr>
<td>Fertilizers</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(NH₄)₂SO₄</td>
<td>11.39</td>
<td>2.26</td>
<td>4.6</td>
</tr>
<tr>
<td>Urea</td>
<td>58.33</td>
<td>10.03</td>
<td>22.4</td>
</tr>
<tr>
<td>Superphosphate</td>
<td>9.68</td>
<td>2.38</td>
<td>4.2</td>
</tr>
<tr>
<td>Others</td>
<td>28.75</td>
<td>6.50</td>
<td>12.2</td>
</tr>
</tbody>
</table>

^a Weighted average of percentages under irrigated and nonirrigated conditions, weights being total irrigated and nonirrigated area in 1976-77. Source: Government of India (1986).
Table 2. Percentage of area under major crops receiving organic manure and/or fertilizer application in Pakistan, 1980.a

<table>
<thead>
<tr>
<th>Crop</th>
<th>Area (%)</th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>M &amp; F</td>
<td>F only</td>
<td>M only</td>
<td>F ± M</td>
<td>M ± F</td>
</tr>
<tr>
<td>Wheat</td>
<td>16.3</td>
<td>61.3</td>
<td>4.7</td>
<td>77.6</td>
<td>21.0</td>
</tr>
<tr>
<td>Rice</td>
<td>8.0</td>
<td>69.8</td>
<td>2.5</td>
<td>77.8</td>
<td>10.5</td>
</tr>
<tr>
<td>Sugarcane</td>
<td>35.6</td>
<td>52.0</td>
<td>4.4</td>
<td>87.6</td>
<td>40.0</td>
</tr>
<tr>
<td>Cotton</td>
<td>16.6</td>
<td>73.7</td>
<td>2.2</td>
<td>90.3</td>
<td>18.8</td>
</tr>
<tr>
<td>Maize</td>
<td>34.5</td>
<td>29.3</td>
<td>17.1</td>
<td>63.8</td>
<td>51.6</td>
</tr>
<tr>
<td>Potato</td>
<td>33.3</td>
<td>47.6</td>
<td>7.1</td>
<td>81.0</td>
<td>40.5</td>
</tr>
<tr>
<td>Onion</td>
<td>14.7</td>
<td>44.1</td>
<td>11.8</td>
<td>58.8</td>
<td>26.5</td>
</tr>
<tr>
<td>Tobacco</td>
<td>61.0</td>
<td>19.5</td>
<td>9.8</td>
<td>80.5</td>
<td>70.7</td>
</tr>
<tr>
<td>Orchards</td>
<td>33.3</td>
<td>26.5</td>
<td>10.5</td>
<td>59.8</td>
<td>43.8</td>
</tr>
<tr>
<td>Av</td>
<td>17.2</td>
<td>62.3</td>
<td>4.6</td>
<td>79.5</td>
<td>21.7</td>
</tr>
</tbody>
</table>

aM = manure, F = fertilizer, F ± M = fertilizer with or without manure, M ± F = manure with or without fertilizer, 0 = neither fertilizer nor manure. Source: Agricultural Census Organization (1983).

and infrequent application of OM is due mainly to limited availability rather than farmers’ attitudes (Jha and Sann 1981).

To raise soil productivity and generate growth in yields over a long time, use of both OM and fertilizers is crucial. Thus, the above evidence clearly indicates a major problem area. To argue that so far nonuse of OM has not obstructed the growth in yields is not valid for two main reasons. First, the relatively short experience of sustained yield-based growth has been confined to a subset of cultivated land. And second, even here the impact of fertilizer use has been less than expected, and fertilizer use efficiency seems to be declining.

Even after two decades of fairly rapid growth, the top two quintiles of districts accounted for about 60% of total fertilizer consumption in Bangladesh, 77% in India, and 85% in Pakistan during the early to mid-1980s (Table 3). More significantly, the share of the bottom two quintiles of districts was as low as 3% in Pakistan and 7% in India. Only in Bangladesh was it as much as 22%. Given the low and infrequent application of OM, this indicates that growth of yields must be severely constrained by low soil fertility (even with respect to N) in a substantial proportion of cultivated land in all three countries.

That this is indeed true in nonirrigated areas of semiarid tropical regions of India is brought out by the surveys conducted by the International Crops Research Institute for the Semi-Arid Tropics in 10 typical villages of 4 states. In 1983-84, two-thirds of nonirrigated sample farms did not receive any nutrient, either from OM or fertilizers, about one-fifth received OM, and only 9% received both OM and fertilizers (Desai and Singh, unpubl. data). These surveys also reveal that infrequent application of even OM is not confined to mixed crop areas planted to leguminous crops.

The geographical pattern of fertilizer use is associated not only with irrigation and the spread of MVs but also with the degree of development in extension, credit, fertilizer distribution, and output marketing systems. The latter are often
Table 3. Distribution (in percent) of total fertilizer consumption among districts in Bangladesh (average 1982-83 to 1983-84), India (average 1986-87 to 1987-88), and Pakistan (average 1981-82 to 1982-83).

<table>
<thead>
<tr>
<th>Country</th>
<th>Share of different quintiles of districts</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>I</td>
</tr>
<tr>
<td>Bangladesh</td>
<td>37.2</td>
</tr>
<tr>
<td>India</td>
<td>54.3</td>
</tr>
<tr>
<td>Pakistan</td>
<td>56.3</td>
</tr>
</tbody>
</table>


more important than the former, as indicated by the evidence from Pakistan, where many districts in the bottom quintiles have more than 25% of their cultivated land under irrigation. Indian data also reveal that many districts with less than 20% irrigation but relatively better development of physical and institutional infrastructure have higher levels and faster growth of fertilizer consumption than those with higher irrigation and even better rainfall environment but poor development of infrastructure (Desai 1985, Desai and Singh 1973, Gujarat Government 1983). Even with high fertilizer subsidies, the degree of development in infrastructure plays a critical role in the geographical pattern of fertilizer consumption in Bangladesh (Ahmed and Hossain, pers. comm.).

The P-N ratio in fertilizer consumption has improved over time in all three countries. But the trends in P-N ratio are still unsteady, and in recent years the ratio fell in Bangladesh (Fig. 1). Furthermore, despite near universal soil P

![P-N ratio graph](image_url)
deficiency, the ratio varies widely across districts, and it was lower than the national average even in many districts with high fertilizer use. Farm level evidence from all three countries also indicates that in high consumption areas many farmers use only N fertilizers.

Surveys carried out by the Indian Agricultural Statistics Research Institute in about 40 districts during the 1970s reveal that the introduction of MVs was soon followed by a rapid adoption of both N and P fertilizers, especially under irrigated conditions. The spread of N use continued, reaching over 80% of cultivated land by the late 1970s at many locations, but that of P began stalling after reaching about 50-60%, even on MVs. On wheat, P use seemed to have picked up after a time lag, but the problem persists with kharif rice. This is confirmed by 1985-86 data from about 1,700 irrigated plots in farmers’ fields planted to MVs in Punjab. As many as 35% of plots did not receive P, and the phenomenon was not confined to plots receiving low rates of N, nor to a few districts or blocks of the state. The problem of lower P use is even more serious under nonirrigated conditions. This was brought out by the 1981-82 Agricultural Input Survey of about 25,000 farms conducted in Gujarat. Even in this state, where fertilizer use under nonirrigated conditions is relatively high, substantial spread of P fertilizer on nonirrigated areas was confined to groundnut (Table 4).

Careful empirical research is needed to identify the relative importance of factors behind persistent lower adoption of P than of N fertilizers even in regions of high N use. The lower spread of P fertilizer use is apparently due more to the difficulties in promoting P fertilizers in the absence of sound location-specific

<table>
<thead>
<tr>
<th></th>
<th>Crop</th>
<th>Irrigated</th>
<th>Nonirrigated</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>N</td>
<td>P</td>
</tr>
<tr>
<td><strong>Foodgrains</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Rice</td>
<td></td>
<td>94</td>
<td>31</td>
</tr>
<tr>
<td>Wheat</td>
<td></td>
<td>95</td>
<td>63</td>
</tr>
<tr>
<td>Bajra</td>
<td></td>
<td>86</td>
<td>18</td>
</tr>
<tr>
<td>Jowar (kharif)</td>
<td></td>
<td>34</td>
<td>17</td>
</tr>
<tr>
<td>Jowar (rabi)</td>
<td></td>
<td>65</td>
<td>34</td>
</tr>
<tr>
<td>Maize</td>
<td></td>
<td>81</td>
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</tr>
<tr>
<td>Gram</td>
<td></td>
<td>55</td>
<td>53</td>
</tr>
<tr>
<td><strong>Nonfoodgrains</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cotton</td>
<td></td>
<td>89</td>
<td>64</td>
</tr>
<tr>
<td>Groundnut</td>
<td></td>
<td>92</td>
<td>90</td>
</tr>
<tr>
<td>Rapeseed and mustard</td>
<td></td>
<td>84</td>
<td>43</td>
</tr>
<tr>
<td>Castor</td>
<td></td>
<td>85</td>
<td>22</td>
</tr>
<tr>
<td>Sugarcane</td>
<td></td>
<td>99</td>
<td>96</td>
</tr>
<tr>
<td>Tobacco</td>
<td></td>
<td>99</td>
<td>4</td>
</tr>
</tbody>
</table>

Table 4. Maximum percentage of cropped area receiving N and P fertilizers on various crop, Gujarat, India, 1981-82. 

\(^{a}\) Source: Gujarat Department of Agriculture (1984).
research on optimal fertilization than to uneconomic response to P fertilizers (Roy and Kanwar 1979, Tandon 1987).

Implications of weaknesses. The most important consequence of low and infrequent OM application, persistent geographical concentration in fertilizer use, less common use of P than of N fertilizer, and many other deficiencies in fertilizer practices (like inappropriate timing, placement, and method of application; and general absence of soil tests in deciding application rates) has been the less-than-expected impact of growth in fertilizer use on crop production. The application rates of N fertilizers at many locations have reached much higher levels than indicated by the averages for the country or even for provinces, states, or districts. Continued dependence on a subset of cultivated land for growth in fertilizer use (often because of infrastructure and institutional constraints) has already started generating pressure for larger fertilizer subsidies and higher support prices for crops (Desai 1986, 1988b).

Conclusion and important policy issues

During the last two decades, the developing countries of Asia have come a long way in introducing two major factors needed for yield-based agricultural growth, namely crop varieties with high yield potential, and fertilizer. This has paid off by breaking the yield barriers in most major crops. But to raise production to the levels needed in the future, major obstacles still exist. Among these, soil fertility constraints are crucial.

Fertilizers have become increasingly important in raising yields, but there are still major deficiencies in policies and efforts to tackle soil fertility constraints through fertilizers. Two aspects deserve particular attention: 1) broadening of the geographical pattern of fertilizer consumption within countries, and 2) balanced use of fertilizers containing different nutrients, especially N and P. Both are equally important for yield-based growth in the entire agricultural sector, and also to sustain efficiency over a long period.

Neither of the two aspects can be effectively dealt with through fertilizer subsidies alone. Favorable price environment is a necessary but not sufficient condition. Similarities in the experiences of India, Pakistan, and Bangladesh, with their significant differences in price environment, point this out. Whether in India, where prices have been less favorable than in many other countries, or in Bangladesh, where they have been quite favorable, the most binding constraints to the geographically broad-based growth of fertilizer use and balanced application of different fertilizers are in the domain of nonprice factors (Desai 1986, 1988b; Stone 1987). These can be divided into three broad categories: 1) location-specific research on soil fertility constraints, agronomic practices, etc. and effective use of research results in extension activities; 2) adequate development and efficient implementation of agricultural credit as well as fertilizer supply and distribution systems; and 3) development of physical and institutional infrastructure. Numerous deficiencies in these matters in the developing world are generally known. Removal of these deficiencies is more crucial than price incentives through budgetary subsidies to tackle effectively the two problem areas mentioned earlier.
To deal with the P constraint, the nonprice factors cited are equally if not more important. A wide variety of factors affect responses of crops to P, and their relative importance differs across locations. Location-specific research and an effective soil testing service are crucial to generate the knowledge farmers need to use fertilizer. Similarly, timely supply of the right type of P fertilizer is crucial, since such fertilizers are needed for basal application under a variety of soil conditions. This calls for a well-developed fertilizer distribution system and its effective interface with local research and extension machinery. Given the high dependence of Asian less developed countries on imports of P fertilizers and their raw materials, removal of the deficiencies in the aggregate fertilizer supply system is also more important in the case of P than in that of N (Desai and Stone 1987b).

The problem of low and infrequent OM use also deserves attention. Vigorous and sustained efforts are required to create awareness among both policymakers and farmers of the relationships between OM use, soil properties, and fertilizer use efficiency. The real question is not just the relative cost of supplying nutrients through OM versus fertilizers. It is whether, and with what efficiency, growth in fertilizer use alone can maintain the required growth in yields on soils poor in OM.

Thus, to sustain yield-based growth in Asian agriculture, a new orientation in policies is needed. So far these policies have been governed mainly by the N constraint and the desire for a rapid impact of fertilizers on food production to lower food imports. These policies should be increasingly guided by the persisting N constraint on a substantial proportion of cultivated land, the emerging constraints with respect to P and other nutrients, and the long-term implications of low OM use for soil properties and fertilizer use efficiency in raising yields.

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Zhu Zhao-liang, Xi Ben-bang (1990) Recycling phosphorus from crop and animal wastes in China. Pages 115-123 in Phosphorus requirements for sustainable agriculture in Asia and Oceania. International Rice Research Institute, P.O. Box 933, Manila, Philippines.

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Acknowledgment: The authors are grateful to Mrs. Suman Rustagi for research assistance in preparing this paper.
Citation information: International Rice Research Institute (1990) phosphorus requirements for sustainable agriculture in Asia and Oceania. P.O. Box 933, Manila, Philippines.
Phosphorus fertilizer use in Asia and Oceania

A. Belmeham and K.F. Nyiri

Ever since the seed- and fertilizer-based Green Revolution started to have an impact in Asia and Oceania, most of the 32 developing countries of the region have performed remarkably well in terms of food production and fertilizer use. Nevertheless, the intensive use of N, the predominance of rice, and the low P requirement of tree crops have meant that large gains in food production have been obtained largely at the expense of soil fertility. Future gains in food output will be more difficult and more expensive, as more and more farmers will have to rebuild soil nutrient reserves. Thus, although significant progress has been made in P fertilizer use, the coming years may witness still higher average application rates. Overall, P fertilizer consumption has doubled over the past 10 yr. It is forecast to grow at an annual rate of 5% over the coming 5 yr. Because of the region’s poor resource base for phosphate rock and its limited phosphoric acid capacity, it has relied heavily on P imports. It will probably grow more dependent on imports in the future. Fortunately, the world-scale producers in North Africa and North America have been investing heavily in P mining and processing. Thus, Asia and Oceania as world-dominant P consumers should have no problem finding sources of supply to meet their import requirements.

There are 32 developing countries in Asia and Oceania, according to the Food and Agriculture Organization of the United Nations (FAO), with a total population of 2.6 billion people in 1985, which was 53% of the world total.

According to a study by the Fertilizer Advisory, Development and Information Network for Asia and the Pacific (FADINAP 1985), the following specific issues affect fertilizer use in the developing countries of Asia and Oceania:

- Agriculture contributes from 15 to 35% of gross domestic product. The economic and social progress of 1.7 billion rural people depends on agricultural development.
- Population is increasing at an average rate of 2%/yr. Considering the dietary requirements of this population, the production of the major food grains will need to expand at about 3%/yr to allow for an increased supply of fruits, vegetables, and other noncereal crops.
- Because the level of land utilization is already high, substantial improvements in crop yields are necessary to ensure future food supplies.
• The next decade and beyond will see production gains becoming more difficult and costly. Most of the less expensive physical resources such as arable land and irrigation water have already been tapped for agricultural production. Additional output will have to be generated from a combination of further improvements in technology: more efficient and adequate fertilizer use, higher yielding crop varieties, better pest management, more skillful planting and harvesting techniques, etc.

• The contribution that fertilizers can make to increasing crop yield has been demonstrated throughout the region. Fertilizer use, as a result, increased at an average sustainable rate of 12%/yr from 1971 to 1981.

• Nevertheless, nutrient usage levels in most countries remain low. For some crops and situations, fertilizer use is often less than 50% of the recommended rate, indicating considerable scope for improvement.

• There is growing concern about nutritional imbalances as farmers opt for fertilizer materials that provide quick returns, e.g., N on cereals, at the expense of long-term soil fertility status (farmers are believed to be using N up to optimum levels where good irrigation is available).

• Less attention has been given to rainfed crops than to irrigated staple crops. This paper will attempt to shed some light on the particular status of P fertilizer use in the developing countries of Asia and Oceania, and the agronomic and economic factors that have contributed to that status. Suggestions will be made about future developments in P fertilizer use, and how those countries will have to meet their P requirements.

Trends and patterns in phosphorus fertilizer use in selected countries

On the basis of P fertilizer use level, countries in the region were classified into four major groups (Table 1):

• Very low users. On the average, very low users increased their P use only slightly from 1976 to 1986.

• Low users. These countries almost tripled their P fertilizer use during the same period.

• Medium users. These increased P fertilizer use from a relatively high average of nearly 5 kg to 13 kg P/ha.

• High users. The Republic of Korea increased its use from 28 to 39 kg P/ha over the 10-yr period.

Let us now look in more detail at some of the overall agronomic and economic factors that have shaped and will likely continue to shape the level of P fertilizer use in the region.

Predominance of rice

In 1985-87, Asia accounted for 90% of world rice production (468 million t). Rice then occupied 145 million ha throughout the world, about 90% of which was in Asia.
India had the world’s largest rice-growing area with 41 million ha, followed by China, with 33 million ha. From 80 to 90% of the populations of Bangladesh, Burma, Indonesia, Sri Lanka, and Thailand depended on rice for their major food intake.

The bulk of rice is grown on the vast areas of flat, low-lying river basins and deltas that are flooded to various depths during the monsoonal seasons. Rice is the only major crop that grows in flooded soils. The water impounded in a ricefield has a number of very important effects (Von Uexkull 1987):

- It provides nutrients directly and indirectly.
- It makes soil nutrients, especially P and K, more available.
- It minimizes the initial requirements for fertilizer P and K compared with that for N, because soil P and K become more available.
- It reduces weed problems.
- It alleviates a number of soil constraints such as Al toxicity.

Because of the high P-supplying capacity of flooded soil, rice frequently does not respond to P addition, even though other crops show large responses when grown on the same soil when this is dry. In contrast, yield response to N in irrigated rice is highly predictable and large, provided that modern varieties are used. This is why, ever since the seed- and fertilizer-based Green Revolution started to have an impact on rice in Asia (post-1965), fertilizer consumption has followed a pattern distinctly different from that of the rest of the world. In 1965, Asia’s N consumption was about
Belmehdi and Nyiri

half that of North America; by 1975, Asia had pulled even; and by 1985-86 Asia consumed about three times as much N as North America (27 against 9 million t) (FAO 1988).

The Green Revolution has had a less dramatic impact on P use and no directly visible impact on K use, as can be expected. The bulk of fertilizer use in Asia today has to do with N application to irrigated rice. Over the years, this has become a “soil mining process” whereby nutrients removed from the soil, other than N, are not returned to it. As a result, over large areas of rice-growing Asia, N efficiency is on the decline because other nutrients, including P, have increasingly become limiting factors.

Fortunately, significant differences among the effects of various P sources on lowland rice are few, except in extremely acid or alkaline soils. This means that cheaper sources of P such as highly reactive ground phosphate rock (PR) and partially acidulated PR can be used. With the extension of rice to marginal upland soils like Oxisols and Ultisols, and to problem soils like acid sulfate soils, there is even a stronger case for the use of P. Being aware of this fact, the World Phosphate Institute has been partially sponsoring a project at the International Rice Research Institute on P source evaluation in acid sulfate soils. The following parameters are being tested in rice-based cropping systems in Bangladesh, China, Philippines, Indonesia, and Thailand:

- single superphosphate or triple superphosphate (TSP) (20, 30, and 40 kg P/ha)
- highly reactive phosphate
- partially acidulated PR (15 and 30% acidulation at 10, 20, and 40 kg P/ha)
- less reactive PR (any local PR at 20, 40, 60, and 80 kg P/ha)

The time may be ripe for another Green Revolution in Asia based on proper P fertilizer management, notwithstanding two facts:

- About 46% of current P consumption is attributed to rice (FADINAP 1985).
- Many countries are trying to diversify their cropping systems in response to the trend for better high-protein diets for their populations. Attention is turning away from rice-based diets to higher protein diets based on such crops as maize and soybean. This trend will certainly entail a higher proportion of fertilizer being used on crops other than rice, with a consequent change in fertilizer consumption pattern.

Prominent position of industrial plantation crops

Asia produces 94% of the world’s natural rubber, 74% of the oil palm kernel, 82% of the coconut, and 78% of the tea. Tree crops are thus prominent in Asian agriculture.

As a general rule, most tree crops have a relatively lower P requirement than field crops would have on the same soil. The fertilizer needs of most tree crops are largest at the young stage, when nutrients are needed for both the harvested crop and the buildup of total biomass. As the trees mature, more nutrients are recycled, and total additional nutrient input tends to decline.
This fact has influenced the pattern of fertilizer use in Malaysia, where nearly the entire steep increase in per hectare fertilizer use is due to a sizable increase in area planted to oil palm—from 19,000 ha in 1972 to 1.32 million ha in 1984. Since on the average about 55-60 kg N, 17.6-19.8 kg P, and 141-149 kg K are applied per hectare of oil palm, the annual fertilizer consumption of 500,000 tin Malaysia is made up of 48% N, 10% P, and 42% K.

Here again, cheaper P sources such as ground PR can be used effectively. Indeed 53 and 35% of total P consumption in Malaysia and Sri Lanka, respectively, is ground PR.

Phosphorus production and supply capabilities

Generally speaking, the region has a poor resource base for P production. Four countries in the Near East accounted for more than half (59%) of Asia’s PR production from 1985 to 1987: Jordan (929,000 t P), Israel (517,000 t P), Syria (216,000 t P), and Iraq (192,000 t P) (IFA 1988c). China accounts for another third of Asia’s PR production, but the bulk of the Asian countries have to rely almost entirely on imports. In Oceania, PR production ceased on Christmas Island and is expected to stop in Nauru by 1995.

Asian and Oceanian countries imported nearly 4 million t of PR in 1987 (Table 2). Asia also has a poor resource base for S, a raw material needed for P fertilizer manufacture. Outside Saudi Arabia and Iraq in the Near East, China and Japan dominate the S supply in Asia. Again, the other countries have to rely mainly on imports. Asian countries imported more than 3.5 million t of S in 1987 (IFA 1988b).

<table>
<thead>
<tr>
<th>Country</th>
<th>P fertilizer imports (t P × 10^3)</th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Phosphate rock</td>
<td>Phosphoric acids</td>
<td>Concentrated phosphates</td>
<td>Total phosphates</td>
<td></td>
</tr>
<tr>
<td>India</td>
<td>290</td>
<td>395</td>
<td>0</td>
<td>685</td>
<td></td>
</tr>
<tr>
<td>China, except Taiwan</td>
<td>45</td>
<td>0</td>
<td>425</td>
<td>470</td>
<td></td>
</tr>
<tr>
<td>Japan</td>
<td>287</td>
<td>18</td>
<td>114</td>
<td>419</td>
<td></td>
</tr>
<tr>
<td>Australia</td>
<td>251</td>
<td>20</td>
<td>114</td>
<td>385</td>
<td></td>
</tr>
<tr>
<td>Indonesia</td>
<td>143</td>
<td>113</td>
<td>0</td>
<td>256</td>
<td></td>
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<td>Philippines</td>
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<td>0</td>
<td>0</td>
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<td>Pakistan</td>
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<td>143</td>
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<tr>
<td>New Zealand</td>
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<td>2</td>
<td>11</td>
<td>121</td>
<td></td>
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<tr>
<td>Iran</td>
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<td>0</td>
<td>115</td>
<td>115</td>
<td></td>
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<td>Saudi Arabia</td>
<td>0</td>
<td>0</td>
<td>97</td>
<td>97</td>
<td></td>
</tr>
<tr>
<td>Malaysia</td>
<td>56</td>
<td>0</td>
<td>7</td>
<td>63</td>
<td></td>
</tr>
<tr>
<td>Taiwan, China</td>
<td>53</td>
<td>1</td>
<td>3</td>
<td>57</td>
<td></td>
</tr>
<tr>
<td>All others</td>
<td>274</td>
<td>12</td>
<td>40</td>
<td>327</td>
<td></td>
</tr>
<tr>
<td>Total P</td>
<td>1700</td>
<td>562</td>
<td>1035</td>
<td>3297</td>
<td></td>
</tr>
<tr>
<td>% of world imports</td>
<td>26</td>
<td>31</td>
<td>38</td>
<td>30</td>
<td></td>
</tr>
</tbody>
</table>
Organic manure is an important P source in Asia. It is estimated that, on the average, 42% of the total P applied to the soil annually in China is as organic manure (Lin and Li 1988).

Aside from that, chemical P fertilizers based on phosphoric acid (the intermediate product from the acidulation of PR with H₂SO₄) are emerging as the dominant P source. But Asia has a limited phosphoric acid capacity, representing only 12% of world capacity (compared with Asia’s ammonia capacity of more than 40 million t, or 36% of world capacity). Furthermore, nearly 50% of the Asian phosphoric acid capacity is concentrated in the Near East, an area that is also known to have more than 50% of Asia’s limited PR supply (Table 3).

Since raw materials for phosphoric acid manufacture must largely be imported into Asian countries, P producers in South and East Asia face higher production costs than producers in the U.S., North Africa, or even the Near East, with their readily available supplies of PR. India has acknowledged this problem and is consequently basing its expanding fertilizer industry on imports of low-cost phosphoric acid, reducing as such its needs for PR and S imports (Table 4).

The situation of PR and phosphoric acid in Asia contrasts sharply with that of ammonia, the basic material required for N fertilizer manufacture. Asia not only has

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**Table 3. World wet-process phosphoric acid capacity, 1980-90 (IFA 1988f).**

<table>
<thead>
<tr>
<th>Region</th>
<th>Phosphoric acid capacity (t P × 10⁶)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1980</td>
</tr>
<tr>
<td>North America</td>
<td>4.6</td>
</tr>
<tr>
<td>Latin America</td>
<td>0.4</td>
</tr>
<tr>
<td>Western Europe</td>
<td>2.1</td>
</tr>
<tr>
<td>Eastern Europe</td>
<td>2.2</td>
</tr>
<tr>
<td>Africa</td>
<td>1.2</td>
</tr>
<tr>
<td>Asia</td>
<td>1.3</td>
</tr>
<tr>
<td>Oceania</td>
<td>0.1</td>
</tr>
<tr>
<td>World</td>
<td>11.8</td>
</tr>
</tbody>
</table>

Asian share (%) 11 12 13

---

**Table 4. Imports of intermediates and raw materials, India (IFA 1988b, c, d).**

<table>
<thead>
<tr>
<th>Material</th>
<th>1980</th>
<th>1987ᵃ</th>
<th>Growth</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>tons</td>
</tr>
<tr>
<td>Phosphate rock (product)</td>
<td>1.35</td>
<td>2.00</td>
<td>0.65</td>
</tr>
<tr>
<td>Sulfur (product)</td>
<td>0.82</td>
<td>1.31</td>
<td>0.49</td>
</tr>
<tr>
<td>Phosphoric acid (as P)</td>
<td>0.16</td>
<td>0.60</td>
<td>0.41</td>
</tr>
</tbody>
</table>

ᵃ Preliminary figures.
more than 36% of world capacity and accounts for more than 25% of world supply, but most of this ammonia is manufactured in areas where it is most needed (Table 5). Partly because of this fact, 73% of the total fertilizer produced in Asia in 1985-86 was N, and only 21% was P. If we discount the Near East, the percentage becomes 79% N against 20% P (FAO 1988). This fact has a strong bearing on P use in Asia. Governments must allocate an increasing proportion of their hard currency earnings to the purchase of PR, phosphoric acid, and/or concentrated P (diammonium phosphate [DAP], monoammonium phosphate, and TSP).

Phosphate fertilizer import requirements as affected by the shift in demand

Because of increasing P fertilizer use, poor resource base, and limited phosphoric acid capacity, Asia and, to a lesser extent, Oceania have grown into a major P fertilizer market. In 1987, 26% of all world PR, 31% of all phosphoric acid, and 38% of all concentrated P exports were shipped into this market. In that year, India ranked as the single largest phosphoric acid importer in the world, while China was the single largest DAP importer.

Overall, Asia and Oceania imported 3.3 million t of P fertilizer equivalent, or 30% of the world’s P imports. Four countries dominated imports, accounting for almost 60% of this tonnage: India, China, Japan, and Australia (Table 2).

Much of this massive import is the outcome of a shift in demand. Asia and Oceania as a region doubled its processed P fertilizer consumption from almost 2.2

<table>
<thead>
<tr>
<th>Table 5. Average Asian raw materials production as percentage of world totals, 1985-87 (IFA 1988a, b, c, e).</th>
</tr>
</thead>
<tbody>
<tr>
<td>Country</td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td>China, except Taiwan</td>
</tr>
<tr>
<td>India</td>
</tr>
<tr>
<td>Indonesia</td>
</tr>
<tr>
<td>Japan</td>
</tr>
<tr>
<td>Republic of Korea</td>
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<td>Malaysia</td>
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<td>Pakistan</td>
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<tr>
<td>Philippines</td>
</tr>
<tr>
<td>Sri Lanka</td>
</tr>
<tr>
<td>Taiwan, China</td>
</tr>
<tr>
<td>Thailand</td>
</tr>
<tr>
<td>Vietnam</td>
</tr>
<tr>
<td>Total World</td>
</tr>
<tr>
<td>86,457.7\textsuperscript{b}</td>
</tr>
</tbody>
</table>

\textsuperscript{a}1987 only. All products. In addition, Saudi Arabia and Iraq produced 1.4 and 0.73 million t S, respectively, in all forms. \textsuperscript{b}Includes only major producing countries.
to nearly 4.5 million t between 1976-77 and 1986-87. Asia alone, excluding the Near
East, accounted for 75% of this regional demand in 1986-87. At this level of
consumption, the region has become the dominant P consumer in the world,
outstripping both North America and Western Europe when put together (4.1
million t P fertilizer in 1986-87). Today, Asia and Oceania represent about 30% of
total world fertilizer demand (Table 6).

By 1992-93, this share is projected to increase to 34%, meaning that about 56% of
future growth in world P demand will probably be generated in Asia and Oceania
within the period. Processed P fertilizer demand will continue to grow at close to
5%/yr from 1986-87 to 1992-93 (Table 6).

Asia and Oceania currently produce 3.2 million t of processed P fertilizer, 48% of
which is based largely on indigenous PR supply in the Near East and China, the
other 52% based on imported PR and phosphoric acid. Overall, the region currently
represents about 19% of the world P supply potential, growing to 21% by 1992-93.
Compared with demand, only about 35% of the future growth in world processed P
fertilizer supply will probably be generated in Asia and Oceania by 1992-93. The

Table 6. Processed fertilizer demand in Asia and Oceania (FAO/UNIDO/WB
1988).

<table>
<thead>
<tr>
<th>Region</th>
<th>Demand (t P × 10^3)</th>
<th>Growth</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1986-87</td>
<td>1992-93</td>
</tr>
<tr>
<td>Near East</td>
<td>632</td>
<td>950</td>
</tr>
<tr>
<td>Far East and Japan</td>
<td>2,073</td>
<td>2,592</td>
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<tr>
<td>Oceania</td>
<td>429</td>
<td>537</td>
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<tr>
<td>China</td>
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<td>1,980</td>
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<tr>
<td>Asia and Oceania total</td>
<td>4,553</td>
<td>6,059</td>
</tr>
<tr>
<td>World total</td>
<td>15,272</td>
<td>17,952</td>
</tr>
</tbody>
</table>

| Share (%)               | 30                  | 34     | 56     |

Table 7. Processed P fertilizer supply potential in Asia and Oceania (FAO/UNIDO
/WB 1988).

<table>
<thead>
<tr>
<th>Region</th>
<th>Supply potential (t P × 10^3)</th>
<th>Growth</th>
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<tbody>
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<td>1992-83</td>
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<tr>
<td>Near East</td>
<td>503</td>
<td>627</td>
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<td>Far East and Japan</td>
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<td>Oceania</td>
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<td>China</td>
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</tr>
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<td>Asia and Oceania total</td>
<td>3,181</td>
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<tr>
<td>World total</td>
<td>16,414</td>
<td>18,709</td>
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</table>

| Share (%)               | 19                  | 21     | 35     |
average future annual growth rate in processed P fertilizer supply will not probably exceed 4%. However, the dominant P fertilizer supplier in the region, China, with its readily available PR resources, will take the largest share in the region’s future expansion (61%). China’s average annual growth rate in processed P fertilizer production will be spectacular (6.8%) compared with the world average (2.2%) (Table 7).

Based on these forecasts, Asia and Oceania will grow even more dependent on P imports in the next 5 yr. The supply and demand balance for 1992-93 (Fig. 1) shows that, despite the potential increase in supply from the 3.2 to 4.0 million t from 1986-87 to 1992-93, the demand will increase at an even higher rate: from 4.55 to 6.1 million t over the same period (Table 6). As a result, the current deficit of 1.35 million t will grow into a 2.05-million t deficit. However, P imports are forecast by the authors to increase only by 1.1 million t to 4.4 million t by 1993, up from the 3.3 million t in 1987. Imports of PR, phosphoric acid, and concentrated P products will all increase over this period (Fig. 2). Fortunately, the world-scale producers in North America and North Africa have been investing heavily in P mining and processing and will stand ready to cater to this import requirement.

Conclusions

Despite agronomic and economic limitations, Asia has made significant progress in P fertilizer use over the past 10 yr. Asia and Oceania have become the dominant P consumers in the world, with more than 4.4 million t annually. Much of this progress has taken place in the huge, densely populated areas of the Far East, where there is

![P supply or demand (t P x 10^6)](image)

still much scope for improvement. China, which ranks medium relative to other countries in the region in terms of P fertilizer use, continues to have the most unbalanced N-P use ratio. Furthermore, the huge rainfed agricultural lands in the region have barely benefited from the fruits of the Green Revolution, with the result that P fertilizer use remains low or nonexistent.

Being aware of this situation, the Asian countries, particularly those in the Far East, are making serious efforts to redress the situation of P use, particularly as rice farming continues to mine the soil P. To do so, China is embarking on an ambitious plan for P fertilizer production whereby the annual growth rate is expected to be close to 7% over the next 5 yr. China can afford to do so because of its available indigenous PR resources, but this is not the case for other countries in the Far East. There, only a modest 2% growth rate is predicted. Because of the increasing demand, the Far East, including Japan, is projected to witness the largest deficit in the region by 1993: 3.3 million t or 70% of the total regional deficit. It is comforting to know that there will be enough P in the world to meet that deficit, as the world-scale producers have been preparing themselves for this eventuality.

REFERENCES CITED


Phosphorus use in Asia and Oceania


Notes

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Citation information: International Rice Research Institute (1990) phosphorus requirements for sustainable agriculture in Asia and Oceania. P.O. Box 933, Manila, Philippines.
The Asia-Pacific region is an area of intense agricultural activity. In many places, agricultural productivity is assisted by high P application to low-fertility soils. However, increased P usage is commonly inhibited by the relatively high cost of P fertilizers due, in many cases, to high transportation costs. Access to indigenous P supplies would greatly help this situation, particularly in the countries of South and Southeast Asia, where the need for P is critical. There is no shortage of P in the Asia-Pacific region, but distribution is very uneven, with a few countries—notably China, Vietnam, and Australia—having large resources and most others having the dual problems of inadequate or no P resources and large populations to feed. There are, nevertheless, possibilities in the region for finding new P resources, particularly in latest Precambrian-Cambrian, late Cretaceous-early Tertiary, and Neogene rocks.

Phosphate rock (PR), the prime source of P in P fertilizers, is one of the world’s most important mineral resources. The world annual production of PR concentrate is in the range of 130-150 million t, with a total value of several billion dollars (Fig. 1). Phosphate rock is also one of the world’s most widely traded mineral commodities, with the United States and Morocco dominating world production, and the developed countries of Europe, North America, and the Pacific rim as the major users. The pattern of supply and demand is not optimal, for many of the countries with the largest populations and the greatest need to increase food production lack indigenous PR supplies (Fig. 2). The Green Revolution has been underpinned by the development of new strains of cereal and the much wider use of fertilizers, most notably P fertilizers. Countries lacking indigenous P supplies as well as the financial capacity to import their P requirements are unable to participate in the Green Revolution to the fullest extent, or in some cases to adequately feed their populations (Fig. 3, 4).

A significant number of countries in the Asia-Pacific region lack indigenous sources of P (Fig. 5). This is also the region where much of the world’s population reside and where much of the world’s most intensive agriculture is carried out. Therefore, perhaps more than in any other part of the world, the P supply/demand picture in the Asia-Pacific area is out of balance. This problem can be tackled in two ways. One way is to generate sufficient income from other activities to
2. Supply routes (1987) for phosphate rock exported from West Africa, the Middle East, USA, Nauru, and Christmas Island (after IFA 1987).

3. Population and P fertilizer consumption expressed as percentages for the Asia-Pacific region (after IFA 1987).
purchase the P; as a consequence of the burgeoning economics of the region, a number of countries are following this course. The second option is to locate new P sources or exploit currently unexploited (or underexploited) deposits in the region to minimize import costs, or, in some cases, even to generate export income. Therefore, we will briefly review P use and the known P resources of the region, and consider the potential for future discoveries.

**Types of phosphorus deposits**

There are three main types of PR: igneous, guano, and sedimentary. In a recent publication, Cook (1984) reviewed the nature and global distribution of the three types briefly discussed here.

**Igneous deposits**

Igneous P deposits are formed in association with alkaline intrusive plutonic rocks such as carbonatites or in alkaline intrusive igneous complexes. Such deposits provide about 16% of the total world source of PR (Howard 1979). There are many occurrences of alkaline rocks in the Asia-Pacific region, but few significant P deposits. Deposits of economic interest include the igneous deposits of the Eppawela region in Sri Lanka, the Singbhum area of India, and the presently unexploited deposits of Mount Weld in Western Australia (Fig. 6).

There may be additional igneous deposits in the Asia-Pacific region, notably in the ancient shield areas of India, China, Korea, and Australia; but in much of the region, there is only limited potential for finding deposits of this type. In addition, because they are generally relatively low grade (except in the weathered...
cap) and require expensive high technology for beneficiation, their capacity for providing a local P source, worked on a village scale, is rather limited. However, where major igneous deposits exist, they can be of considerable economic significance, not only for their P but also because of the wide range of other economically important minerals and minor element by-products that are commonly found in them.

**Guano deposits**

Guano is found as cave deposits and insular deposits.

*Cave deposits.* Small P deposits occur in caves, primarily through the accumulation of bat droppings and less commonly from bird droppings or the accumulation of small vertebrate remains. Phosphorus reserves are generally on the order of a few hundred to a few thousand tons and can be worked only by villagers on a small scale for local consumption. Total production for the Asia-Pacific region is negligible, but such deposits are nevertheless locally important, particularly in Southeast Asia (Fig. 7). The concentration of such deposits in Southeast Asia is due to the occurrence of bedrock suitable for the formation of caves, e.g., limestone and dolomite, and to the warm, humid climate (to support large bat populations). Overall, there is little documentation of cave deposits in the Asia-Pacific region, the only comprehensive publication being that of Hutchinson (1950).
Insular deposits. Insular P deposits are more important than cave deposits but still provide only a small proportion (10-15%) of total PR production for the Asia-Pacific region. The most comprehensive review of insular guano was provided by Hutchinson (1950); White and Warin (1964), and Warin (1968) provided detailed information on a number of deposits, and Cook (1984) provided an overview of this type of deposit. Total P reserves from insular deposits constitute a relatively small percentage of the total P reserves of the region.

Insular deposits form directly or indirectly from the accumulation of bird excreta. There appear to be two types: those on low coral islands as a result of the leaching of fresh guano to form thin accumulations (usually cemented caps and crusts); and the high island deposits, which are the major deposits such as in Nauru and Christmas Island and which show abundant evidence of post-depositional phosphatization of the underlying bedrock (usually coralline limestone).

Small insular deposits of local economic interest occur throughout the region, including parts of the Indian Ocean and Arabian Sea, the southern and west Pacific Ocean, and the South China Sea (Fig. 7). The major deposits are much more restricted in their distribution. Christmas Island in the Indian Ocean, and Nauru (the major deposit), Daito Jima, Makatea, and possibly Anguar in the Pacific Ocean are the only deposits of significance. Ocean Island (Kiribati) was worked out a few years ago. Insular deposits are most common in warm, arid, or
semi-arid areas with large bird populations at present or in the recent past. High marine fertility appears to be essential to support the large bird populations, and this most commonly occurs in oceanic areas where there is an upwelling of cold deep P-rich waters, for example, along the zone of equatorial upwelling.

**Sedimentary deposits**

Sedimentary P deposits (phosphorites) are by far the most important of the world's sources of PR. They currently provide about 82% of the total world P production and 95% or more of the world's P reserves (Howard 1979). Reserves of phosphorites in the Asia-Pacific region are about several billion tons of PR. Phosphorites occur throughout the Asia-Pacific region (Fig. 8) and range in age from Precambrian to recent, though almost all the commercially exploited deposits are Phanerozoic. The Asia-Pacific region is unique in that so much of its P production (and reserves) is from late Precambrian-Cambrian sediments (Fig. 9).

Most commonly, phosphorites occur as beds ranging in thickness from a few centimeters to tens of meters and are composed of grains (frequently termed 8.

pellets) of crypto-crystalline carbonate fluorapatite or collophane. Stromatolitic phosphorites, where the cyanobacterial laminae are composed of collophane, have also been described. This type of phosphorite is especially common in the Precambrian (Banerjee 1971, Bushinski 1969) but also occurs in the Phanerozoic (Krajewski 1984, Southgate 1980).

Reviews on this topic include those of Cook (1976a), Baturin and Dubinchuk (1979), Cook and Shergold (1979a,b), Sheldon and Burnett (1980), Bentor (1980), Slansky (1986), Kolodny (1981), Sheldon (1981a,b), and Cook and Shergold (1986a).

The most widespread phosphorites of the Asia-Pacific region occur in late Proterozoic-Cambrian sediments (Cook and Shergold 1986b). Major deposits of this age are found in Pakistan, India, Vietnam, China, and Australia, and it appears that the greatest potential for future discoveries lies in sediments of this age. Minor deposits are also found in younger sediments (Fig. 9). A considerable amount of exploration for phosphorites has been undertaken throughout the region in recent years, particularly in China, India, and Australia, and a number of major discoveries have been made such as the deposits in Rajasthan (Banerjee 1971) and northern Australia (Russell 1967).

While the majority of P exploration has been onshore, there has been some offshore exploration, particularly on the continental shelf off India, eastern Australia (Cook and Marshall 1981), and New Zealand (Cullen 1980). This has resulted in the discovery of P in continental shelf sediments in a number of areas, most notably off Sew South Wales and on the Chatham Rise. A large number of seamounts and guyots have also been found to have P cappings (Cullen and Burnett 1986). None of these offshore occurrences are being exploited at present, but they do constitute a significant potential P resource for the region.
Phosphorus resources and potential of the Asia-Pacific Region

In this paper the Asia-Pacific region is divided into four subregions. *Phosphorus deposits* are those occurrences of PR that can be economically exploited. *Phosphorus resources* are those sediments in which the P content is elevated above the normal background levels, but not sufficiently high to constitute a deposit.

**South Asia**

One of the most densely populated portions of the globe, South Asia has in excess of one billion people. In many parts of the region, soil fertilities are low and food production is inadequate. Consequently, cheap supplies of PR are needed. Unfortunately, there are few indigenous P supplies, and the prospect of finding more is poor.

The most vigorous search for P to date has been undertaken in India; it has resulted in the discovery of a number of diverse deposits and resources. Igneous Archeozoic or Proterozoic deposits are found in the Kashipatnam area of Andhra Pradesh, the Singhbhum District of Bihar, Newania in Rajasthan (a carbonatite), and other parts of Rajasthan. Igneous apatite is currently mined in Beldih and Kutni in the Purulia District of West Bengal. However, the total igneous apatite reserves of India are only about 10 million t.

By far the most important P resources in India are Proterozoic and early Palaeozoic phosphorites (Banerjee 1986). Lower Proterozoic phosphorites occur in the Hirapur-Bassia areas of Madhya Pradesh and the Lalitpur-Sonrai areas of Uttar Pradesh. Mid-Proterozoic phosphorites are markedly stromatolitic and are associated with dolostones. These deposits are located primarily in Udaipur in the Banswara region of Rajasthan, the Khatamba-Jhabua area of Madhya Pradesh, and the Pithoragarh-Bageshwar area of the Lesser Himalaya. In Rajasthan, open pit mining operations in the Matoon, Kanpur, Kharbaria, and Jhamarkotra mines account for the major part of the present total Indian P production of several million tons of PR/yr (reserves about 80 million t) (Choudhuri and Roy 1986). The P content varies from 6.6 to 15.4% in these rocks. The Upper Proterozoic rocks of the Vindhyan Groups of the Palamau District and Cuddapah Group have P contents of 2.2-6.6%, with occasional values above 13.2% P.

The Birmania deposits of the Jaisalmer District contain phosphorites with about 4.4-5.28% P. This deposit is possibly Cambrian. Such an age implies contemporaneity with the phosphorite deposits of the Mussoorie syncline in the Lower Himalaya, which recent palaeontological studies indicate a Lower Cambrian age (Brasier and Singh 1987), and the Hazara phosphorites of Pakistan. Minor Cretaceous and Eocene occurrences are found in the Tiruchirapalli District of Tamil Nadu (up to 11% P) and near Fatehgarh in Jaisalmer District. Some Eocene P nodules are also known in Khasi-Jaintia and the Garo hills. Pleistocene guano deposits are found in the Laccadive-Amindivi Islands of the Arabian Sea (P values range up to 6.6%), but the prospects of finding commercially significant guano deposits are very low.

Undoubtedly the most important interval from the point of view of reserves and future potential is the Proterozoic-Cambrian (Banerjee 1986). The Jhamarkotra
Phosphorus resources of Asia and Oceania

Phosphorite deposits of the Udaipur District in Rajasthan are the most important and productive P mine in the country. The average chemical compositions of some Indian phosphorite types are given in Table 1.

The low grade (~6.6% P) Cambrian phosphorites of the Mussoorie area are utilized for direct application to acidic soils, while the MgO-rich stromatolitic, calcareous phosphorites of Rajasthan (Jhamarkotra, Kanpur, Matoon) with an average P content of 11-13.2% are beneficiated by a unique process in a small plant with a capacity to treat around 4,000 t of ore/d.

The P resources of Pakistan are confined primarily to early Cambrian marine deposits in the Hazara area. Because it is near the Western Himalayan region, the area is structurally complex, making exploitation and evaluation rather difficult. The phosphorite occurs in the Abbotabad Formation and lower parts of the Hazira Formation in the Hazara region (Hasan 1986). Sirban, Lagarban, Kakul, Kaludi Banda, and Bagla Gali are some of the important localities where deposits occur in mineable quantities. Deposits in the Kakul-Mirpur sector are located about 10 km from Abbotabad and are of some economic interest, extending for 500 m along the strike with an average thickness of about 45 m. Elsewhere, phosphorites occur as lenses and streaks of 0.4-1.4 m thickness. Small occurrences in Rashain, Nari-de-Gali, and Lambi-Dogi are lenticular in nature. The Lagarban-Kaludi and Banda areas, located 40 km north of Abbotabad, contain phosphorite beds within the upper parts of the Abbotabad Formation and occur as irregular lenses on top of the cherty dolomite. The area is structurally complex, and the beds are repeated at different stratigraphic levels. In the Dalola area, close to Garhi Habibullah, phosphorite beds are associated with silty layers of the Hazira Formation and extend for 2 km along strike. In the Chura Gali area, manganiferous sediments are prominently associated with phosphorite beds; the phosphorites are dense, black, and structureless, unlike those of the Mirpur-Kakul area, where they are typically pelletal and granular. The Sirbun Hill Deposit is a low-grade ore; it extends for 500 m along the strike and thickens to a maximum of 4 m.

Exploration and evaluation of the Sirbun Hill deposits in 1975-78 indicated the possibility of mining 300,000 t PR/yr with an average grade of 11.4% P. Mining is progressing in the Kakul-Mirpur and Lagarban areas, but the ore is hard to grind and contains impurities that make it unsuitable for normal H₂SO₄ treatment. The ore is less reactive; hence its beneficiation is expensive. The total estimated reserves for Pakistan are 23 million t.

Small phosphorite occurrences are recorded in Sind Province, where Lower Cretaceous, Jurassic, and Miocene formations contain nodules and layers of phosphatized shale; Punjab Province, where there are numerous bedded phosphorites and nodules; and Northwest Frontier and Baluchistan Provinces, where there are Cretaceous, Jurassic, or Palaeocene phosphorites. In the Khyber area, apatitic carbonatite could constitute an important source of PR.

The P resources of Sri Lanka are derived from two major carbonatite bodies. The major deposit is in Eppawela in northwest Sri Lanka, where P contents range from 14.5 to 16.7% P. The ore is a brecciated leached rock and occurs as a thick capping over the granulite grade metamorphics. The matrix is composed of mar-

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<tr>
<th></th>
<th>P</th>
<th>C</th>
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<td>18</td>
<td>1.8</td>
<td>1</td>
<td>1.1</td>
<td>4.2</td>
<td>18.8</td>
<td></td>
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<tr>
<td>Lagarban-Kaludi-Banda</td>
<td>12</td>
<td>32</td>
<td>0.6</td>
<td>0.8</td>
<td>1.1</td>
<td>3.5</td>
<td>9.4</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Vietnam - Cambrian</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Lao Cai (weathered)</td>
<td>15</td>
<td>37</td>
<td>0.2</td>
<td>8.6</td>
<td>2.99</td>
<td>1.2</td>
<td>1.2</td>
<td>0.1</td>
<td></td>
<td>0.53</td>
<td></td>
</tr>
<tr>
<td>Lao Cai (unweathered)</td>
<td>14</td>
<td>34</td>
<td>1.0</td>
<td>0.88</td>
<td>1.8</td>
<td>0.02</td>
<td>3.3</td>
<td>8.1</td>
<td></td>
<td>8.1</td>
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<td><strong>Iran - Lower Cambrian</strong></td>
<td>6</td>
<td>30</td>
<td>0.1</td>
<td>4.7</td>
<td>1.9</td>
<td>0.3</td>
<td>1.4</td>
<td>2.3</td>
<td>0.2</td>
<td>28.07</td>
<td></td>
</tr>
<tr>
<td><strong>New Zealand</strong></td>
<td></td>
<td></td>
<td></td>
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<td></td>
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<td></td>
<td></td>
</tr>
<tr>
<td>Chatham Rise</td>
<td>10</td>
<td>30</td>
<td>0.5</td>
<td>2.88</td>
<td>0.6</td>
<td>3.8</td>
<td>4.6</td>
<td>1.2</td>
<td>1.21</td>
<td>1.2</td>
<td>12.19</td>
</tr>
<tr>
<td><strong>Christmas Island</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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</tr>
<tr>
<td>Grade A - guano</td>
<td>16</td>
<td>34</td>
<td>3.5</td>
<td>2.25</td>
<td>1.3</td>
<td>1.7</td>
<td></td>
<td></td>
<td></td>
<td>4</td>
<td></td>
</tr>
<tr>
<td>Nauru -guano</td>
<td>17</td>
<td>38</td>
<td>0.3</td>
<td>0.4</td>
<td>2.62</td>
<td>0.1</td>
<td>0.1</td>
<td>0.2</td>
<td></td>
<td>trace</td>
<td>2.78</td>
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<tr>
<td>Ocean Island - guano</td>
<td>18</td>
<td>38</td>
<td>0.3</td>
<td>1.06</td>
<td>2.97</td>
<td>0.1</td>
<td>0.1</td>
<td>0.2</td>
<td></td>
<td>trace</td>
<td>1.88</td>
</tr>
<tr>
<td><strong>Sri Lanka</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Eppawela - carbonatite</td>
<td>16</td>
<td>37</td>
<td>0.1</td>
<td>0.1</td>
<td>nil</td>
<td>2.43</td>
<td>1.2</td>
<td>1.6</td>
<td>0.1</td>
<td>nil</td>
<td>2.65</td>
</tr>
</tbody>
</table>
tite and goethite, with fluorapatite as the primary apatite mineral. Reserves of 60 million t of 14.5% P grade ore are estimated for the Eppawela region. A chemical analysis of average Eppawela leached apatite rock is given in Table 1.

The Seruwila copper-magnetite ores of northeast Sri Lanka also contain P, with apatite constituting 25% of the nonmagnetic fraction. Mineralization is confined to an area of about 39 km². The principal P mineral is fluorapatite, with a high chlorine content. An unusual chemical composition and low solubility are major drawbacks to the utilization of this rich PR for the manufacture of superphosphate.

Western Nepal has P-bearing Proterozoic dolomites extending from the Pithoragarh District of India. The P interval is up to 6 m thick; it is associated with stromatolitic carbonates and analyzes at 4.4-6.6% P, but with values up to 15.4% P. Minor P beds also occur in southern Nepal, but the potential reserves are very small. The Barakhshetra and Tangsar areas of eastern Nepal have minor P beds ranging in age from Permo-Carboniferous to Eocene.

Little is known about the P potential of Afghanistan. A palaeogeographic connection is possible between the Afghanistan mountain ranges and P intervals in the Hazara belt of Pakistan in the east and southeast, and Iran in the west.

Iran has two distinctly different kinds of P occurrence. The Upper Proterozoic to Lower Cambrian occurrence extends from the Russian border in the northwest to Kerman in the southeast, a distance of almost 1,750 km, and is best developed in central Alborg Mountain. The Cretaceous-Eocene occurrences are all located in the Zagros Mountain range in the southeast. The phosphorite deposits are concentrated in the Lower Cambrian Soltanieh Formation and are best developed southeast of Zanjan. The P contents in these beds vary from 2.2 to 4.4%, with individual beds ranging from 2 to 3 m. The high MgO content of these phosphorites makes them unfit for superphosphate production, but some recent breakthroughs have been made in the refinement of this ore.

Apatite-magnetite deposits of the Esfodri-Bafq area in central Iran are another potential source of PR. The rocks are highly deformed, folded, and faulted, and the apatite-magnetite occurs as lenticular bodies in the Infracambrian Rizu Series. The main apatite-rich horizon contains 7.5% P and has a reserve of 3.75 million t of PR. The tremolite-actinolite-apatite horizon assays at 5.3% P and 1.90 million t of reserve. Mining is by open pit methods.

**Australasia**

Australia and New Zealand are major P users, with 1986 consumption of 685,000 and 300,000 t of P fertilizers, respectively. PR was mainly from Christmas Island and Nauru, but an increasing proportion comes from Florida, with minor amounts from the Middle East and North Africa. Because the Nauru deposits have reserves for no more than 10 yr at present production levels, and a decrease in quality led to the closure of the Christmas Island operation, the Australasian region will need either to import an increasing proportion of its P needs or to find new indigenous resources. New Zealand has put considerable effort into evaluating the offshore deposits of the Chatham Rise (Cullen 1980, Kudrass and Cullen 1982). The average content of 9.7% P for Chatham
Rise nodules (Table 1) is comparable with that of many commercial deposits, though the relatively high Fe and Si contents (mainly in the form of glauconite) are a negative feature. Total reserves are estimated at 18 million t for an area of 284 km$^2$ when a cutoff grade of 15,000 nodules/km$^2$ is assumed (Kudrass and Cullen 1982). This would be sufficient to meet New Zealand’s needs for several years; however, the high cost of offshore mining precludes exploitation of these deposits in the near future.

Australia also has offshore deposits, but these are not of any economic interest at present (Cook and O’Brien 1990). Most interest has centered on the search for onshore deposits.

Following the initial discovery of PR in northwest Queensland (Russell and Trueman 1971), most exploration has focused on the Cambrian deposits of central and northern Australia. This has resulted in the discovery of 17 deposits in the Georgina Basin of northwest Queensland and the Northern Territory, with demonstrated economic reserves of 27 million t of direct shipping-grade ore (with a cutoff of 13.6% P) at Duchess and total paramarginal reserves for the basin of $2.75 \times 10^9$ t with a cutoff ranging from 5.7 to 7.5% P. The deposits at Duchess were worked intermittently since their discovery, but are not presently being exploited. The major barrier to their economic exploitation is the high cost of transporting the PR more than 1,000 km from the mine to the port facilities at Townsville. High coastal shipping costs from Townsville have probably also contributed to the cost problem, and for the present, with the cost of 70% bone phosphate of lime PR FOB Tampa at around US$31-37/t and FOB Casablanca at around US$37-42/t, Australian fertilizer manufacturers are meeting their P requirement over and above those met by Christmas Island and Nauru by importing rock from overseas.

Some exploration has been undertaken outside of the Georgina Basin. Currently the greatest potential for commercially viable deposits is judged to lie in the Tertiary rocks of southeastern Australia, though only minor onshore occurrences are known.

There is also some potential for finding P deposits associated with carbonatites. Igneous apatite occurs in the Strangways Ranges area of central Australia, and there are alkaline igneous rocks in a number of other areas. To date, however, the only significant igneous P discovery is at Mount Weld in Western Australia (Willett et al 1986). This deposit is still being evaluated, but it seems fairly high grade and may be suitable for meeting the needs of the Western Australian market.

**Southeast Asia**

Southeast Asia is undoubtedly one of the areas where P demand (and requirement, which is not necessarily the same thing) is most out of balance with P supply. This imbalance is even more marked if population is taken into consideration, with around 400 million people living in the region. The lack of indigenous P in most parts of the region probably also causes lower than desirable levels of P fertilizer use to boost food production, given the relatively low soil fertility of many tropical areas. The problem is exacerbated for a number of the countries by insufficient foreign exchange to buy P.

The only known major deposits are at Lao Cai in northern Vietnam, about 260 km northwest of Hanoi (An and Khoa 1986). Identified reserves of PR are about 260 million t, with a P content ranging from 4.4 to 15.8% P.
Elsewhere in Southeast Asia, the search for P has been disappointing, despite major exploration programs. The greatest potential for new discoveries is in the Cambrian sediments of Burma and possibly adjacent parts of Thailand and Malaysia. Elsewhere, particularly in Indonesia, the Philippines, and Papua New Guinea, the search has concentrated on younger parts of the sequence in the hope that the Tethyan phosphogenic province, which is well developed in the Middle East, might extend into Southeast Asia. Most areas have little chance of igneous deposits; however, many small guano deposits make significant local contributions. To date, Devonian sediments have not been the target for much exploration. However, compilation of known P occurrences (Fig. 9) suggests that this part of the geologic column has some potential, based on the model of Cook and McElhinny (1979) indicating that phosphogenesis has occurred at particular times in earth history.

East Asia
Phosphorus deposits have rather variable distribution in East Asia. Japan, Taiwan, northern China, and the Republic of Korea have a few significant P deposits. This is unfortunate because this is a major agricultural area with a massive population. The principal deposits are found in southern China and are mostly Cambrian or possibly late Proterozoic (Bushinski 1969, Li 1986). They are found mainly in the provinces of Guizhou, Yunnan, Sichuan, Hubei, Hunan, and Jiangxi and, while reserves are probably many billion tons of PR, high transportation costs restrict the extent to which Yangtse Platform PR is utilized in other parts of China or elsewhere in Asia.

There is considerable potential for finding more phosphorites, particularly in the late Proterozoic-early Cambrian rocks of China. Little has been published on northern Korean occurrences of igneous deposits; however, there may be significant potential there, and possibly also in parts of China. Conversely, there is little prospect that guano-type deposits will have a significant impact on P reserves, although as in Southeast Asia such deposits provide local supplies. At present, the P potential of Japan appears to be low, but given the country’s foreign exchange reserves, the low supply does not constitute a problem.

Discussion
Overall, there is no shortage of P resources in the Asia-Pacific region; however, the very uneven distribution of those resources, even within the same country, inhibits the optimum use of P fertilizers. Australia has massive P resources, but these continue to be uneconomic. China has large P reserves in the southern half of the country but inadequate resources in the north. India has a significant level of P production, but this is inadequate to meet all of its current requirements, and identified reserves are completely inadequate for likely future needs. Japan and the Republic of Korea have no P resources but have adequate foreign reserves to purchase their P from outside the region.

This leaves a large number of countries in the region with inadequate or no reserves of P and insufficient foreign currency to purchase supplies. Countries
falling into this category are Pakistan, Sri Lanka, Bangladesh, Burma, Thailand, Indonesia, Laos, Kampuchea, and the Philippines. To some extent the use of village-scale technology can offset the lack through the exploitation of small deposits, but in many areas this is not a viable option.

In this paper we have considered P resources from a geological perspective, because knowledge of the geology of the Asia-Pacific region is a key element in the search for future P resources. Throughout much of the Asia-Pacific region, rocks of late Proterozoic and particularly Cambrian age offer the best prospects for finding P deposits, because this region forms part of a major phosphogenic province of early Cambrian age extending from Australia through much of Asia and into Europe and Africa. Therefore, rocks of this age throughout South and East Asia and, to a lesser extent, Southeast Asia offer the best P prospects.

A phosphogenic event of similar magnitude also occurred during the late Cretaceous-early Tertiary through the so-called Tethyan Belt, which may have extended through parts of South Asia and into Southeast Asia. That also constitutes a target for P exploration.

Similarly, there are suggestions of a phosphogenic period in the Devonian (but this requires more work), and in the Neogene there was certainly a third major global phosphogenic event, which is most evident in some of the offshore deposits of the Pacific region but which may have shoreward equivalents in areas flanking the Pacific such as New Zealand, eastern Australia, and the Philippines.

In conclusion, there are no grounds for pessimism regarding the P prospective of the Asia-Pacific region, but neither are there grounds for complacency. The region already has large populations and, for many of its people, inadequate levels of nutrition. There is undoubtedly a need to increase the average level of P usage per hectare in many areas, particularly in South and Southeast Asia. To some extent this can be achieved by purchasing P from outside regions. For many countries this is not a viable option for financial reasons, and for such countries the only option available is to locate indigenous supplies. The secret to doing this lies in building up an adequate picture of the geology of the region and of the factors influencing the distribution of P resources.

References cited


Notes

Authors’ addresses: P.J. Cook and P.N. Southgate, Division of Continental Geology, Bureau of Mineral Resources, Canberra, Australia; D.M. Banerjee, Department of Geology, University of Delhi, Delhi, India.
Acknowledgments: P.J. Cook and P.N. Southgate publish with the permission of the Director, Bureau of Mineral Resources, Canberra, Australia.
Citation information: International Rice Research Institute (1990) Phosphorus requirements for sustainable agriculture in Asia and Oceania. P.O. Box 933, Manila, Philippines.
Recycling phosphorus from crop and animal wastes in China

ZHU ZHAO-LIANG AND XI ZHEN-BANG

Recycling of P through the reuse of crop and animal wastes has contributed substantially to sustained agriculture in China. Even in 1986, 1.45 million t P was applied as organic amendments, accounting for 42% of total P inputs in agriculture. Pig excreta contributed 36% and cattle excreta 25% to the total P applied as organic amendments. Straw and stalks (including ash) contributed 14%, and the reuse of crop residues is accelerating along with the development of rural Industry. The contribution of green manure crops was negligible, and their cultivation is limited. Human excreta from cities and animal excreta from large livestock farms may become an environmental problem. The availability of inorganic P in organic amendments seems comparable to that of water-soluble P, while that of organic P depends on its mineralization rate, which varies greatly among the forms of organic P in different organic amendments. Field experiments revealed that crops recovered 12-18% P from farmyard manure in the first year of application, equivalent to 75% of the P recovered from superphosphate. We emphasize that the sole recycling of organic amendments cannot maintain soil P fertility, and increased P input by chemical fertilizer is definitely necessary.

Recycling of nutrients through the reuse of agricultural and human wastes as organic amendments has played a substantial role in maintaining soil fertility and in sustaining crop production in China. However, Lu (1979) and the Institute of Soils and Fertilizers of the Chinese Academy of Agricultural Sciences (ISF 1986) showed that up to 74% of the agricultural land of China is deficient in P. Thus, a large increase in P fertilizer application is one of the most important strategies for improving the country's crop production. The input of P fertilizers has been raised tremendously in the last 3 decades and reached 2 million t P in 1986. The forecast requirement for P fertilizers in the year 2000 is 3-4 million t P (ISF 1986, Lu 1987). In this paper the quantity of P in different organic wastes and their contribution to P balance, as well as the availability of P in them, are discussed.

Contribution of organic waste to phosphorus balance

The quantity of P in organic wastes and its contribution to total P input, as well as the P balance in Chinese agriculture, have been estimated (ISF 1986, Jin et al 1983, Shen 1985b, Zhang 1984). The estimates made by ISF (1986) for 1949-82 (Table 1) show that a P deficit lasted for many years and was reversed only around 1975, when
Table 1. Contribution of organic amendments to total P input and P recycling in Chinese agriculture, 1949-83 (ISF 1986).

<table>
<thead>
<tr>
<th>Year</th>
<th>Total P input (× 1000 t)</th>
<th>Contribution of organic amendments (%)</th>
<th>P output (in harvest) (× 1000 t)</th>
<th>P recycling (%)</th>
<th>P balance (× 1000 t)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1949</td>
<td>348</td>
<td>100</td>
<td>607</td>
<td>57</td>
<td>-259</td>
</tr>
<tr>
<td>1957</td>
<td>562</td>
<td>96</td>
<td>1038</td>
<td>52</td>
<td>-476</td>
</tr>
<tr>
<td>1965</td>
<td>850</td>
<td>72</td>
<td>1043</td>
<td>58</td>
<td>-193</td>
</tr>
<tr>
<td>1975</td>
<td>1561</td>
<td>55</td>
<td>1469</td>
<td>58</td>
<td>+92</td>
</tr>
<tr>
<td>1980</td>
<td>2171</td>
<td>42</td>
<td>1664</td>
<td>55</td>
<td>+507</td>
</tr>
<tr>
<td>1983</td>
<td>2689</td>
<td>36</td>
<td>2106</td>
<td>45</td>
<td>+583</td>
</tr>
</tbody>
</table>

aTotal P input refers to the sum of the P of chemical fertilizers and organic amendments applied.

The input of P from chemical fertilizers reached about 0.7 million t. The corresponding net gain of P increased to 0.6 million t that year.

The P input through reuse of organic wastes is increasing along with the increase in P input of chemical fertilizers (Table 1). However, the percentage contribution of reused organic wastes to the total input of P is decreasing. This can be attributed to the rapid increase in P fertilizer input, combined with the fact that only a part of the P in the harvest can be recycled. As shown in Table 1, only around half of the P output is being recycled in agriculture, and the percentage of P recycling appears on the decrease, implying that the loss of P during recycling is increasing along with the intensification of agriculture.

Shen (1985a,b) assumed that as much as 80% of the P in the harvest could be recycled, irrespective of agricultural intensification. From this estimate, the quantity of P in organic wastes reused in 1980 and 1982 was 1.7 and 1.9 million t P, respectively, and the corresponding figure for the contribution of reused organic wastes to the total P input was about 59%. These figures are considerably higher than those shown in Table 1.

Though the two estimates differ to a certain extent, the common conclusion is that, even in the last few years, the recycling of P through the reuse of organic wastes is still an important source of P in Chinese agriculture.

Quantity of phosphorus in organic waste

The organic wastes being reused to a considerable extent in Chinese agriculture are human and animal excreta, crop residues (straw and stalks) and their ash, and seed cake (as from cotton, rape, peanut, and soybean). The amount of poultry dung available for reuse is much less but may increase due to the recent development of poultry farms around big cities. Table 2 shows the P content of organic wastes and the estimated reuse extent of their P in 1986. Table 3 shows the contribution of reused P in individual organic wastes to the total P input applied through organic amendments. For comparison, the corresponding data pertaining to N and K are...
Table 2. P content and the estimated percentage of reuse of P in organic wastes in Chinese agriculture, 1986 (after ISF 1962, 1986; Lu and Shi 1982; Wen 1984).

<table>
<thead>
<tr>
<th>Waste</th>
<th>Content of P (%)</th>
<th>Estimated reuse (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Human feces</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Countryside</td>
<td>0.22</td>
<td>80</td>
</tr>
<tr>
<td>Cities and towns</td>
<td>0.22</td>
<td>40</td>
</tr>
<tr>
<td><strong>Human urine</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Countryside</td>
<td>0.06</td>
<td>30</td>
</tr>
<tr>
<td>Cities and towns</td>
<td>0.06</td>
<td>20</td>
</tr>
<tr>
<td><strong>Pigs</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Feces</td>
<td>0.18</td>
<td>80</td>
</tr>
<tr>
<td>Urine</td>
<td>0.03</td>
<td>50</td>
</tr>
<tr>
<td><strong>Cattle</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Feces</td>
<td>0.08</td>
<td>70</td>
</tr>
<tr>
<td>Urine</td>
<td>0.01</td>
<td>25</td>
</tr>
<tr>
<td><strong>Horses, donkeys, and mules</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Feces</td>
<td>0.13</td>
<td>50</td>
</tr>
<tr>
<td>Urine</td>
<td>0.004</td>
<td>25</td>
</tr>
<tr>
<td><strong>Sheep</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Feces</td>
<td>0.22</td>
<td>45</td>
</tr>
<tr>
<td>Urine</td>
<td>0.01</td>
<td>10</td>
</tr>
<tr>
<td><strong>Straw and stalks</strong>&lt;sup&gt;a&lt;/sup&gt;</td>
<td>0.06-0.15</td>
<td>30&lt;sup&gt;b&lt;/sup&gt;</td>
</tr>
<tr>
<td><strong>Ash from burned straw and stalks</strong></td>
<td>0.9</td>
<td>25&lt;sup&gt;b&lt;/sup&gt;</td>
</tr>
<tr>
<td><strong>Green manure crops</strong></td>
<td>0.15</td>
<td>80</td>
</tr>
</tbody>
</table>

<sup>a</sup>Used for bedding and applied to soil directly. <sup>b</sup>Percentage of the sum of rice and wheat straw and maize stalks.

Table 3. Contribution of organic amendments to the total P input in Chinese agriculture, 1986.

<table>
<thead>
<tr>
<th>Waste</th>
<th>Quantity available (t x 1000)</th>
<th>Percentage of total quantity in organic amendments&lt;sup&gt;a&lt;/sup&gt;</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>N P K</td>
<td>N P K</td>
</tr>
<tr>
<td><strong>Humans</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Feces</td>
<td>352 128 179</td>
<td>7 9 3</td>
</tr>
<tr>
<td>Urine</td>
<td>219 54 139</td>
<td>4 4 2</td>
</tr>
<tr>
<td><strong>Pigs</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Feces</td>
<td>1057 462 1062</td>
<td>21 32 17</td>
</tr>
<tr>
<td>Urine</td>
<td>411 64 683</td>
<td>8 4 11</td>
</tr>
<tr>
<td><strong>Cattle</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Feces</td>
<td>1012 356 523</td>
<td>20 24 8</td>
</tr>
<tr>
<td>Urine</td>
<td>312 9 704</td>
<td>6 0.6 11</td>
</tr>
<tr>
<td><strong>Horses and other draft animals</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Feces</td>
<td>161 59 90</td>
<td>3 4 1</td>
</tr>
<tr>
<td>Urine</td>
<td>81 0.4 141</td>
<td>2 0.03 2</td>
</tr>
<tr>
<td><strong>Sheep</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Feces</td>
<td>73 41 39</td>
<td>2 3 0.6</td>
</tr>
<tr>
<td>Urine</td>
<td>13 0.18 31</td>
<td>0.3 0.01 0.5</td>
</tr>
<tr>
<td><strong>Straw and stalks</strong>&lt;sup&gt;b&lt;/sup&gt;</td>
<td>655 99 1324</td>
<td>13 7 21</td>
</tr>
<tr>
<td><strong>Ash from burned straw and stalks</strong></td>
<td>0 88 1098</td>
<td>0 7 18</td>
</tr>
<tr>
<td><strong>Seed cakes</strong></td>
<td>414 73 90</td>
<td>8 5 1</td>
</tr>
<tr>
<td><strong>Green manure crops</strong></td>
<td>186 23 132</td>
<td>4 2 2</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td>4946 1459 6235</td>
<td></td>
</tr>
</tbody>
</table>

<sup>a</sup>Columns do not total 100% because of rounding error. <sup>b</sup>Used for bedding and returned to soil directly.
also presented. The statistics for 1986 in the Almanac of China’s Agriculture (1987) were used for the estimates.

**Extent of reuse of phosphorus in organic wastes**

*Human excreta.* In estimating the reuse of P from human excreta, several factors are taken into consideration:

- The reuse of human excreta deposited in towns and cities is decreasing, owing to transportation difficulties. Therefore, the population in the countryside is counted separately from that in towns and cities.
- The reuse of human feces is much greater than that of urine.
- The factor 0.7 is used to calculate the adult equivalent.

The reuse of P from human feces and urine is thus assumed to be about 80 and 30% in the countryside, and 40 and 20% in towns and cities, respectively. The estimated percentage of reuse of the P in human excreta, as a whole, is only about 50%. Even though reuse is not great, increasing it seems difficult; in fact, reuse may become even less and may create an environmental problem in the future.

*Pig excreta.* Pig raising is the major animal husbandry in China, the total count of pigs at the end of 1986 being 337 million. Although most pigs are raised in pig sties, a considerable portion are raised without sties. Thus, the loss of part of the P from pig excreta, particularly from urine, is inevitable. The reuse of P is assumed to be 80% of feces and 50% of urine. The figure for pig excreta as a whole is 75%.

*Excreta of cattle, sheep, and other draft animals.* The reuse of P from cattle excreta may be lower than that from pigs, because some cattle are raised for draft power in the countryside. The reuse of P from the excreta of other draft animals such as horses, donkeys, and mules is even less. As for sheep, only a portion are raised in pens, and the collection of excreta is very inefficient. In addition, only half of the population of horses and sheep in northwestern China and Inner Mongolia is taken for estimating the total production of excreta, since reuse in those areas is minimal.

The estimated reuse of P is 68% from the excreta of cattle, 49% from horses and other draft animals, and 44% from sheep.

*Straw and stalks.* Straw and stalks are used as fodder and as bedding material for animals. A certain amount is returned to the field directly. A considerable portion is used as fuel for cooking, with the ash being returned to the field as fertilizer. For simplification, only the straw and stalks of the most important crops (rice, wheat, and maize) are considered here; this may result in an underestimation. However, as shown in Table 4, the P harvested in these 3 crops accounts for more than 70% of the P output.

A part of the straw is left in the field after harvest. Liu (1985) indicated that 14-20% (average of 17%) of the P in the straw of rice, wheat, barley, and naked barley was left as stubble in the field after harvesting at ground level (Table 5). Recently, the direct use of straw and stalks as an organic amendment to the field—mulching or incorporation of harvested straw or the long stubble left by harvesting at a higher level—is being encouraged. Zhu et al (1987) estimated that around 60% of wheat straw is left in the field when harvest is at the height of 30 cm from the ground (Table 6). If this technique is widely practiced, the recycling of P from straw and stalks will greatly improve. However, it is more reliable to take 30%
Table 4. Quantity of P in Chinese harvest, 1986.

<table>
<thead>
<tr>
<th>Crop</th>
<th>Quantity of P in harvest (× 1000 t)</th>
<th>Percentage of P output</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rice</td>
<td>758</td>
<td>35</td>
</tr>
<tr>
<td>Wheat</td>
<td>475</td>
<td>22</td>
</tr>
<tr>
<td>Maize</td>
<td>312</td>
<td>14</td>
</tr>
<tr>
<td>Cotton</td>
<td>93</td>
<td>4</td>
</tr>
<tr>
<td>Soybean</td>
<td>66</td>
<td>3</td>
</tr>
<tr>
<td>Rapeseed</td>
<td>65</td>
<td>3</td>
</tr>
<tr>
<td>Sorghum</td>
<td>64</td>
<td>3</td>
</tr>
<tr>
<td>Millet</td>
<td>34</td>
<td>2</td>
</tr>
<tr>
<td>Peanut</td>
<td>26</td>
<td>1</td>
</tr>
<tr>
<td>Others</td>
<td>278</td>
<td>13</td>
</tr>
<tr>
<td>Total</td>
<td>2171</td>
<td>100</td>
</tr>
</tbody>
</table>

Table 5. P in stubble of major crops after harvest at ground level in Tai-lake region, China (Liu 1985).

<table>
<thead>
<tr>
<th>Crop</th>
<th>P in stubble</th>
<th>Percentage of P in whole straw</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rice</td>
<td>1.7</td>
<td>17</td>
</tr>
<tr>
<td>Wheat</td>
<td>0.5</td>
<td>14</td>
</tr>
<tr>
<td>Barley</td>
<td>0.4</td>
<td>20</td>
</tr>
<tr>
<td>Naked barley</td>
<td>0.5</td>
<td>18</td>
</tr>
<tr>
<td>Mean</td>
<td>0.7</td>
<td>17</td>
</tr>
</tbody>
</table>

Table 6. Amount of wheat stubble left after harvest at different heights from ground (Zhu et al 1987).

<table>
<thead>
<tr>
<th>Grain yield (t/ha)</th>
<th>Stubble left as percentage of whole straw at harvest from ground at</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>10 cm</td>
</tr>
<tr>
<td>5.2</td>
<td>23</td>
</tr>
<tr>
<td>4.0</td>
<td>26</td>
</tr>
<tr>
<td>2.4</td>
<td>26</td>
</tr>
<tr>
<td>Mean</td>
<td>3.9</td>
</tr>
</tbody>
</table>

as a rough estimate of the present situation. As for ash, it is assumed that 150 kg of straw or stalks/ capita is being burned for cooking in the countryside each year. The loss of P by burning may be 20% (Ponnamperuma 1984), and 5% more may be lost during collection and storage. Thus, the reuse of ash is assumed to be 75%. As a whole, the reuse of straw and stalks is estimated as 55% (the portion used as fodder is already counted as animal excreta and is not counted here).

Seed cake. Most seed cake derived from soybean and peanut is used as fodder, and its P has already been taken into account as the P in animal excreta. Seed cake
derived from cotton and rapeseed is used mostly as manure applied directly to the crop. Therefore, for estimating reuse of P from seed cake, 90% of the total production of cotton and rapeseed cake is taken arbitrarily.

Green manure crops. Recently the total hectarage of green manure crops was reduced drastically. In 1986, it was only 4.4 million ha. Since a part of the harvested green manure crops was used as fodder, which has already been counted as animal excreta, the reuse of green manure crops applied directly as organic amendments is estimated as 80%.

Quantity of phosphorus in organic wastes

The quantity of reusable P from organic waste depends upon the total weight of waste, its P content, and the extent of reuse. As shown in Table 2, the P content of human and animal feces ranges from 0.08 to 0.22%, while that of urine is only 0.004-0.06%. Since the reuse of urine is considerably lower than that of feces, the quantity of P reused from feces is much higher than that from urine, although the fresh weight of feces is markedly less than that of urine. For example, the sum of the reused P in human and animal feces was 1,047,200 t P while that in urine was only 128,480 t. Consequently, using the human and animal feces as completely as possible is of vital importance in P recycling.

From Table 3, the P from pig and cattle excreta contributed 36 and 25%, respectively, to the total P input as organic amendments; they were the most important components of P recycling.

The contribution of the other organic wastes was in the order: straw, stalks, and their ash (14%) > human excreta (13%) > seed cake (5%) > draft animal excreta (4%) > sheep excreta (3%) > green manure crops (2%). The majority of P for recycling in Chinese agriculture thus comes from farmyard manure, particularly from pig and cattle excreta. This is also true for N and K, except for the contribution of straw, stalks, and their ash to the total K input as organic amendments. The latter was 39%, which is of primary importance in meeting the need for K in agriculture.

From these data, the estimated contribution for 1986 of P in organic amendments to the total input of P by fertilizers and manures was 42%, and the recycling percentage of P was 67%. These values are intermediate between ISF (1986) estimates for 1983 and Shen’s (1985b) for 1982.

Effect of organic amendments on phosphorus nutrition

Reusing organic wastes in agriculture has several benefits. Apart from environmental concerns, it is essential for improving soil fertility by providing organic C and mineral nutrients. The application of organic amendments is favorable both for improving P reserves as a long-term effect, and for current crop nutrition, directly by providing available P and indirectly by improving P availability in the soil through solubilization or reduced fixation (Felleca et al 1983, Patrick and Mahapatra 1968, Ponnampерума 1984, Tomar et al 1986). However, because of the very low P content of straw, the effect of its application on the availability and reserve of soil P is usually not apparent (Table 7).
### Table 7. Effect of application of organic amendments on P content of soil.

<table>
<thead>
<tr>
<th>Period (yr)</th>
<th>Kind of manure</th>
<th>Total amount applied (t/ha)</th>
<th>Total P (%)</th>
<th>Olsen P (ppm)</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>6</td>
<td>Farmyard manure (from pig sties)</td>
<td>11</td>
<td>0.099</td>
<td>—</td>
<td>Wang and Zhou 1986</td>
</tr>
<tr>
<td></td>
<td>Check</td>
<td>0</td>
<td>0.066</td>
<td>—</td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>Compost (from horse excreta)</td>
<td>4.5</td>
<td>—</td>
<td>7&lt;sup&gt;a&lt;/sup&gt;</td>
<td>Zhang 1988</td>
</tr>
<tr>
<td>Wheat straw</td>
<td>Check</td>
<td>12</td>
<td>—</td>
<td>6&lt;sup&gt;a&lt;/sup&gt;</td>
<td></td>
</tr>
<tr>
<td>Rice straw</td>
<td>Check</td>
<td>12</td>
<td>0.044</td>
<td>26</td>
<td>Liu et al 1984</td>
</tr>
<tr>
<td>Wheat straw</td>
<td>Check</td>
<td>6</td>
<td>0.044</td>
<td>14</td>
<td>Liu et al 1983</td>
</tr>
<tr>
<td>Rice straw</td>
<td>Check</td>
<td>6-9</td>
<td>0.069</td>
<td>13</td>
<td>Du and Wu 1983</td>
</tr>
</tbody>
</table>

<sup>a</sup>Extracted with 0.2 N HCl.

The availability of P in organic amendments to the current crop depends mainly on its content of inorganic P and the mineralization of organic P in it during the growth period. The availability of inorganic P in animal feces is much higher than that of organic P and is comparable to that of water-soluble P (Blair and Bolland 1978, Bromfield 1961, Gracey 1984, McAuliffe and Peech 1949).

The mineralization of organic P in organic wastes differs widely, depending on the form and the percentage of P or C-to-P ratio (Bowman and Cole 1978, Tate 1984). Consequently, a net mineralization of organic P in organic wastes may occur under incubation in some cases. For instance, there was no significant net mineralization of organic P in sheep feces and straw under incubation (Bromfield 1961, Enwezor 1976, Mo et al 1979), while the mineralization of organic P in pig feces and cattle manure was apparent (Mo et al 1979, Singh et al 1981). Therefore, the availability of P in organic wastes is governed primarily by the relative proportion of organic P to the total P content. This proportion is generally not high for animal feces; it ranges from 5 to 47%, depending upon the kind of animal and forage (Bromfield 1961, Gerritse and Vriesema 1984, Mo et al 1979, Peperzak et al 1959). Thus, the overall availability of P in animal excreta may be near or below that of water-soluble P. As shown by Bromfield (1961) and McAuliffe and Peech (1949), the availability of P in 32P-labeled sheep feces to wheat and Italian ryegrass was almost equivalent to that of water-soluble P in a pot experiment. In a field experiment, the recovery of P by crops from pig manure was 12.3%, which was equivalent to 75% of that recovered from superphosphate in a rice - rice - barley cropping system (Xi and Zhou 1983).

Investigations with 32P showed that the overall availability of P in plant residues was related to its maturity (Fuller et al 1956), and the availability of P in roots of 32P-labeled white clover was similar to that in tops (Dalal 1979). Drought may
Table 8. Recovery by rice plant of P in animal manure.

<table>
<thead>
<tr>
<th>P source</th>
<th>Treatment</th>
<th>P recovery in plant (%)</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pig manure</td>
<td>98 kg P/ha applied to rice - rice - barley</td>
<td>12.3a</td>
<td>Xi and Zhou 1983</td>
</tr>
<tr>
<td>Farmyard manure</td>
<td>13 t/ha, 1st yr</td>
<td>15</td>
<td>Ito et al 1982</td>
</tr>
<tr>
<td>Farmyard manure</td>
<td>13 t/ha yr, 2d yr</td>
<td>9.5</td>
<td></td>
</tr>
<tr>
<td></td>
<td>13 t/ha yr, 3d yr</td>
<td>5.1</td>
<td></td>
</tr>
<tr>
<td>Farmyard manure</td>
<td>13 t/ha yr, 4th yr</td>
<td>6.0</td>
<td></td>
</tr>
<tr>
<td>Farmyard manure</td>
<td>2.5 t/ha</td>
<td>18</td>
<td>Inoko 1984</td>
</tr>
<tr>
<td>Farmyard manure</td>
<td>5.0</td>
<td>18</td>
<td></td>
</tr>
<tr>
<td>Farmyard manure</td>
<td>8.3</td>
<td>14</td>
<td></td>
</tr>
</tbody>
</table>

*aCumulative recovery of P in the 3 crops.

seriously reduce the recovery of P in white clover by oats; with adequate irrigation, the recovery may be high (Blair and Bolland 1978).

The recovery by rice plants of P in pig manure and farmyard manure in field experiments is shown in Table 8. In the first year of application, the recovery was around 12-18%, becoming lower with continuous application of the manure, which may be attributed to the cumulative high rate of P application to the soil.

Thus, the application of organic amendments not only is a measure for improving soil P reserves but also favors the P nutrition for the current crop, provided the total and inorganic P contents are high enough.

References cited


Recycling phosphorus in China


Notes

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Citation information: International Rice Research Institute (1990) Phosphorus requirements for sustainable agriculture in Asia and Oceania. P.O. Box 933, Manila, Philippines.
New approaches for developing and improving low-cost P fertilizers are considered, and management strategies that can improve the efficiency of P use by crops are discussed. Emphasis is on selecting soils, plants, and climates that are suitable for exploiting indigenous and low-cost, imported phosphate rock (PR); and on manufacturing techniques, such as co-granulation with S or N fertilizers and partial acidulation or composting, that increase the agronomic value of PRs as P fertilizers. Wastes from the sugar, palm oil, and rubber industries are identified as the source of approximately 73,000 t P in Asia and Oceania. This review presents a brief discussion on each subject area, with a comprehensive listing of recent research literature.

In 1982, fertilizer use accounted for approximately 70% of the energy input into agriculture in developing countries (FAO 1986). Fertilizer consumption in Asia and Oceania increased steadily from 1982 to 1986 (FAO 1987b) to meet the need for increased food production. Inevitably, where imported fertilizers or imported energy sources for fertilizer manufacture are used, the foreign exchange cost of food production will also increase.

More than 80% of costly P fertilizers will remain in the soil, strongly fixed by soil minerals. Therefore, considerable potential exists both for developing lower cost P fertilizers, particularly ones using indigenous P sources, and for increasing the efficiency with which fertilizer P is utilized by the crop. Two main approaches can help achieve these objectives:

• development and use of new P sources, including lower cost P forms with improved plant availability, high-analysis forms to reduce transport and spreading costs, and recycling of waste materials; and
• improving crop and fertilizer management to increase P use efficiency, including selection of plant species tolerant of low-P-status soils, better utilization of mycorrhizae, and improved fertilizer application techniques.

In this paper we highlight some recent developments in P fertilizer research that will allow P fertilizer costs to be reduced or P fertilizer use to become more efficient. Particular emphasis is given to technologies that allow use of less expensive imported P fertilizers, or indigenous phosphate rocks (PRs) and waste materials.
Phosphate rock for direct application

The last decade has seen renewed interest in the use of PR as a directly applied fertilizer, which can reduce the cost of P fertilizer inputs and therefore extend the use of P fertilizer where local PR sources are available. The direct application of PR is not new; in fact 60% of P fertilizer used on Malaysian estate crops is PR (Belmehdi 1987). However, much recently published research originating from the International Fertilizer Development Center in the United States and Israel (IFDC 1978), India (Kothandaraman et al 1987, Tandon 1987), New Zealand (Syers and Gregg 1981, White and Currie 1987), Australia (Bolland et al 1989), and the United Kingdom (Davies 1984) has extended our knowledge of PR usage.

Selection of phosphate rock materials and application sites

For direct application, sedimentary PRs containing carbonate apatite have the highest agronomic value (Hammond et al 1986, Khasawneh and Doll 1978). Typically, the most reactive PRs have a high degree of isomorphic substitution of phosphate by carbonate, with molar PO$_4$-to-CO$_3$ ratios <5. Although the solubility characteristics of PRs can be predicted from chemical principles (Kirk and Nye 1985, 1986b), lengthy and sophisticated analytical techniques are required first to establish their empirical formulas. Partly for this reason, rapid empirical extraction tests, using weak acids and chelating agents, have been used to characterize PR reactivity. The most useful single extraction test for predicting the agronomic value of PRs appears to be that using 2% formic acid. Formic acid extraction results correlated to agronomic data have now been reported for a wide range of PRs (Chien and Hammond 1978, MacKay et al 1984). Although this empirical test can be used to identify PRs that have potential agronomic value, much of the variation in actual agronomic value is due to the influence of soil, climate, plant, and management factors. Several recent papers, reviews, and conference proceedings summarize agronomic evaluations and factors influencing the agronomic performance of PRs (Bekele et al 1983, Bolan et al 1989, Bolland et al 1989, Hammond et al 1986, IFDC 1978, Khasawneh and Doll 1978, Luken and Blumel 1984, Syers and Gregg 1981, Tandon 1987). Some of these factors are diagrammatically represented in Figure 1.

Nye and Kirk (1987) have shown how the physicochemical principles determining the soil solution P concentration, maintained by a PR of known chemical composition, and the principles determining plant P uptake can be integrated into a model to predict the actual agronomic value of a PR. A sensitivity analysis conducted using this model (Kirk and Nye 1986c, Nye and Kirk 1987) confirms previous field and laboratory observations that soil pH (Bolan and Hedley 1989, Kanabo and Gilkes 1987), rate of soil acid generation (Apthorp et al 1987, Bekele et al 1983), and PR particle size (Kirk and Nye 1986a) have the greatest influence over the extent of PR dissolution. In addition, the density of roots in the soil and the soil P buffering capacity influence the proportion of dissolved PR-P taken up by plants. The Kirk and Nye model provides the agronomist with a tool to choose soils and PR fertilizer forms and to design agricultural production systems that have the greatest potential to take advantage of low-cost PR. For example, even in soils of neutral pH
it may be possible to apply heavy initial dressings of finely ground PR, provided that a regular rotation of a fine rooted legume (or a plant species with an alkaline uptake pattern [Bekele et al 1983]) is included to generate a low-pH rhizosphere with low Ca concentration, which will increase PR dissolution. Later the legume can be used as a green manure for a rapidly growing cereal crop for which release of PR-P would normally be too slow. If this legume rotation is a grazed pasture, then the increased N cycling and NO₃⁻ leaching loss, induced by the grazing animal, will induce more permanent soil acidity (Helyar 1976). This would favor PR dissolution. A small number of field evaluations of the Kirk and Nye model are now required, with experiments designed so that the behavior of PR and plant growth in structured field soils can be adequately modeled. Successful models of this kind would obviate the need for numerous agronomic trials in different soil types, climates, and farming systems.

**Fertilizer amendments to increase phosphate rock dissolution**

As discussed in the previous section, the agronomic performance of a PR is highly dependent upon the ability of soils and plants to supply acid. Most soils are only mildly acidic, so PR-P release is slow. This slow P release characteristic may well suit less
intensive agricultural systems such as permanent pastures but makes PR poorly suited as fertilizer for cropping systems that require a short-term, high soil P status. One way of overcoming this slow P release is to increase the acidity in the immediate environment of the PR. Only two main fertilizing agents are capable of markedly and rapidly increasing soil acidity in situ: elemental S (S$^0$) and ammonium forms of N.

**Sulfur amendments.** Much of the early research on S$^0$. PR mixtures is referenced by Swaby (1983), whose method of inoculating the mixtures with S-oxidizing microorganisms gave them the name “biosuper;” however, this name was strictly for mixtures inoculated with *Thiobacilli* spp. Most biosupers developed in Australia using S$^0$ and ground (<150 µm) unreactive PR release P too slowly to meet the requirements of fast-growing annuals and remain more suited to pastoral fertilization (Swaby 1983). Similar results were obtained on forage crops in Fiji (Partridge 1980). Bromfield (1975), however, using much finer (<75 µm) S$^0$ in a mixture with ground (<100 µm) Togolese PR, achieved on Nigerian aeolian drift soils groundnut kernels yields that were greater than those produced by single superphosphate (SSP). The finer the particle size of S$^0$, the more rapidly H$_2$SO$_4$ is generated by S oxidizers; and the finer the PR in the product, the greater is the acidulation of the PR. Effective acidulation occurs when most of the acid produced during S$^0$ oxidation acts on the PR and is not dissipated on the soil.

Whereas the original idea of adding S$^0$ or pyrites (Kothandaraman et al. 1987, Tandon 1987) was to improve the agronomic value of low-grade, unreactive PRs (Rajan 1981, Swaby 1983), in New Zealand the success of reactive phosphate rocks (RPRs) as pastoral fertilizers (Fig. 2) means that S$^0$ is required only to fulfill the S requirement of pastures and not to increase the dissolution of the RPR (Rajan 1987, Rajan and Gillingham 1986). Under these circumstances, the advantages of using S-RPR mixtures are that finely ground RPR can be granulated using molten S$^0$ as the granulating agent, and that the high-analysis S$^0$ addition does not significantly reduce the P content of the fertilizer—an important consideration for reducing transport and spreading costs. To ensure rapid granule breakdown, a swelling clay can be added to the mixture (Owers 1988) or the PR can be sparingly acidulated with H$_2$SO$_4$. Using this approach, a lowcost high-analysis SP fertilizer can be produced from local or imported RPR or PR that may not have been suitable for full acidulation.

**Nitrogen amendments.** Through the process of nitrification, NH$_4^+$-based fertilizers (or NH$_4^+$ derived from urea) provide a very rapid method of acidifying soils with active nitrifier populations. As well as providing a valuable source of N for plants, when such N forms are combined with RPRs by banding (Apthorp et al 1987), granulating (Hedley et al 1989), or compacting (Chien et al 1987b), the dissolution of RPR and the plant uptake of P are increased (Fig. 3, 4). Chien et al (1987b) provided some evidence that under high pH conditions resulting from urea hydrolysis, RPR dissolution may also be enhanced by the chelating activity of solubilized soil organic matter. More important, whereas Apthorp et al (1987) and Hedley et al (1989) found that combining either urea or (NH$_4$)$_2$SO$_4$ with RPR increased plant P uptake in soils of low and high P retention, with pH 5.3-5.8 (Fig. 3), Chien et al (1987b) showed that urea-PR produced a more positive interaction
2. Effect of time on the relative effectiveness of P fertilizers relative to triple superphosphate (TSP) at each harvest, applied annually to 19 permanent pasture trial sites in New Zealand (average data taken from Sinclair and Dyson 1988). PAPR = partially acidulated phosphate rock, SSP = single superphosphate, NCPR = North Carolina phosphate rock.

3. Effect of N form on soil pH and P uptake by lettuce grown on loamy sand fertilized with Sechura PR-N fertilizer mixtures (80 mg N and 60 mg P/500 g soil) (from Apthorp 1987).
than NH$_4$Cl-PR. Part of the decreased effect of NH$_4$Cl-N on RPR dissolution may be that nitrification is inhibited in the presence of the chloride ion (Darrah et al 1987). Care must be taken when applying NH$_4$-N fertilizers to already acid soils. Not only can they increase P sorption (Chien 1979) but they can also increase the exchangeable Al$^{3+}$ concentration, which leads to Al toxicity.

As with the addition of S$^0$ to PR, urea and (NH$_4$)$_2$SO$_4$ can act as binding agents for the granulation or compaction of finely ground PR; however, surface application of North Carolina phosphate rock (NCPR) granulated with urea can reduce the effectiveness of urea to solubilize NCPR (Fig. 4). This does not occur with (NH$_4$)$_2$SO$_4$-NCPR granules or with simple mixtures of urea-NCPR. Many N and S sources are cheaper per kilogram of nutrient than P in imported PRs. Thus, reasonably inexpensive NPS fertilizer can be manufactured. An effective blend for neutral soils may be 10:9:0:9 (N:P:K:S) using urea, finely ground RPR, and S$^0$. To avoid NH$_3$ volatilization, granules should be incorporated into the soil. Hydrolysis and nitrification of the urea-N would enhance initial RPR dissolution, followed by slower production of acidity from oxidation of S$^0$. The oxidation of S$^0$ is not inhibited severely by low soil pH (Attoe and Olsen 1966, Nor and Tabatabai 1977) and would maintain a low soil pH in the environment of the RPR for an extended period of time. More research is required to determine which blend of fertilizer produces the greatest amount of plant available P.

**Organic amendments.** The technique of composting animal manures and organic waste materials with PR—phosphocomposts—for increasing the agronomic value of PR has long been practiced (Kothandaraman et al 1987, Tandon 1987). The largest potential sources of organic wastes for composts in Asia and
Oceania are rice straw and rice husks, which presently cause disposal problems in many countries. It would be appropriate to develop composting systems (Gasser 1985) capable of turning both the rice residues and local PR materials into valuable fertilizers. Unfortunately, these lignocellulosic wastes are not rapidly decomposed (L'honeux et al 1988, Lynch and Wood 1985) and in an unaltered state do not provide effective substrates for acid-producing bacteria or fungi such as *Clostridium* sp. or *Aspergillus* sp. For example, in 10:1 rice straw:NCPR slurries with added N, Olegario (1988) observed a decrease in organic matter of only 6% under anaerobic conditions with a soil inoculum, and 23% under aerobic conditions with an *A. niger* inoculum. This resulted in 16 and 25% of the PR dissolving in the anaerobic and aerobic cultures, respectively. Chemical pretreatment of the straw (L'honeux et al 1988) or novel mixed inoculants of fungi with lignocellulase activity and anaerobic N₂-fixing bacteria (Lynch and Wood 1985) could both improve the digestibility of straws and increase their potential for acidulating PRs. More research is required in this area, which could provide cheap recycled N and a low-cost P fertilizer for rice-growing regions.

Another avenue worth pursuing is to combine these new microbiological technologies with macrobiological composting technologies of vermiculture (compost worm production [Edwards et al 1985]). The products of a successful union would be a high quality compost and a valuable protein feed for fish and poultry farming (Satchell 1983). This raises the tantalizing question: will worm activity in phosphocomposts increase PR dissolution and P availability to plants in a manner similar to that observed by MacKay et al (1983) for *Lumbricus rubellus*?

**Partially acidulated phosphorus fertilizers**

Partial rather than full acidulation of PRs (PAPRs) offers an obvious cost saving by reducing the quantity of acid used in manufacture. For H₃PO₄ acidulation, the acid can account for up to 83% of the raw material costs in triple superphosphate (TSP) manufacture (Braithwaite 1985). Even if manufacturing costs are not cut, such as in H₂SO₄ acidification for SSP production (H₂SO₄ factories are less economic when run below maximum efficiency), the product is of higher P analysis than SSP and offers savings in transport and spreading costs, provided no S fertilizer is required. Partially acidulated products can be made in three ways: by direct acidulation of PR with less than the stoichiometric amount of H₃PO₄ or H₂SO₄ required to make TSP or SSP, respectively (Braithwaite 1986), or by dry mixing SSP or TSP with unacidulated PR (Chien et al 1987a), or by adding PR to an immature SSP reaction mixture and granulating the final mixture (Bolan et al 1987, Hedley et al 1988).

Research on the agronomic effectiveness of PAPRs has been extensively reviewed by Davies (1984), Engelstad and Terman (1980), Garbouchev (1981), Gregg et al (1988), Hagin (1985), Hammond et al (1986), Marwaha (1983), and Stephen and Condron (1986). The important information presented in these reviews is that in many agronomic situations, mixtures of water-soluble and -insoluble P not only provide a more cost-effective way of utilizing PR but can also produce yields equal to or higher than those with fully acidulated SSP or TSP (Mishra et al 1987). Partially acidulated P fertilizers have successfully found two particular niches.
Low-cost improvement of the agronomic value of phosphate rock

This technology has been most extensively researched (IFDC 1985, 1986) and reviewed (Hammond et al 1986) for agriculture in tropical regions. The benefit of using PAPR instead of the direct use of a local indigenous PR is that some P is supplied in soluble P form, which can be utilized by short-season crops and stimulates earlier shoot and root growth that may lead to greater utilization of the PR residue. For products of this type, $\text{H}_2\text{SO}_4$ acidulation is often the most economic and also provides a valuable S supply. Cogranulation of PAPRs with $\text{SO}_4^2-$ can improve their agronomic value, presumably by enhancing the dissolution of the PR residue through S oxidation (Friesen et al 1987). The agronomic evaluation of this type of product is reviewed by Chien et al (1990).

Cost-competitive high-phosphorus fertilizers

The objective of recent research into PAPRs made from finely ground (100%, <150 µm) RPRs is to develop suitable replacements for SSP or TSP. Products made by 30% $\text{H}_3\text{PO}_4$ acidulation have proved to be suitable fertilizers for permanent pasture and forage crops (Garbouchev 1981, Hагин and Katz 1985, Rajan 1985, Rajan and Quin 1985) and in some cases were suitable long-term P fertilizers for cereals and sugar beet (Hагин 1985) in previously fertilized soils. In glasshouse trials (Rajan 1986) and other situations that place a high P demand on short-term P supply from fertilizer rather than the soil (Buwalda et al 1987, Stephen and Condron 1986), the agronomic effectiveness of PAPR can be directly related to the level of PR acidulation. In soils with an actively cycling pool of P, however—such as temperate, highly productive grasslands—these partially acidulated forms of P fertilizer are proving to be at least as effective as SSP and TSP. For example, average data prepared from a report (Sinclair and Dyson 1988) on the national series of P trials conducted by the New Zealand Ministry of Agriculture and Fisheries on 19 permanent pasture sites show that for all 4 yr of the trial, finely ground NCPR acidulated to 30% with $\text{H}_3\text{PO}_4$ was as effective as TSP. Even a fertilizer made from a 50:50 mixture of SSP and unground NCPR (SSP-NCPR) produced yields similar to (p <0.05) those with SSP and TSP. In the fourth year, however, this mixture was less effective than the PAPR made from finely ground NCPR (Fig. 2). In these pastoral conditions the relative agronomic effectiveness of directly applied unground NCPR increases with each annual application, until after 4 yr the rate of P supply to plants presumably equals that of TSP and the other acidulated fertilizers.

Mixtures of soluble P and RPR offer relatively cheap, effective, long-term fertilizers for crops, particularly for permanent pastures, where the continuous recycling of P in animal excreta reduces the demand for the fertilizer material to exhibit fast P-release characteristics.

New soluble phosphates and polyphosphates

The development of new forms of soluble P fertilizer has mainly been directed towards large-scale mechanized crop production in North America (Mann and Sample 1988, Young et al 1985). Emphasis has been on the increased production of
high-analysis liquid (TVA 1984), suspension, and solid fertilizers such as fluid ammonium polyphosphates and, more recently, urea phosphates. Although liquid and suspension fertilizers are ideal for reducing handling costs and improving the efficiency of fertilizer use by accurate placement, they better suit the scale of agriculture, the manufacturing cost structures, and the transport systems of a developed country than those of a developing country. Traditionally, considerable quantities of diammonium phosphate (DAP) and TSP have been both produced in and imported by the Asian and Pacific countries (Belmehdi 1987, FAO 1987b). DAP is one of the major fertilizers used for cereal production, mainly because it is produced widely, is relatively cheap to import, and serves as an important N source. With urea costs continuing to fall, urea-P is likely to become more available in the region. Urea ammonium phosphates have been manufactured in India for a number of years (Tandon 1987). An advantage of urea-P over directly applied urea is that, with the former, less NH₃ volatilization occurs from surface-applied granules (Young et al 1985).

**Phosphorus fertilizers from wastes**

Agricultural wastes are generally well utilized for their fertilizer value because of their proximity to the farm. However, much improvement can be made in the way that municipal and industrial wastes are utilized. Most wastes have inherent nutrient value, and if processed correctly can be used to increase crop yields. Large-volume wastes in Asia and Oceania that can be considered important for their P content are sewage sludge and wastes from the sugar, palm oil, and rubber industries.

**Sewage sludge**

Each inhabitant produces approximately 800 kg of sewage sludge (95% water) per year, with some variations between countries (Kofoed et al 1986). Raw sludge contains pathogens and should not be applied directly to agricultural soils (Walker 1975). To obtain high fertilizer value, sludge should be treated anaerobically or aerobically and dewatered by centrifuging, vacuum filtration, or sludge drying beds. Depending upon the pretreatment, sewage sludge P and N contents vary from 0.06 to 0.48C%, and from 0.17 to 1.5%, respectively (Kofoed et al 1986). The P content of sludge has increased with the increased use of household detergents. Most of the P in sewage sludges is present as inorganic Ca, Fe, Al, and Mg phosphate, depending on the process used in the treatment plants (Kirkham 1982).

Most sludges contain P that is 50% as as available to plants as that in monocalcium phosphate, but this varies according to treatment method (Hall and Williams 1983). Application of sewage sludge at 25 t/ha increased the yields of soybean and maize (Giordano et al 1975, Hinesly et al 1979, Walker 1975). Digested sludge can be applied to soils by irrigation using rain guns, injection (Kofoed et al 1986), or trenching (Reed 1973). Dewatered sludge can be surface-spread and plowed in. Composting the sewage sludge by mixing N with wood chips (1 part sludge and 3 parts chips) can increase its solid content to 65% and make it easier to handle.
Filter cake from sugar refineries
Sugarcane production in Asia and Oceania is increasing (FAO 1987a), and filter cake, the residue produced when mixed cane juice is clarified, is an effective P fertilizer for sugarcane and lowland rice (Chanchareonsook et al 1988; Prasad 1976a,b). Filter cake is variable in moisture and nutrient content but can be expected to contain 1-2% N, 0.5-2.4% P, 0.4-0.5% K, and 2-3% Ca and has a pH of 7.5-9.0. Asia and Oceania produce approximately 9 million t of filter cake annually, giving a potential of approximately 69,000 t P (Table 1). Filter cake and a similar product from the sugar beet industry have been used as soil amendments for many years; however, the maximum fertilizer value of these materials can be gained from heavy dressings (up to 20 t/ha) applied to acid soils with high P sorption capacities. In Thailand, it has proved to be a very effective fertilizer for rice grown on acid sulfate soils (Chanchareonsook et al 1988); as a P source for pot-grown lowland rice, filter cake was as effective as KH₂PO₄, TSP, and PRs under conditions where the efficiency of fertilizer P recovery by the plant was 14-165.

Palm oil mill and rubber factory effluents
Palm oil and rubber are produced extensively in Malaysia and Indonesia, the two industries in Malaysia alone producing approximately 9 and 36 million t of effluent, respectively (John 1981, PORIM 1981). Waste from palm oil mills includes empty bunches, fiber, shell, sterilizer condensate, hydrocyclone waste, and centrifugal/separator waste. The empty bunches, fiber, and shell are recycled as fuel in the mills, and the remaining three wastes constitute the bulk of the palm oil mill effluent (POME) (Yeow 1983). Similar effluents originate from rubber factories (John 1981). The biological oxygen demand of the effluents is normally reduced by aerobic or anaerobic digestion in tanks or in “facultative” ponds (Maheswaran 1982, Yeow 1983). Depending upon the type of treatment, the P content of the effluents from palm oil mills varies from 12 ppm in the supernatant to 1,180 ppm in the bottom slurry; the effluent from rubber processing varies from 48 to 81 ppm (Chan et al 1983b). It has been estimated that the annual amounts of P in POME and rubber

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<th>Table 1. Potential amounts of P available from sugarcane filter cake, and effluents from the palm oil and rubber industries.</th>
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⁸1 kg of raw sugar produces 0.38 kg filter cake; 1 kg oil palm, 2.5 kg effluent; and 1 kg rubber, 25 kg effluent. The P concentration is 1.2%, 120 ppm, and 20 ppm, respectively.
effluents discharged from factories in Malaysia alone are equivalent to 10,266 and 5,333 t, respectively, of Christmas Island PR.

The raw or digested POME, both in slurry and liquid forms, can be applied directly to plantations by sprinkler, furrows, or tanker (Chan et al. 1983a, Yeow 1983). Application of POME and rubber effluents gave positive yield responses with oil palm, cacao, grasses, maize, and vegetables (Chan et al. 1980, Yeow and Singh 1983). Application of 540 liters POME/palm tree per yr increased the fresh fruit bunch yield of oil palm by 10%; application of mixed concentrate latex rubber effluent increased yield by 24% (Nazeeb et al. 1983).

In all, Asia and Oceania have approximately 1,900 t P/yr available each from the rubber and oil palm industries (Table 1). From the sugarcane industry, 73,000 t P/yr is available; by FAO (1987b) statistics, that is equivalent to 50% of the fertilizer P imported into Asia.

Management strategies to increase phosphorus use efficiency

The development and selection of suitable P fertilizers for particular soils provide the basis for improving P fertilizer use efficiency. In many situations, however, the nature of animal, crop, and soil management techniques may have a greater influence on the economic value of the fertilizer.

Selection of phosphorus-efficient plant species

For many years, efforts have been focused on making soils suitable for plant growth by applying various soil amendments. Recently, more emphasis has been placed on adapting plants to the soil conditions by selecting alternative plant species or by genetically improving existing species. Plants vary widely in their ability to survive and grow in soils of low P status (Barber 1980). Three root attributes may explain the differential ability of plants to absorb P from soils: 1) ability to explore the soil volume, 2) ability to absorb P from low soil solution concentrations, and 3) physiological activity resulting in solubilization of soil P. For example, grass species are more efficient than legumes in absorbing P from low-P-status soils because of the large total length of fine root associated with grasses rather than the rate of P absorption per unit root length (Fig. 5). Similarly, varietal differences in P uptake have been observed for many plant species such as rice (Gopalakrishna Pillai et al. 1984), wheat (Saggar et al. 1974), barley (Nielsen and Schjorring 1983), maize (Nielsen and Barber 1978), and white clover (Caradus 1980). Species differences in P uptake characteristics can be used to selectively introduce plants with greater P uptake efficiencies into soils of low P status to be fertilized with PR (Bekele et al. 1983). Varietal differences induced by genetic manipulation can be used in a similar manner.

Mycorrhizal association

During the last decade, it was established that both ectomycorrhizal and vesicular-arbuscular mycorrhizal (VAM) fungi increase the plant uptake of P from low-P-status soils (Gianinazzi-Pearson 1986, Tinker 1978). Various mechanisms have been suggested for the increased uptake of P by mycorrhizal plants (Bolan et al. 1984),
Dry weight at low P concentration as percentage of dry weight at high P concentration of grasses and legumes grown in solution culture (after Caradus 1980).

There are two main approaches to the utilization of mycorrhizae (Abbott and Robson 1982). The more practical approach is the efficient use of indigenous mycorrhizal fungi in the soil. The efficiency of this indigenous population can be increased by proper management, such as use of selective fungicides that are not detrimental to mycorrhizal fungi, growing plants that respond to the indigenous fungi, and maintaining a stable level of soil P by applying PR. The second approach involves selection of P-efficient fungi, their mass production, and inoculation of plants. The inability to culture VAM fungi axenically, however, has limited the mass production of inocula. Recently a method has been developed to cultivate VAM fungi in root organ cultures derived from roots infected with tumor (callus)-inducing plasmids (Mugnier et al 1986). This method has the potential to mass produce VAM fungi and has the advantage of conserving the ability of the fungi to colonize plant roots, a property that might be lost in axenic culture. In soils with indigenous mycorrhizal fungi, the probability of inoculated strains surviving in the soil and forming successful associations with roots may be low, but in soil materials that are subjected to sterilization, such as horticultural nursery soils and mine spoils, inoculation of mycorrhizal fungi is essential and has proven profitable.

**Fertilizer application techniques in general**
Changes both in form of fertilizer materials, such as the introduction of liquid fertilizers, and in farm operations, such as reduced tillage, have resulted in new
New approaches to phosphorus fertilization

methods of fertilizer placement, reviewed by Murphy and Dibb (1986), Randall and Hoeft (1986), and Tandon (1986). In general, fertilizer placement has three objectives: 1) to increase the efficiency of fertilizer use by plants, 2) to reduce the cost of application, and 3) to prevent plant injury by fertilizers. In the case of P fertilizers, fixation and immobilization in soil reduce plant recovery of added P to 10-20%. Consequently, application methods that reduce the length of soil-fertilizer contact time and the volume of soil in contact with soluble P fertilizer should be adopted, e.g., placement at seeding and using point application (banding, injection, or fertigation). However, for poorly soluble fertilizers, such as PRs, contact time and the volume of soil in contact with fertilizer should be increased to increase dissolution. Thus, whereas band placement is recommended for soluble fertilizers, broadcasting and soil incorporation are normally recommended for poorly soluble fertilizers. In soils with high P sorption capacity, however, long contact time can also reduce the availability of PR-P. Similarly, P is not generally recommended for application by drip-irrigators (fertigation), because strong adsorption by soils restricts the movement of P away from the point of application.

Progress with fertilizer application techniques has been made in three areas: 1) application of liquid fertilizer (Beaton and Murphy 1988, Murphy and Dibb 1986), 2) application of animal slurries and slaughterhouse effluents (Kofoed et al 1986), and 3) application under reduced tillage conditions (TVA 1984). In the case of liquid fertilizers, a newly developed point injection technique employs a wheel spoke to inject fluids or gases to a depth of 10-13 cm in the soil. This technique has the following advantages: 1) fertilizer can be placed close to the seed or growing plant with minimal damage to the roots, and 2) in reduced tillage systems, fertilizer can be injected through the crop residues (TVA 1984). In the case of animal manure, techniques have been developed to inject the slurry into the soil (Kofoed et al 1986). Injection overcomes the problems of noxious odors and reduction of the palatability of the plant produce. Shallow injection of slurries reduces NH$_3$ loss by volatilization while conserving nutrients in the root zone.

**Increasing accessibility of information on fertilizer requirements**

Promoting relatively inexpensive soil and herbage testing procedures to predict fertilizer requirements is likely to provide the most immediate rewards in terms of improving the productivity and profitability of both low- and high-profit margin agricultural enterprises. The principles of relating soil test information and fertilizer application rate to predicted yield have been discussed by Greenwood et al (1980) and in earlier papers referenced therein. Other aspects of this subject area are covered by Cornforth and Sorn-srivichai (1990). With the increased availability of personal computers, a major contribution could be made if agronomists and computer programmers could integrate soil, plant, climate, fertilizer, and management data to produce user-friendly, interactive, expert systems for predicting crop nutrient requirements. In such systems, simple questions, posed to a regional agricultural advisor, about fertilizer availability and costs, farming practice, soils, crop production, and climate could provide estimates of parameters to run more sophisticated computer models that would predict the quantities and types of fertilizer material to use and when and how to apply it. In this way, fertilizer and crop response knowledge could be transferred to
a general agricultural advisor without lengthy teaching of the principles involved. In larger scale farming systems, human input might be required only at the data input stage; for example, Luellen (1985) reported the development of highly sophisticated application techniques for large-scale farms. Spatial variations in soil type and soil test data are used by a computer to control the application rates of up to six dry fertilizer products at once from a single large boom applicator. The applicator can cover 1 ha/min. While the machinery is not readily transferable to rice production in Asia or pastoral farming in New Zealand, the principle of extending the use of soil information for customizing and improving fertilizer use efficiency is.

Conclusions

With the continued increase in fertilization costs, the principal aim is to maintain or increase crop yields while reducing the fertilizer cost-to-crop yield ratio. This involves increasing not only the efficiency of fertilizer and soil P use by plants but also the use of local P sources, such as indigenous PR materials, as well as improved recycling of waste materials. We have identified some specific areas where improvements can be made:

- selection of soils, farming systems, and fertilizer amendments that increase the agronomic value of low-cost PR materials;
- improved methods for recycling municipal and industrial wastes;
- selection and introduction of plant species that exhibit efficient P uptake in soils of low P status; and
- increased accessibility to general agricultural advisors of methods of predicting fertilizer requirements.

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Hedley et al


IFDC—International Fertilizer Development Center (1978) Seminar on phosphate rock for direct application. Haifa, Israel. Jointly sponsored by Israel Fertilizer Research Center (IFRC) and International Fertilizer Development Center (IFDC), Muscle Shoals, Alabama, USA. 463 p.


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Acknowledgments: We are grateful to S. Rajapakse for help with the section on mycorrhizae and indebted to the following for assistance in sourcing some of the literature: J.D. Beaton, S.H. Chien, D.P. Day, M.L. Griere, J. Jung, T.S. Manickam, L.S. Murphy, E.C. Sample, A.N. Sharpley, J.W.B. Stewart, H.L.S. Tandom, and A.G. Vaes.

Citation information: International Rice Research Institute (1990) Phosphorus requirements for sustainable agriculture in Asia and Oceania. P.O. Box 933, Manila, Philippines.
Comparison of the effectiveness of phosphorus fertilizer products

S.H. CHIEN, P.W.G. SALE, AND L.L. HAMMOND

Phosphorus is critically needed to improve soil fertility for crop production in a large area of Asia and Oceania. In recent years, some nonconventional P fertilizers such as phosphate rock and partially acidulated phosphate rock have been tested as potential alternatives to conventional, water-soluble P fertilizers like single superphosphate and triple superphosphate. This paper discusses the agronomic results of experiments to compare the relative agronomic effectiveness of various P fertilizer products as influenced by four important factors: fertilizer properties, soil properties, management practices, and crop species. Water solubility is not the only criterion in selecting the most suitable P fertilizer. Under certain conditions, nonconventional P fertilizers can be agronomically effective.

Phosphorus is one of the macronutrients essential to plant growth. Although plants contain considerably less P than N, P is needed for energy production and transfer in young, rapidly growing plants. Many agricultural soils in Asia and Oceania are low in both total and available P. Use of P fertilizers is thus essential to successful crop production. This paper presents, discusses, and compares the agronomic results obtained with various P fertilizer products varying widely in solubility and in agronomic effectiveness. Additional information on this topic is also reviewed by Hedley et al (1990).

Sources and properties of phosphorus fertilizers

The effectiveness of a P fertilizer for a particular crop depends on its capacity to provide the crop with P over and above that which the plant can get from the unfertilized soil and at a rate to meet the crop’s requirement for optimum growth. Phosphorus forms that are water soluble release a large proportion of their P immediately upon wetting, although a significant portion of Ca-P fertilizers will revert to less soluble forms (Lindsay and Stephenson 1959). Phosphorus forms that are insoluble in water but soluble in neutral ammonium citrate generally become available to plants during the crop growing season, depending on soil factors (Hammond et al 1986b). An indication of the rate at which a fertilizer can release P is therefore its solubility in water or in neutral ammonium citrate. The following classification of existing P fertilizers is based on their respective solubilities in these solutions.
Water-soluble phosphorus fertilizers

The two major groups of solid P fertilizers in which all the P is water soluble (or almost so) are the soluble Ca-phosphates or -superphosphates and the various types of NH$_4^+$-phosphates. The superphosphates are prepared by mixing phosphate rock (PR) with H$_2$SO$_4$ or H$_3$PO$_4$ or a combination of the two. When H$_2$SO$_4$ is used, the resulting product is single superphosphate (SSP), which consists essentially of a mixture of monocalcium phosphate and gypsum. The gypsum component is most beneficial when S is required for optimum plant growth. However, gypsum results in a lower grade P (7-9.5% P). When H$_3$PO$_4$ is used instead of H$_2$SO$_4$, the product is triple superphosphate (TSP), which has 19-23% P. Not surprisingly, there has been a worldwide trend away from the use of low-grade SSP and toward the more concentrated TSP.

Because N is the major limiting nutrient for nonlegume crops, there is much merit in manufacturing fertilizers containing both N and P. This can be achieved effectively by reacting NH$_3$ with H$_3$PO$_4$ to produce NH$_4^+$-phosphates that are almost completely water soluble. These materials are now the most popular P fertilizers worldwide because of their high analysis (20-24% P) and good physical properties (IFDC 1979). The mole ratio of NH$_3$ to acid determines whether monoammonium phosphate (MAP, 12% N) or diammonium phosphate (DAP, 19% N) will be produced.

Partially water-soluble phosphorus fertilizers

Partially water-soluble P fertilizers may be citrate-soluble or partially citrate-soluble.

**Citrate-soluble.** There are two approaches to producing NP fertilizers in which the P fraction is insoluble in water but soluble in neutral ammonium citrate. The first approach is to react anhydrous or aqua NH$_3$ with SSP or TSP. Ammoniation of superphosphate offers the prospect of incorporating urea into the product to overcome the incompatibility of superphosphate and urea for bulk blending. But it results in the formation of some water-insoluble P (50-65% of total P) in the fertilizer. Furthermore, the amounts of N that can be incorporated are minimal (2-6% N). The second approach to producing NP fertilizers is to acidulate PR with HNO$_3$ to produce nitrophosphates (14-28% N, 6-12% P). One of the problems with this process is formation of calcium nitrate, which is undesirable because of its objectionable hygroscopicity, and because its presence leads to the reversion of soluble P to the water-insoluble dicalcium phosphate (DCP). By removing the calcium nitrate, it is possible to produce materials in which 80% of the P is water soluble.

**Partially citrate-soluble.** Phosphorus fertilizers that contain a mixture of citrate-insoluble, citrate-soluble but water-insoluble, and water-soluble P forms can be produced by mixing acidulated superphosphates and unreacted PR. The same effect can be achieved by acidulating PR with less than the stoichiometric amount of H$_2$SO$_4$ or H$_3$PO$_4$ required to produce fully acidulated SSP or TSP, respectively. The benefit from the partial acidulation approach is the savings from using less acid; the disadvantage is the lower water and citrate solubility in the product. Partially acidulated phosphate rocks (PAPRs) based on H$_2$SO$_4$ use the cheaper acid, and the resultant products also
contain S at a P-S ratio more appropriate to crop requirements; however, their P grade and water solubility are substantially less than in H$_3$PO$_4$-based PAPRs (Schultz 1986).

**Water-insoluble phosphorus fertilizers**

Water-insoluble P fertilizers may likewise be citrate-soluble or partially citrate-soluble.

*Citrate-soluble.* Another group of P fertilizers are those that are essentially insoluble in water, yet are substantially soluble in neutral ammonium citrate. These include the heat-treated phosphates such as defluorinated (9% P), Rhenania (12-14% P), and Ca-Mg phosphates (10% P) in which the crystal structure of the apatite has been destroyed when it was fused with added silica compounds, sodium carbonate, or serpentine minerals at around 1,500 °C. Basic slag (4-6% P), a by-product of the open-hearth method of making steel from pig iron, and calcined aluminum phosphates (13-15%) have similar solubility characteristics, although the temperature of calcination (400-600 °C) for the latter group is considerably lower. Dicalcium phosphate (21% P) is water-insoluble but citrate-soluble. It can be produced by acidulating PR with HCl and adding limestone and slaked lime or by using HNO$_3$ with ammoniation and carbonation steps (Tisdale et al 1985). An alternative approach is to use sulfonic acid, which is prepared from water, SO$_2$, and acetone (Ralph 1984).

*Partially citrate-soluble.* The P sources that have the lowest P solubility are the untreated PRs, which are insoluble in water. They need to be finely ground and mixed into the soil to be effective. Another key factor determining the effectiveness of direct applications of PR is the chemical reactivity of the apatite in PR, which is directly related to the degree of substitution of phosphate by carbonate in the apatite structure (Hammond et al 1986b). As a result of this substitution, the apatite matrix has a finer crystallite size, which contributes to increased citrate solubility (Chien and Hammond 1978).

**Factors influencing effectiveness of various phosphorus fertilizers**

Four important factors influence the relative agronomic effectiveness (RAE) of various P fertilizers: fertilizer properties, soil properties, management practices, and crop species. Because of the voluminous literature on this topic, the agronomic data presented in this paper are extracted only from experiments conducted either in Asia and Oceania or in greenhouses at the headquarters of the International Fertilizer Development Center in Alabama, USA.

**Fertilizer properties**

The most important property of P fertilizers in relation to agronomic performance is solubility, which is normally measured by water or citrate solution. It is difficult to compare crop responses to P fertilizers in relation to the solubility of the fertilizers because of the interactions between fertilizer and soil. Therefore, it is difficult to
predict RAE of P fertilizers based on their solubility. For instance, finely ground PR can be as effective as water-soluble P fertilizers or inferior to them, depending on the PR source (Fig. 1). In this example, the citrate-soluble P contents of North Carolina, Jordan, and Togo PRs were 3.9, 2.7, and 1.7%, respectively. The importance of the citrate solubility of PR for grain yield of flooded rice was also reported by Engelstad et al (1974) in Thailand.

Several field trials on PAPR in India during 1984-85 used locally available Mussoorie PR (Hammond et al 1986b). In all crops studied, there were no significant yield differences due to applications of TSP and PAPR produced from Mussoorie PR at 50% acidulation level with H$_2$SO$_4$ and the low reactivity of the finely ground PR made it less effective than TSP.

According to Tandon (1987), SSP, TSP, MAP, DAP, urea-ammonium phosphates, ammonium phosphate sulfates, and other NP and NPK complexes, excluding nitrophosphates being produced in India at present, are classified as fertilizers containing mostly water-soluble P. Such materials are generally considered to be agronomically equivalent sources of P, and any differences in their performance are usually ignored or not attributed to P nutrition. When nitrophosphate containing 30% of total P in water-soluble form was used on wheat in alluvial neutral-alkaline soils (pH 7.6-8.5) in India, its performance ranged from 82 to 96% of that of water-soluble P fertilizers (e.g., SSP, TSP, DAP) (Tandon 1987). However, in a millet - wheat rotation trial on an alkaline sandy loam soil (pH 8.3, Chahel (1982) found that grain yields increased with increasing amounts of water-soluble P applied from nitrophosphates, and thus the effectiveness of nitrophosphates followed the water solubility of 80 > 50 > 30%. In Punjab, India, Hundal et al (1977) reported that the RAE of various P fertilizers in a rice - wheat sequence on a clay loam (pH 7.1) followed the order of urea ammonium

1. Maize dry matter yield obtained with various P fertilizers on Hartsells silt loam (pH 4.8).
Effectiveness of phosphorus products

Phosphate = 100%; SSP = 98%; nitrophosphates with 70, 50, and 30% water solubility = 90, 80, and 65%, respectively; and Jordan PR = 50%.

In New Zealand, DCP and SSP were equally effective in increasing the dry matter yield of ryegrass-clover pasture on a soil with pH 5.5 (MacKay et al. 1980). In soils with low available P, the degree of acidulation required for PAPR to be as effective as TSP was 50% H₃PO₄, whereas in soils with high levels of available P, even PAPR-30% H₃PO₄ applied as a maintenance fertilizer for pasture production was as effective as TSP (Rajan 1986). For subterranean clover in western Australia (Bolland 1987), the initial and residual values of P from calcined Christmas Island (C-grade) PR and Duchess (Queensland) PR were very low with respect to SSP and TSP in a 6-yr trial on a lateritic gravelly loam (pH 5.9). The poor performance of the two PRs was due mainly to their low reactivity.

In Zhejiang Province, eastern China, locally produced PAPR-50% H₂SO₄ and Ca-Mg phosphate were equally effective in increasing crop yields (maize, rice, wheat, and sweet potato) in three acid red soils (Ho Nian Zu, Zhejiang Agricultural University, 1987, pers. comm.). In this study, only 40% of the total P in PAPR-50% H₂SO₄ was water-soluble, and 12% was citrate-soluble. This again suggests that water solubility is not the only property that determines RAE of P fertilizer.

**Soil properties**

The soil properties that have the greatest influence on RAE of various P fertilizers are soil pH, P-fixing capacity, and organic matter (OM) content. The influence of soil pH on the effectiveness of various PRs with respect to TSP for flooded rice is shown in Figure 2. Soil pH had little effect on rice response to TSP; however, the effectiveness of PRs greatly depended on soil pH. At pH 4.6, flooded rice responded to PRs, the

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2. Rice grain yields obtained with TSP and various PRs under field conditions in Thailand and India (Engelstad et al. 1974).
degree of response depending on the PR’s reactivity. At pH 8.0, however, all PRs were ineffective and did not differ from the check in grain yield produced.

Early workers (McLean and Logan 1970, McLean and Wheeler 1964) with PAPR hypothesized that it would be as effective as or sometimes better than superphosphates on acid soils possessing high P-fixing capacity. A recent greenhouse study (Chien and Hammond 1988) that compared RAE of PAPR with respect to SSP in increasing dry matter yield of maize confirmed that hypothesis (Fig. 3). Regression analysis showed PAPR and SSP to be equally effective in soil with a P-fixing capacity of 27.6%. (Figure 3 does not represent absolute fixation, but rather the percentage of P fixed at a specific rate of P application. It is therefore rate-dependent. The methodology has been described by Fassbender and Igue [1967].)

Work done by Harris (1985) in the Philippines and Indonesia showed that RAE of water-insoluble P fertilizers such as PRs with respect to SSP or TSP was higher in an acid soil with low P-fixing capacity (Typic Paleudult) than in a soil with high P-fixing capacity (Hydric Dystrandept) (Fig. 4). For the first crops on the two soils, large differences in yield between sources were evident on the Dystrandept in the order of fused Mg-P > SSP = North Carolina PR > central Florida PR, whereas there were no significant differences between TSP and PRs on the Paleudult. This indicates that soil properties can overcome the effect of fertilizer solubility. Field data reported by Hammond and Leon (1983) also indicate that finely ground low-reactivity PRs (Pesca and Huila in Colombia) applied to Latin American Oxisols and Ultisols were relatively more effective with respect to TSP than the same PR sources applied to Andepts, which exhibited significantly higher P-fixing capacity than did the Oxisols and Ultisols. Hammond et al (1986a) suggested that, because the P concentration initially released during PR dissolution was low, rapid development of the plant was not promoted, as it was with a soluble form of P. Additionally, P entering the soil solution from the PR

3. Relative agronomic effectiveness (RAE) of PAPR-50% H₂SO₄ prepared from Pesca PR (Colombia) with respect to SSP in increasing dry matter yield of maize as influenced by soil P-fixing capacity (Chien and Hammond 1988).
was equally susceptible to reaction with the soil to form compounds unavailable to plants. Thus, the initial P availability from low-reactivity PRs directly applied may decrease more rapidly than that from soluble P sources as soil P-fixing capacity increases.

The influence of soil OM on the effectiveness of PR relative to TSP can be seen in data from a pot trial (Fig. 5). In this study, both soils (Mountview and Hartsells) were classified as Ultisols and had approximately the same soil pH (4.8), exchangeable Ca, and P-fixing capacity. The Hartsells soil, however, had a much higher OM content (4.2%) than did the Mountview soil (1.8%). The better performance of PR with respect to TSP in the Hartsells soil than in the Mountview soil may be attributed to the formation of soil OM complexes with Ca$^{2+}$, which would enhance the dissolution of PR (Chien 1979, Chien et al. 1987).
Management practices

The management practices used in fertilizer application can also influence RAE of water-insoluble P sources with respect to SSP and TSP. The two most important factors in this regard are method of placement and time of application.

In a greenhouse study (D. Degufue, IFDC, 1985, pers. comm.), the response of flooded rice to TSP was found to be little influenced by placement method. Grain yield response was about the same to broadcast and incorporated TSP as to deep-placed TSP. Deep placement of urea supergranules containing DAP was also found to be as effective as broadcast and incorporation of TSP or DAP in terms of P availability to flooded rice (Savant and Chien, IFDC, 1988, unpubl. data). The effectiveness of North Carolina PR, however, was greatly influenced by placement method. The PR, when broadcast and incorporated, was found to be as good as TSP in increasing rice grain yield, whereas it was less effective than TSP when deep placed (D. Degufue, IFDC, 1988, pers. comm.). Thus, to be most effective for flooded rice, PR should be broadcast and incorporated.

A practice often recommended with the use of finely ground PR for direct application to an acid soil is to apply the PR at least 1 mo before planting (Ellis et al 1955). This allows more time for PR dissolution. This practice, however, may not be warranted in acid tropical soils with high P-fixing capacity. Figure 6 shows that the effectiveness of North Carolina PR was the same whether the PR was applied at planting or 6 wk before planting in a soil (Lawrenceburg) with low P-fixing capacity. But in a soil (Hartsells) with high P-fixing capacity, the effectiveness of PR was reduced when it was applied 6 wk before planting. Similar results were obtained in Latin American soils under field conditions (Hammond et al 1986b).

Crop species

The usefulness of P fertilizers with different degrees of solubility may vary with the crop species. In general, RAE of water-insoluble P sources (e.g., PRs) with respect to water-soluble P sources (e.g., SSP and TSP) would be higher for long-term or
perennial crops (e.g., pastures, rubber, oil palm, tea, fruits) than for short-term or annual food crops (e.g., rice, maize, millet). In fact, PRs have been used extensively for tree crops in Asia, particularly for rubber in Malaysia.

Khasawneh and Sample (1979) suggested that the concentration of soil solution P required by cowpea for maximum growth potential may be only two-thirds the concentration required by maize. Thus, RAE of PRs would be higher for crops with lower P demands, such as legume crops, than for cereal crops. Flach et al. (1987) reported that the mobilizing capacity of three cereal crops on several PRs increased in the order of maize < pearl millet < finger millet. It was reasoned that a comparatively high Ca uptake capacity, and not an alkaline uptake pattern, was responsible for the high P-feeding capacity of finger millet.

Figure 7 shows the effectiveness of Sechura PR relative to TSP on the same soil (Mountview silt loam, pH 4.8) with five different crops. The Sechura PR was less effective than TSP, for wheat and maize, but bas as good as TSP for ryegrass. The efficient use of PR by ryegrass was probably due to its high rooting density. Upland rice was more effective than flooded rice in using PR, probably because of the soil pH effect. The PR was applied to the flooded soil at transplanting, after the soil had been flooded for 2 wk. This preflooding practice resulted in an increase in soil pH, which reduced PR dissolution.

Methods used for comparing fertilizer effectiveness

A major problem encountered in the methodology for comparing RAEs of various P fertilizers is the fact that their yield response curves are usually nonlinear and often do not share a common limiting yield.
Three contrasting approaches described in the literature are used for evaluating the effectiveness of P fertilizers. In such evaluations, the fertilizer of interest (e.g., PR or PAPR) is usually evaluated against a standard product (e.g., SSP or TSP). All three approaches attempt to measure the relative effectiveness or RAE index of the test fertilizer, the definition of which may depend on the method used for its determination as discussed in qualitative (i.e., descriptive) terms in this section.

**The vertical comparison**

One approach defines the RAE index as the ratio of the yield response with the test fertilizer (yield with fertilizer less yield of control) to the yield response with the reference fertilizer at the same fertilizer rate (Chien and Hammond 1978, Terman and Engelstad 1976). This index therefore provides a “vertical comparison” of yields at the same fertilizer rate on a yield response curve. The method is attractive because of the ease of calculating RAE: one has only to record the yields, subtract the control yield, and divide the test fertilizer yield response by that for the reference fertilizer. The disadvantage of this approach is that the RAE values are usually not constant but instead vary with P rate. The value obtained therefore depends on the P rates chosen by the researcher. To overcome this, a mean RAE value is determined for the range...
of rates applied (Engelstad et al. 1974). However, the number of fertilizer rates is often restricted to one or possibly two plus the control. Thus, the results of vertical comparison can be misleading if the effect of P rates is not taken into account.

Alternatively, if a suitable response function with a one-term coefficient for the independent variable (i.e., P rate) can be found to fit the experimental data, then the ratio of the two fitted coefficients obtained with the test and the standard P fertilizers can be used to represent the RAE index of the test P fertilizer. For example, Leon et al. (1986) used a semilog response function for TSP and various PRs. The advantage of using the ratio of two regression coefficients to express the RAE index is that the ratio is independent of rates of P applied. The disadvantage of this method is that the same response function sometimes may not be suitable for all P sources studied in the same experiment.

**The horizontal comparison**

Another approach to comparing RE of two P fertilizers is to define the RAE index in terms of the levels of applied fertilizers that give the same yield in the responsive region of the curve (Palmer et al. 1979, Terman and Engelstad 1976). The RAE index is calculated by dividing the rate of the reference fertilizer for a particular yield by the rate of the test fertilizer that gives the same yield according to the response curves. Thus a “horizontal comparison” or “substitution rate” of fertilizers is made at a selected common yield (Barrow 1985, Colwell and Goedert 1988). Palmer et al. (1979) contended that this approach would give a constant RAE index that is independent of fertilizer rate only when common limiting yields are obtained. This condition, however, may not be met with some P fertilizers. If the condition is not met, the RAE index of less soluble fertilizer (e.g., PR) with respect to a standard fertilizer (e.g., SSP or TSP) is not constant, and it generally declines with increasing P rates of less soluble fertilizer (Bolland and Barrow 1988). However, D. K. Friesen (IFDC, 1989, pers. comm.) pointed out that if the response function is in the form of

\[ y = a + bx \]

where \( y \) is yield and \( x \) is P rate, the RAE index is constant (i.e., \( b_2^2/b_2^2 \)) and is independent of yield goal and P rate applied from the test and the standard P fertilizers. Such a response function has been used by some researchers (Kpomblekou 1989; A. Bationo, IFDC, 1989, pers. comm.).

**The linear-response comparison**

Often, the region of primary interest in fertilizer performance is that of the most responsive part of the response curve. This region represents the level of response at which a farmer with limited resources will add fertilizer. In this region, the response to added P is often linear or nearly so. In this situation, a comparison of the slopes of the linear portions of the response curve is a simple means of arriving at a rate-independent estimate of RAE (Bolland 1987). One difficulty with this procedure, however, is deciding on the number of levels of fertilizer input to include in the linear regression. A comparison of \( R^2 \) values for regressions using different levels of input is misleading,
because the $R^2$ value is influenced by the degrees of freedom. An objective solution to this problem (D. K. Friesen, IFDC, 1988, pers. comm.) is to successively fit first- and second-order polynomial regressions to the data set, each time including the data for an additional fertilizer rate. The number of fertilizer rates selected to define the linear regression would be one less than the number used for the regression where the quadratic coefficient becomes significant ($P < 0.05$). It should be pointed out that the RAE index of a test fertilizer determined by the linear-response comparison method is the same whether it is compared vertically or horizontally.

In view of the overall advantages and disadvantages associated with each method for comparing the RAE of various P fertilizers, the choice of method may depend on the objective of the researcher. If the goal is to make an economic evaluation by comparing the different sources on the basis of the amount of P required to give a particular yield, then horizontal comparison should be used. If the objective is to rank a series of test fertilizers with respect to standard fertilizers according to their agronomic potential to produce a yield response relative to that of a reference fertilizer, then an RAE index derived from the ratio of coefficients from fitted response functions has merit. However, the use of such an index in making an economic assessment of the test fertilizer can be misleading if the researcher does not recognize the curvilinear nature of the response functions. If the goal is to provide resource-poor farmers with cheaper alternative P sources, then the linear-response comparison of test sources in the most responsive region of the response curve may be the most suitable method.

Research needs

As interest in the use of nonconventional P fertilizers such as PAPR and PR for crop production in Asia and Oceania increases, more information will be required, especially under field conditions, on their RAE as compared with conventional, water-soluble P fertilizers such as TSP and SSP. Evaluation of sources should also be conducted over extended periods to obtain information on residual effects.

More research is also needed to compare the RAE of various P fertilizers as influenced by fertilizer properties, soil properties, management practices, and crop species. Finally, more work is needed to develop appropriate methodologies for analyzing the experimental data for an unbiased comparison of the RAE of various P fertilizers.

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Notes

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Citation information: International Rice Research Institute (1990) Phosphorus requirements for sustainable agriculture in Asia and Oceania P.O. Box 933, Manila, Philippines.
Fertilizer is used by farmers to increase profits. Its use can be justified only if it increases income by more than the cost of applying it. For a nutrient such as P, with a marked residual effect, the benefits to production over a number of years must be taken into account. Sustainable production requires that nutrient losses be replaced.

Several other principles should be considered when developing a fertilizer advisory system (Sinclair and Cornforth 1985):

• **Cause and effect.** Mechanistic systems are based on understanding and quantifying the causes of a response, whereas empirical systems involve experimentally derived numerical relationships. There are biological, chemical, and physical reasons for the differences in observed requirements in different situations. This means that recommendations can be based on rational, or mechanistic, rather than empirical systems. Similarly, requirements can be changed by altering the factors that influence them, and alternative strategies for obtaining the same production targets can be replaced.

• **Uncertainty.** A degree of uncertainty surrounds every fertilizer recommendation, because our knowledge of all factors influencing requirements is incomplete or difficult to quantify and because of climatic and economic factors that are unpredictable.

• **Diminishing returns.** The return sought from a fertilizer advice scheme is accuracy in recommendations for achieving a specified objective. Major improvements in accuracy occur from the first relatively simple inputs, e.g., soil group, land use, or stocking rate. Ultimately, a stage will be reached when further refinements are not worth the effort that goes into establishing or operating them.
• Accountability. The real test of a fertilizer advisory system is not the elegance of the nutrient model it employs, but the accuracy of the advice it gives to farmers. An extension of this principle is that the performance of the scheme must be assessed and monitored under authentic farming conditions.

This paper examines some recent approaches to deriving economically sound fertilizer advice and illustrates how these four principles can be incorporated. The first part deals with the use of P fertilizers to maintain production in grazed pastures that have already gone through a development phase. Discussion in the second part will emphasize cropping situations involving both development phases, when fertility is being built up, and maintenance phases, when the fertility of the developed soil is being maintained.

Phosphatic fertilizers for grazed pastures

Scobie and St. Pierre (1986a) have shown that economic efficiency—the relationship between product value and the cost of fertilizer needed to produce it—has three main components:

• Pasture efficiency: the relationship between P input and pasture production
• Management efficiency: the percentage of pasture produced that is consumed by livestock
• Animal efficiency: the conversion of pasture into salable animal products

Models designed to maximize economic efficiency must incorporate pasture, management, and animal efficiency (Fig. 1).

Fertilizer models

The New Zealand Ministry of Agriculture and Fisheries (MAF) Soil Fertility Service uses a simple mechanistic balance model (C-S model) of P cycling in grazed pastures (Cornforth and Sinclair 1982, Sinclair and Cornforth 1984; Fig. 2). This model assumes that in developed pastures P is cycled through the soil, plant, and animal system and that to maintain production at any given rate, fertilizer P is required only to replace P lost from the cycling pool. The C-S model is used to estimate losses for individual farms and from them the amount of fertilizer P required to maintain production. The amount of P lost in produce, in waste transfer, and by reactions with soil constituents depends on the type and number of livestock, soil type, land slope, and management practices. The pasture production required for a given farming situation is estimated from animal stocking rates and pasture utilization. An asymptotic function relates P losses (and hence fertilizer required) to relative pasture dry matter production. This is a “maintenance requirement curve” as distinct from a response curve (Helyar and Godden 1977). Soil tests (Olsen et al 1954) are used to modify fertilizer recommendations estimated by the balance model (see the following section on soil testing).

In its original form, the C-S model was designed as a steady-state model, unable to deal with changing P inputs, and was not suitable for calculating economically optimum fertilizer rates. A number of modifications since then have incorporated economic principles and the concepts of error and risk.

2. P cycle in a grazed paddock.

Scobie and St. Pierre (1986a) developed the original C-S model to incorporate economic principles. This allowed the identification of optimal, or profit-maximizing, values of P use, pasture, and animal production.

Scobie and St. Pierre (1986b) also incorporated the effect of varying fertilizer use on the size of the cycling P pool. To do this, they included the residual effects of fertilizer into the C-S balance model. The size of the “soil P capital” was estimated either by soil tests or from a record of fertilizer history coupled with a residual value function. In Scobie and St. Pierre’s equations, the residual value functions are independent of the soil and management factors used to assess P losses in the C-S model. Unfortunately, few experimental data are available to derive and test the factors
required to estimate soil P capital. The model allows various fertilizer strategies to be compared by taking into account the effects of a year’s fertilizer use on the amount of P available in the subsequent year.

Metherell (unpublished data) has also adapted the original C-S model to allow it to predict changes in soil P status and production caused by using P fertilizer. The size of the cycling P pool is estimated by soil testing every 3-5 yr. A response function estimates the expected relative yield, and hence pasture and animal production, from soil P status and fertilizer input. Changes in the size of the pool in intervening years are calculated using the original concepts of the C-S balance model, but with relative yield determined by the P response function. Thus, changes are related to actual production conditions on the farm and not to an independent residual value function. This approach is more in harmony with the original model and has been adopted by the commercial Soil Fertility Service run by MAF in New Zealand.

Maling et al (1984) used an asymptotic response function to predict optimal P fertilizer requirements; their model is called Superate (Fig. 3). Maximum yields are derived from rainfall, yields without fertilizer P from soil tests, and the curvature of the response function (C) from soil texture. Only two values of C are used as opposed to the individual values calculated from soil and animal factors for each example in the C-S model. A single term is used for the residual value of superphosphate, independent of soil properties.

Superate is an economic model. Produce value can be calculated either from estimated increases in pasture production and gross margins for the farm or region, or from the more complex relationship between pasture production and animal production. The former method is more generally applicable, but the latter includes differences in economic performance for various types of livestock. Stocking rates may depend on factors other than the economically optimum fertilizer rates, in which case the fertilizer recommendation should be appropriate for the chosen stocking rate.

It is not possible to compare the effectiveness of the mechanistic New Zealand model with the more empirical Australian model directly: both appear valuable in their own circumstances. However, the mechanistic approach may be more flexible in that it can accommodate changes in management factors that influence curve parameters without the need for an extensive field experimental program.

Soil testing
It is unreasonable to expect soil P tests alone to predict economically optimum fertilizer requirements for grazed pastures. This is because of the inherent variability of soils (McIntyre 1967), the numerous factors influencing the relationship between test values and plant performance (summarized by Mattingly 1980), and the complex relationship between pasture production and animal performance. In New Zealand, Olsen P values explain only 50% of the variations in pasture relative yields (St. Pierre and Scobie 1986).

Saunders et al (1987) developed an interpretation of soil P test values for grazed pastures that overcomes some of the problems associated with variable responses and at the same time allows at least some of the risk associated with recommendations to be specified. They showed that there is a reasonably well-defined pattern in the relationship between soil test values and the relative production of pasture. At small test values, relative yields vary from 40 to 100%, due frequently to the influence of climatic factors on responses to fertilizer P. As soil P status increases, the range of relative yield becomes narrower. They defined the “probable minimum yield” (PMY) as the value below which the actual relative yield will fall on only 20% of observations at a given soil test value. (The frequency with which observed yields fall below the PMY can, of course, be changed if a greater or smaller risk factor seems appropriate.)

This approach to soil test calibration is used to derive short-term corrective fertilizer requirements by the New Zealand Soil Fertility Service. A continuous function is used to modify fertilizer recommendations calculated to replace P losses using the basic C-S balance model. If the soil test value is above or below the value appropriate to the production required, a modifying factor is used to respectively decrease or increase the calculated maintenance requirement. This will decrease or increase soil P status and bring it closer to the appropriate value. Metherell’s recent extension of this system has already been discussed.

Probable minimum yields have also been used to estimate the probability of achieving a specified relative yield (St. Pierre and Scobie 1986) and the average and maximum feed deficits resulting from not using P fertilizers (Cornforth and Sinclair 1986).

Accuracy of recommendations
Imperfect knowledge of the relationships between factors influencing optimum fertilizer requirements, soil variability, and unpredictable climatic, management, and economic factors means that every fertilizer recommendation has an associated error. Ideally, recommendations should indicate not only the “most likely” performance in the coming year, but also some measure of the risk associated with actual performance.

The risks associated with the recommended rate of fertilizer P being more or less than that actually required are decreased by the natural buffering capacity of many soils so that recommendations based on, for example, average climatic conditions or potential yields will, over a period of years, be close to the optimum (Middleton 1980). Unfortunately, the pasture/animal system is less well buffered,
at least at stocking rates approaching carrying capacity. Here, actual production targets will reflect the farmer’s attitude to risk; if product value-fertilizer cost ratios indicate that high relative yields are optimum, a cautious farmer may choose to aim for a smaller but less risky rate of production. At lower stocking rates, flexibility in pasture utilization can compensate for at least some fluctuations in annual dry matter production. The subsequent section on soil testing indicates how the chances of achieving a certain rate of production can be estimated.

Assigning risk to predictions from empirical models is straightforward; Maling et al (1984) quote residual standard deviations for the parameters of the response function in their Superate model.

Using farm gross margins to evaluate responses to P fertilizers reflects the stocking rate on a property and hence introduces an aspect of the farmer’s attitude toward risk (Maling et al 1984), while using the C-S model to predict the P required for a specified stocking rate, rather than the economically optimum rate, also leaves the selection of degree of risk to be taken to the farmer.

Phosphorus fertilizers for crops

Research on P fertilizer requirements in the tropical countries of Southeast Asia and the Pacific has concentrated more on crops than on grazed pastures. Although nutrient cycles in cropping systems are much simpler than those involving grazing animals, few attempts have been made to use crop nutrient cycles to predict fertilizer requirements in the ways described in the previous section.

Field trials

Phosphorus fertilizer requirements by crops have been commonly assessed using traditional field trials in which yield information is presented as a function of the amount of P supplied. These yield response curves are different for different crops and vary greatly from site to site because of variations in soil and environmental conditions. Therefore, regional fertilizer recommendations are often estimated simply by averaging the fertilizer requirements of a number of field trials in a region.

Douglas and Dyson (1980) discussed statistical significance in crop fertilizer trials in relation to the profitability of applying fertilizer. To give sound advice, trial LSDs have to be at a value similar to or less than the yield required to pay for the fertilizer. Douglas and Dyson (1980) showed that, in deriving fertilizer advice from individual trial results, using lower confidence levels and one-tailed tests of significance will bring LSD values more in line with the crop yield responses that relate to the cost of the fertilizer.

A different approach is appropriate for fertilizer advice estimated on a regional basis, where it is better to have a large number of simple trials than to strive for greater precision in individual trials. This approach was recommended by Hauser (1970) and Middleton (1976); its main disadvantage is the loss of a viable statistical analysis for individual trials and the ability to identify subsets of trials in which responses differ (Douglas and Dyson 1980).
Soil testing

An approach to assessing P requirements was proposed by the World Phosphate Institute (IMPHOS) in 1980 (Roche et al. 1980). Based on results of 500 soil samples (covering 13 FAO/UNESCO soil groups) from 42 countries in tropical regions, it was suggested that soils containing less than 10 ppm resin-extractable P (48 h) are P deficient. The ability of an anion exchange resin to stimulate root action appears to explain why this method was the best of nine chemical and biological tests studied. IMPHOS suggested a classification of soils with respect to their responses to P fertilizer based on physical, chemical, and biological soil properties and field experimental data. This classification divides soils into five groups, ranging from those with very serious deficiencies demanding first-investment fertilizer application to richer soils simply requiring maintenance fertilization (Table 1). Analyses of soil texture and various P parameters (including P-fixing capacity) were used as the basis of classification. Each group has its own minimum critical threshold soil test value, which provides the scale of fertilizer P to be applied at the beginning of the cropping season.

- **Group 1.** The soils are generally medium to fine in texture, with considerable P-fixing capacity because of high extractable Al content (0.3 g/kg soil) and the presence of clay minerals such as iron hydroxides, aluminum hydroxides, gibbsite, goethite, and kaolinite. The pH is less than 5.5. Group 1 soils are widespread in the tropics; they are classified as seriously deficient in P and require first-investment or capital fertilization. The lower critical threshold value is for minimum soil P correction, and the greater value relates to 60% of maximum production.

- **Group 2.** Soils in this group have medium to fine texture with clay and silt content totaling more than 35%. This group differs from Group 1 in that the P-fixing capacity and extractable Al figures are lower.

- **Group 3.** This group is made up of coarse-textured soils with a much smaller P-fixing capacity than those in Groups 1 and 2. Group 3 soils have very diverse origins, but Alfisols and Ultisols dominate in tropical conditions.

### Table 1. Classification of 5 soil groups by the IMPHOS concept (Roche et al. 1980).

<table>
<thead>
<tr>
<th>Group</th>
<th>Deficiency level</th>
<th>Texture</th>
<th>Critical threshold (resin P)</th>
<th>Constant (a)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Seriously deficient</td>
<td>Medium to fine</td>
<td>10–17</td>
<td>0.097</td>
</tr>
<tr>
<td>2</td>
<td>Medium-seriously deficient</td>
<td>Medium to fine</td>
<td>10–17</td>
<td>0.235</td>
</tr>
<tr>
<td>3</td>
<td>Medium-seriously deficient</td>
<td>Coarse</td>
<td>10</td>
<td>0.374</td>
</tr>
<tr>
<td>4</td>
<td>More or less deficient, high fixing capacity</td>
<td>Variable</td>
<td>23–33</td>
<td>0.351</td>
</tr>
<tr>
<td>5</td>
<td>Rich in P</td>
<td>Variable</td>
<td>–</td>
<td>–</td>
</tr>
</tbody>
</table>

Qualifications where ranges of values are given depend in some instances on soil type and in others on production targets; see Roche et al. (1980) for details.
- **Group 4.** The soils in this group vary in texture, but all have high P-fixing capacity with average extractable Al content of 0.1 g/kg soil and average free Fe content of 2.5%.
- **Group 5.** These soils are naturally fertile in P or have received large applications of P for some time, and require only maintenance P.

Originally, critical threshold test values were those required for the highest possible yields of crops for a given time and a given soil. However, this is not always applicable to tropical soils with serious or very serious P deficiencies. The IMPHOS method was proposed on the basis that the initial correction improves yield significantly without necessarily attaining the maximum possible yield to take socioeconomic conditions into consideration. A figure of 60% of maximum possible yield is used because the relationship between yield and fertilizer P application is practically a straight line up to this value. The relationship between agricultural production return and fertilizer cost is therefore constant.

The amount of P required to bring the soil to reach the critical threshold is calculated from the equation:

\[
P \text{ requirement (kg/ha)} = \frac{\text{Critical threshold value} - P \text{ (48-h resin)}}{a}
\]

where \(a\) = constant for each group. The values of constant “a” were derived from slopes of desorption isotherms of the soils studied.

Although this system has been tested and found suitable for a wide range of soil types, it relies on a number of generalized assumptions that may reduce the accuracy with which fertilizer requirements are assessed for individual soil types. Improvements in this approach could result from incorporating the varying external P requirements of different crop species.

**Fertilizer models**

A basic model for calculating crop fertilizer P requirements has been proposed by Driessen (1986). The P required is the difference in P uptake by unfertilized and fertilized crops divided by an index of fertilizer P recovery. The fertilizer requirement \((D)\) is calculated from

\[
D = (U_m - U_o)/R
\]

where \(U_m\) is P uptake by the crop at the desired yield, \(U_o\) is P uptake from unfertilized soil, and \(R\) is the recovery of applied P; both \(U_m\) and \(U_o\) are determined from field experiments. Phosphorus recovery from fertilizer depends on fertilizer and soil types. This model has been used by Driessen (1986) for simulation studies in tropical soils; predictions compare favorably with the results of field trials, but there appears to be little information on its applicability to commercial production.
Conclusion

In addition to yield response functions and estimates of soil P status, reliable systems for predicting economical fertilizer recommendations require an understanding of the variability of production systems and hence the likely accuracy of recommendations. Unpredictable effects of climate, soil variability, and management on economics suggest that there is little scope for improving the accuracy of the Australian and New Zealand pasture fertilizer models described in this paper. There may, however, be greater scope for refining prediction systems for tropical crops. It is essential to collate the large volume of experimental data that are available for some crops to refine fertilizer recommendations, to relate requirements to soil P status, and to generate economically based advice.

References cited


Notes

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Phosphorus losses occur from soil-vegetation systems of different kinds. This paper considers losses through organic and physical transfers from nested or subtended systems of different dimensions. It especially examines transfers in pastoral systems on once forested terrain and quantifies losses from pastoral systems to freshwaters. Pastoral systems in New Zealand have substantial animal-mediated P losses, but storms and drainage conditions greatly affect their export of P to aquatic systems. The significance of riparian lands and their management is indicated by small catchment studies as well as those of great waterways. Transformations of P in lentic and lotic systems are outlined, contrasting small streambed conditions with those of large waterways, illustrated by the Changjiang River in China. Several topics identified demand increased research, especially for improved management of P resources on a landscape dimension. They include the biological significance of particulate P transformations in different soil and aquatic conditions; subsurface P losses; sources and mechanisms of particulate P entrainment in surface runoff during storms; changes in P status of hillside soils subject to landslides and soil renewal, mechanisms of controlling P enrichment of riparian lands, especially in pastoral systems; and roles of agroforestry in averting P loss and improving P utilization.

Phosphorus losses occur in soil erosion and in runoff. Phosphorus losses in surface or subsurface runoff increase with the use of P fertilizers under intensive pastoral or agricultural farming. Although volume of use in New Zealand has declined by 50% during the last decade, approximately 80,000 t P/yr are currently applied over about 6 million ha of the 10 million ha of improved pastures. Phosphorus fertilizers comprise more than 95% of the total fertilizers used other than lime, and most—over 1 million t of P fertilizer (New Zealand Department of Statistics 1987)—is applied not to cropland but to clover-based pastures to increase plant growth and to balance losses from the system. These losses include removal of P in animal products and transfer of dung to unproductive sites as well as losses to waterways through runoff, erosion, and leaching. Such losses raise production costs and lower net farm income. Although they may be only a small proportion of the applied P, their implications for water quality can be severe.

Some agricultural scientists accept P losses in soil as fixation or retention of some kind, but discount P losses from soil by subsurface runoff or leaching. Even in
considering mechanisms of element transfer in biogeochemical cycles, Reiners (1983) acknowledged the importance of sediment P and particulate dust P in erosion transport, but omitted dissolved P from his brief treatment of leaching.

We emphasize, along with Ryden et al (1973), that there are conditions where assumptions of relative immobility of P in soil systems should be questioned. Ryden et al’s (1973) review of North American and European studies demonstrated that in arable farming systems, especially artificially drained ones, P losses in subsurface runoff can be similar to or even greater than those in surface runoff.

The influence of agricultural land use on water quality in New Zealand was first assessed 20 yr ago (O’Connor 1968). That review noted ameliorative effects from reduction of soil erosion through pasture improvement, and deteriorative effects from animal wastes. Since then, several detailed studies have demonstrated that both particulate P and dissolved inorganic P may be lost in surface runoff and subsurface drainage from topdressed pastures. It has also been shown that pastoral agriculture has had a severe effect on some New Zealand lakes and rivers (McColl and Ward 1987, Rutherford et al 1987), although the rate of lake eutrophication has not been as rapid as was earlier expected (White 1982). Runoff measurements from New Zealand catchments under different land uses indicate that pastoral catchments contribute more P to inland waters than native forest or exotic forest catchments (Cooke 1980, Cooper and Thomsen 1988). In one comparison, total P export from fertilized pasture catchments, even on soils of high P retention, was estimated as 1.67 kg/ha per yr, contrasting with 0.09 kg/ha per year from pine forest and 0.12 kg/ha per yr from native forest catchments (Cooper and Thomsen 1988).

In one of the few long-term studies in New Zealand, made during a period of pasture development from tussock grasslands or pine plantations, Malthus and Mitchell (1988) related these changes in land use in the drainage basin of Lake Mahinerangi, Otago, to changes in dissolved reactive P and annual average phytoplankton productivity in the lake. The results (Table 1) indicate that dissolved reactive P levels in streams feeding the lake increased fourfold between 1965 and 1981, along with an increase in pasture development to 39% of the catchment.

The larger part of this paper is concerned principally with P losses from pasture systems through animal transfer, dung movement, runoff, and erosion. Pasture and arable land together comprise 53.5% (14.4 million ha) of the total land area of New Zealand (New Zealand Department of Statistics 1987). Most of the arable land is used for pastures in rotational systems, principally for dairying and lamb production. Approximately 10 million ha are “improved grasslands,” most of which have at some time been topdressed with P fertilizer, although the annual area of topdressing has markedly declined. More than half the land used for pastureage, however, has a slope of more than 18°. This hill and high country land supports more than 40% of the total sheep and about 60% of all beef cattle (Gillingham 1983).

The animal-mediated loss of P from eutrophic terrestrial systems warrants our particular attention to pastoral ecosystems in New Zealand. This is indicated by the distribution of values evident in Table 2. All such data are subject to the limitations of the hydrologic experience under which they have been measured. Erosion of cultivated soils has been more widely studied in North America than in New Zealand; but there
Table 1. Changes in land use in the 33,000-ha drainage basin of Lake Mahinerangi with changes in annual averages for light-saturated rate of phytoplankton productivity (Pmax) and dissolved reactive phosphorus (after Malthus and Mitchell 1988).

<table>
<thead>
<tr>
<th>Year</th>
<th>Land under agricultural development (%)</th>
<th>P fertilizer applied (t/yr)</th>
<th>Pmax (mg C/m³ per h)</th>
<th>Dissolved reactive P (mg/m³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1965</td>
<td>0.2</td>
<td>50</td>
<td>2.9</td>
<td>1.5</td>
</tr>
<tr>
<td>1969</td>
<td>3.3</td>
<td>200</td>
<td>8.0</td>
<td>1.9</td>
</tr>
<tr>
<td>1977</td>
<td>15.7</td>
<td>1080</td>
<td>19.1</td>
<td>3.1</td>
</tr>
<tr>
<td>1981</td>
<td>39.0</td>
<td>2400</td>
<td>27.2</td>
<td>5.8</td>
</tr>
</tbody>
</table>

Table 2. Ranges of export values of dissolved reactive P (DRP) and total phosphate (TP) from New Zealand catchments under different land uses (Malthus 1986) compared with summary of range of values from North American watersheds (Berg 1980, Ryden et al 1973).

<table>
<thead>
<tr>
<th>Land use</th>
<th>New Zealand¹</th>
<th>North America</th>
<th>Export values (kg/ha per yr)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>DRP</td>
<td>TP</td>
<td>DRP</td>
</tr>
<tr>
<td>Forest</td>
<td>0.01-0.57</td>
<td>0.07-0.75</td>
<td>0.01-0.07</td>
</tr>
<tr>
<td>(n = 9)</td>
<td>(n = 9)</td>
<td></td>
<td>(n = 2)</td>
</tr>
<tr>
<td>Native grassland</td>
<td>0.04-0.29</td>
<td>0.10-1.43</td>
<td>0.01-0.07</td>
</tr>
<tr>
<td>and shrubland</td>
<td>(n = 6)</td>
<td>(n = 6)</td>
<td>(n = 3)</td>
</tr>
<tr>
<td>Pasture</td>
<td>0.14-0.91</td>
<td>0.15-1.64</td>
<td>0.02-0.2</td>
</tr>
<tr>
<td>(n = 14)</td>
<td>(n = 13)</td>
<td></td>
<td>(n = 2)</td>
</tr>
<tr>
<td>Cropland</td>
<td>–</td>
<td>–</td>
<td>0.05-0.4</td>
</tr>
<tr>
<td></td>
<td>–</td>
<td>–</td>
<td>(n = 3)</td>
</tr>
</tbody>
</table>

¹(–) = no data.

has been a concentration of catchment studies in more recent years in developed pasture catchments in New Zealand, in comparison with the native forests and shrubby grasslands from which they are derived (Table 2).

The translation of P to water bodies is a worldwide phenomenon (Table 3). It may not always occur by the same mechanisms or processes. From the contrasting culture and landscapes of New Zealand and China, this paper attempts to form some perspective on the role of agricultural land use in the two countries in contributing P to water bodies by different physical mechanisms. It does not attempt to review the larger topic of P loss from soils, but it accepts the evidence of water enrichment that has been accumulating in New Zealand over the last two decades. With this it attempts to join the quantification of P transfers and transformations in the Changjiang (Yangtze) system in China, and invites soil scientists and ecologists in particular to examine their own soil and land use systems more critically.
Table 3. Distribution of movement of P from soil to fresh water in g × 10^{12}/yr in major geopolitical zones (after Richey 1983).

<table>
<thead>
<tr>
<th>Zone</th>
<th>P movement from soil to fresh water (g × 10^{12}/yr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>North America</td>
<td>0.7</td>
</tr>
<tr>
<td>Europe</td>
<td>0.3</td>
</tr>
<tr>
<td>USSR</td>
<td>1.0-1.8</td>
</tr>
<tr>
<td>Pacific developing countries</td>
<td>0.3-0.6</td>
</tr>
<tr>
<td>China</td>
<td>0.4-0.6</td>
</tr>
<tr>
<td>Latin America</td>
<td>0.5-0.8</td>
</tr>
<tr>
<td>North Africa and Middle East</td>
<td>0.2-0.3</td>
</tr>
<tr>
<td>Tropical Asia</td>
<td>0.6-1.0</td>
</tr>
<tr>
<td>South Asia</td>
<td>0.2-0.3</td>
</tr>
<tr>
<td>Southeast Asia</td>
<td>0.4-0.7</td>
</tr>
</tbody>
</table>

System dimensions and mechanisms of phosphorus loss

We recognize the necessity of defining systems from which losses may occur in dimensions of space and time. Lindeman (1942) defined an ecosystem as “a system composed of physical-chemical-biologic processes active within a space-time unit of any magnitude.” We acknowledge the significance of the range of interaction processes of aqueous and sediment P in streams and lake beds as described by Syers et al (1973), Syers (1974), and Ryden et al (1973), as well as those to be outlined in this volume by Syers and Lu (1990) and Kirk et al (1990). We conceive these processes as occurring in successively nested or subtended systems. Accordingly, we shall deal with field site and whole field systems, then small catchment systems, then national or large catchment systems, and finally fluvial and lacustrine systems.

Following Wilkinson and Lowrey (1973), Figure 1 illustrates an idealized and simplified P (or other nutrient) cycle in a pasture system involving soil, plants, and animals. The spatial and temporal definition of systems determines whether all compartments, phases, and processes occur in it, which processes represent accessions of an element, and which represent losses. Woodmansee et al (1981) hypothesized six potential areas of differing N status within any pasture as an outcome of spatial and temporal variability. In pasture studies in New Zealand we have been able to identify several main kinds of site condition with relevance to the simplified P cycle described in Figure 1. Variations of this cyclic picture occur where processes are interrupted or where transfers to other sites occur because of variations in ingestion and excretory behavior of grazing animals. Further variations may occur on hillsides when there is a mosaic of landslide scars of differing ages (Trustrum and de Rose 1988). Systems of increasing size up to whole catchments generally increase in complexity because of different topographic conditions and their different interactions with animal behavior.

Wherever there are grazing animals, an estimate of P export as animal products can be made. For dairy cattle, where P in milk accounts for 26% of P consumed in herbage (Hutton et al 1967), estimates of product P loss vary from 10 kg P/ha per yr (Parfitt 1980) to about 14 kg P/ha per yr (Wilkinson and Lowrey 1973).
For meat-producing animals, carcass P accounts for 3-8 kg P/ha per yr for high-producing systems. These losses are comparable in magnitude with animal-mediated P losses in drainage from small systems. They are probably much smaller than the animal-mediated local P transfers within small field systems, which arise from interactions of topography and animal behavior.

Field sites and whole field systems

Phosphorus losses from small-scale systems arise from pastoral and erosion processes.

Phosphorus losses from pastoral processes

At a particular site in a pasture, P loss will be most influenced by site conditions as affected by management and animal behavior. Some sites, whether grazed or not, may accumulate P from fertilizer topdressing. Some sites, which are well grazed but where animal feces do not fall or lie, may be losing P in animal products and transfer at a greater rate than it is replaced by fertilizer. Gillingham et al (1980) found annual losses from hillslopes varying from 14 to 27 kg P/ha, whereas sheep campsites gained from 50 to 110 kg P/ha. On 25° slopes, 31-58% of annual pasture P uptake was returned as dung from sheep grazing. On areas with 45° slopes, the return was only 8-17%. Tracks, flatter areas, and stock camps gained 2-3 times the annual pasture uptake of P.
Slope affects animal behavior and dung deposition, accumulation, and decomposition. Thorrold et al (1985) found less uneven distribution of dung on a steep sheep pasture with higher stocking rates; the amount of dung accumulated per unit area was correlated with the distribution of grazing sheep. Night stock camps, however, remained disproportionately high in dung volume and Olsen P values.

The fate of P in dung under different regimes is inadequately known. Phosphorus in dung on pastures may be subject to leaching into runoff or soil. Katznelson (1977) estimated 50% of P in fresh cattle dung to be soluble if washed immediately by water, but found that solubility declined as dung dried. Rowarth et al (1985) found that sheep feces decomposed within 1 mo in pastures during moist winter conditions but lasted 3 or 4 times longer in summer. Dung may be washed from sloping ground during storms. Closely grazed swards may especially suffer from such wash effects (McColl 1983). Rowarth et al (1985) found dung breakdown to be much more rapid on flatter sheep camps than on steep slopes. New Zealand lacks herbivorous mammals and their dung beetles in its evolutionary fauna. Earthworms, especially introduced species, play a significant role in incorporating into soil both dung and plant residues and may improve P solubility and enhance P losses (Sharpley and Syers 1976b).

In a bounded field system, animal grazing and resting patterns may set up marked nutrient gradients, with extreme P accumulation occurring in loafing or sheltering areas. Such sites may resemble the conditions of unpaved feedlots or arable land on which large dressings of animal manure are spread in winter, as reviewed by Ryden et al (1973). Where large accumulations of dung occur, snow melt or rainstorms may bring about dramatic P movement in surface runoff. It is possible under such conditions that P may pass in solution through soil cracks, continuing into deeper horizons, as has been indicated for other solutes (Francis et al 1988). The possibility of such direct losses is worth investigating in view of the evidence of long-term downward movement of topsoil P from pastures subject to subsoil cracking (Lynch and Davies 1964), as well as the evidence of enhanced P loading in subsurface runoff accelerated by artificial drainage of croplands (Ryden et al 1973) and of topdressed pastures (Sharpley and Syers 1979b, Turner et al 1979).

The magnitude of P losses in different forms from small-scale field research in high-intensity pastoral use systems has been summarized in a recent review of New Zealand pastures and soil fertility (O’Connor 1989). Included in this summary are the following features:

- total losses on the order of 3.7-5.6 kg P/ha per yr (Sharpley and Syers 1979b) for surface runoff from fertilized dairy pastures in the Manawatu district; half of the total P loss was particulate P;
- subsurface drainage losses on the order of 1.1-2.1 kg P/ha per yr (Turner et al 1979) from artificially drained, fertilized dairy pastures in the Manawatu district, again with approximately half the total P loss being measured as particulate P;
- surface runoff losses of 2.5 kg P/ha in the 5 mo following topdressing of a developing pasture on a gley-Podzolic soil in humid Westland (Powell and Taylor 1979); approximately 40% of P in surface runoff was associated with suspended particles;
in both the Manawatu and Westland studies, calculation of P lost in all forms in surface runoff represented the equivalent of 6-8% of annual applied P; and
direct application of fertilizer to waterways results in P loss, and cattle are implicated in accelerating loss of dissolved inorganic P and of particulate P in dairy pastures, especially when they have access to waterways, even though such effects, like direct fertilizer applications, may be short-lived (Sharpley and Syers 1976a, 1979a; Turner et al 1979).

These losses are generally considerably greater than those reported later from small catchment studies or those used as the bases for estimating national losses of P from the pastoral estate.

**Phosphorus losses from erosion processes**

As Ryden et al (1973) noted, estimating soil fertility losses due to soil erosion is the primary objective of many field plot studies. From a range of studies of agricultural practices in the U.S., they indicated total P losses from as low as 0.1 kg/ha per yr to more than 50 kg/ha per yr. Surficial processes of soil erosion are generally minimal under a pasture sward, except after close grazing, but soil P losses under such conditions may be confounded with P losses from organic residues, because dung and detached litter may be readily transported in overland flow.

Soil erosion in mass movements may be much more serious as an occasion for soil P loss, especially on deforested hillslopes, as described for different parts of New Zealand (O’Loughlin and Pearce 1976, 1982; Trustrum et al 1984). In a New Zealand-wide review (Crozier et al 1982), mass movement activity is related not only to the interplay of climate, topography, and rock but also to human activity. Clearing for pastoral farming of steep forested hillslopes on some rock types has led to decades of landslides as root nets decay and severe rainstorms occur. The original forest soils may be progressively replaced by new pasture soils developed on the landslide scars. Such new soils are initially shallow and of low productivity (Lambert et al 1984). They progressively increase in depth with time (Trustrum and de Rose 1988). The initial P loss by erosion following forest clearance (Vitousek 1983) may be followed by periodic mass export of forest soil P from the site and then succeeded by gradual accretion of pasture soil P from bedrock weathering, colluvial accumulation, fertilizer application, and animal transfers. The rates of such changes in P have not yet been measured in New Zealand, but current research indicates that it is a vital topic for guiding future land use.

**Phosphorus losses from small catchments**

Ryden et al (1973) reviewed several studies from forest watersheds and found that total P loss in streams was generally low—less than 0.1 kg/ha per yr. In contrast, the few studies of specific watersheds in agricultural use showed much greater variation in total P loss, from 0.1 in pasture to 6.3 kg/ha per yr in row crops (Table 2).

Losses of P through surface runoff from agricultural and intensive pastoral land are affected by amount, intensity, and timing of rainfall; land and soil physical
properties; nature and distribution of soil P and applied P and soil cover conditions, including effects induced by animal grazing behavior (Cullen 1983, Ryden et al 1973). Phosphorus may be transported to streams in dissolved form, as when rain occurs soon after topdressing or when dung deposits or other residues are leached on saturated or frozen ground. Most P is thought to move in particulate forms as soil or plant fragments (Cooke 1988, Cullen 1983). In any system involving soil and water, dissolved P may become particulate P by being sorbed on soil particles as it moves through or over soil. If such particles are not detached and transported, soil P is augmented by particulate or sorbed P. The amount of particulate P lost in surface erosion is affected by the size of particles with which it is related and the energy in the surface flow. These factors affect particle detachment and transport. Similar factors may operate in subsurface flows, especially in subsoil channels: both natural channels in fragipan soils and mole and tile drains. Smith (1987) found a significant relationship between concentration of total dissolved P in runoff and rainfall intensity, suggesting that disturbance of surface soil by heavy rain might release soil P into runoff from a pastoral catchment. Other explanations might be offered, such as larger areas contributing to runoff and thus to P dissolution from soil, dung, and plant residues.

Animal type, plant and animal residues, and animal disturbance of soil are also implicated in the contribution of total P and dissolved inorganic P to surface runoff. Lambert et al (1985) found in a hill catchment study that particulate P losses associated with sediment losses were greater under rotational grazing of cattle than under rotational grazing or set stocking of sheep. Total P losses were also greater (1.5 kg P/ha per yr) under cattle than under sheep (0.7 kg P/ha per yr). Close grazing by sheep and trampling by sheep were implicated by McColl (1983) in increasing the effectiveness of surface runoff in transferring total N, total P, organic matter, and total solids; he demonstrated the capability of longer (8 cm vs 2 cm) grass swards to trap and retain recently applied P fertilizer. Total P concentration in surface runoff was raised 22-fold by fertilizer application on closely grazed pastures. A similar prefertilizer-postfertilizer comparison of pastures rested from grazing showed only 17% higher total P in surface runoff than the outcome of topdressing. Furthermore, McColl and Gibson (1979), Gillingham (1983), Lambert et al (1985), and Smith (1987) all pointed to the significance of less closely grazed pastures in sieving particulates, such as soil and dung fragments, from surface runoff. McColl (1983) and McColl et al (1985) pointed to the significance of storms in small pasture catchments in progressively increasing the proportion of catchment soils that are saturated. Pearce and Mc kerchar (1979) inferred runoff mechanisms in a range of storms from 17 small catchments by examining how the ratio of “quickflow” to rainfall varies with size of storm event. “Quickflow” is the principal component of stormflow, as partitioned by Hewlett and Hibbert (1967), and is now widely used in Europe and North America. Saturation overland flow from small contributory areas, generally riparian, accounted for most of the storm runoff in small rainstorms (1- to 100-d return period) in all 17 catchments. The concept of partial contributing areas could therefore be applicable in nutrient management as well as hydrology. McColl (1983) and McColl et al (1985) examined
the theoretical implications of reducing animal influence on the limited areas of surface-saturated soil that generate stormflow. Results of this analysis supported the view that land management to reduce nutrient or pollutant losses in overland flow could be concentrated on areas that predominate as sources of runoff, rather than on whole catchments.

It therefore appears that riparian land may warrant special management for hydrologic, nutrient control, aesthetic, and special product purposes. It may even provide a mechanism for P recycling to the atmosphere as indicated by the detection of phosphine (Devai et al 1988). Riparian zones are increasingly emphasized in New Zealand as newer studies emerge with more meticulous measurements. The most recent work (Smith 1989) demonstrates the quantitative success of reducing N and P contributions to waterways in small and medium storms by excluding animal use from the riparian zone.

Some of the most important detailed studies of stormflow generation in New Zealand (Cooke and Dons 1988) and of sources and sinks of P and N (Cooke 1988, Cooke and Cooper 1988) were in a 16-ha Scotsman Valley catchment near Hamilton in Waikato. As far as the total P export of 1.3 kg/ha per yr was concerned, about 40%, and virtually all that entering the stream manuring 4 major storm events in 1 yr, was entrained in surface runoff. Incidental direct aerial application of fertilizer to the stream system could account for 20% of total annual P export. Beyond that, annual topdressing in autumn at a nominal 25 kg P/ha markedly increased the levels of dissolved reactive P in surface runoff, but baseflow and small storm events accounted for only 2.4% of estimated annual P export. The permanently saturated riparian seepage zone had a total P concentration 10 to 100 times that of rainfall. Virtually all was particulate. The interaction of major storm events with the release of these temporary P storages in riparian lands gives new insights on a small catchment scale into the dynamics in space and time of the interchanges between aqueous P and sediment P compartments expounded by Syers et al (1973).

Likewise, the comparative study of adjacent pasture, pine, and native forest catchments near Lake Taupo (Cooper and Thomsen 1988) revealed very uneven N and P export from the pasture catchment during the year, with most P loss (1.55 of 1.69 kg P/ha per yr) occurring as particulate forms during storm events. Significantly, particulate N in stormflow was the dominant form of N loss from pasture, two-thirds of a total annual export of 12 kg/ha per yr. This suggests that biological residues, rather than primary fertilizers, are the major source of P lost in particulate form from pastures in such storm events. The large difference between pasture catchments and forested catchments in the export of dissolved reactive P as well as total P export arises from the much higher concentrations of P in stormflows from pasture catchments (Cooper et al 1987, Cooper and Thomsen 1988). As has been indicated, these small catchment studies do not consider the much less frequent major flood events that are responsible not only for the extension of P-contributing areas beyond riparian lands but also for the occurrence of mass movements on hillslopes that contribute topsoil, subsoil, or parent material P in stormflow sediments. It is impossible to plan to accommodate these extreme events.
Phosphorus losses in national or large systems

Phosphorus losses from large systems include point and diffuse source discharges and large losses through erosion.

**Point source and diffuse source discharges**

Phosphorus losses from agricultural systems are conventionally classified as point or diffuse source discharges. Point source discharges include effluents from dairy sheds and piggeries and, on a larger agricultural industry scale, discharges from dairy factories and meatworks. Estimates of P entering New Zealand freshwaters from all these agricultural point sources are shown in Table 4 to be approximately 5,300t. Two-thirds of these point source losses (milking sheds, 2,037 t P/yr; piggeries, 1,629 t P/yr) occur from within farm systems, one-third (dairy factories, 407 t P/yr; abattoirs, 1,222 t P/yr) from beyond the farm gate industry. Animals other than some pigs and poultry are not housed in New Zealand, even in winter. Were they housed as in Europe or other cold winter climates, the point source P losses might be much larger. Rates of P lost in small catchment studies led to estimates (Rutherford et al 1987) of 2,900-16,000 t P/yr entering freshwaters from diffuse sources in improved pasture systems on 10 million ha. Table 4 shows the means of current and earlier estimates of total P lost to New Zealand freshwaters from pastoral agriculture in relation to national levels of P fertilizer use recorded for the same time.

Improved treatment of point source discharges since the early 1970s is indicated in Table 4. However, overlap and substitution occur between point and diffuse sources of P to aquatic systems. When effluents from dairy sheds and piggeries are spread on land, they may become diffuse sources of P loss. How much of the apparent increase in actual level of diffuse source P is a consequence of improved treatment of point source material and how much is a matter of estimation method is a moot question. The proportion of total P currently applied that may be calculated to be lost to receiving waters (i.e., 19%) is misleading. This proportion is very much affected by both previous and current P application levels. As well as some natural P from unfertilized areas, we may be losing the P we applied in the 1960s and 1970s! The enrichment of

<table>
<thead>
<tr>
<th>Period</th>
<th>Applied</th>
<th>Loss from point sources</th>
<th>Loss diffuse sources</th>
</tr>
</thead>
<tbody>
<tr>
<td>Early 1970s</td>
<td>147,000</td>
<td>12,800 (8.7)</td>
<td>5,500 (3.7)</td>
</tr>
<tr>
<td>Early 1980s</td>
<td>139,000</td>
<td>6,600 (4.7)</td>
<td>5,500 (4.0)</td>
</tr>
<tr>
<td>Late 1980s</td>
<td>77,000</td>
<td>5,300 (6.9)</td>
<td>9,300 (1.2)</td>
</tr>
</tbody>
</table>

waters with P, N, and S is our evident national experience. The earlier proposition (O’Connor 1968), "It becomes difficult to have highly fertile land drained by infertile rivers," remains trite but unpleasantly true.

**Large phosphorus losses by erosion**
Phosphorus may enter water bodies from aerial depositions and soil erosion. Erosion rates vary greatly in New Zealand, and many spectacular sediment outputs are functions of geologic and climatic factors rather than the direct outcome of human impact (Duncan 1987). As pointed out, however, mass movements may contribute to soil P losses from field sites, and much of the eroded material may pass into water bodies. Using relatively conservative estimates (100mg/kg) of biologically available P in unfertilized New Zealand soils (Hedley 1978), losses of P from 14 million ha of grassland at erosion rates of 0.1-0.5 kg/ha per yr (Rutherford et al 1987) are estimated at 1.400-7.000 t/yr.

More P than is biologically available is delivered to water bodies from soil erosion, especially where mass movements are involved. Parent material apatite eroded from mountainous terrain may not have high initial biological availability (Ryden et al 1973), but, as Reiners (1981) observes in terrestrial systems, biological acid production accelerates P availability and N₂ fixation. Evidence from China indicates that this is valid for some aquatic systems (Gan 1985).

**Phosphorus transformations in lotic and lentic systems**
In lotic ecosystems, with flowing water, long-term downstream losses of P will generally equal inputs from upstream watersheds, but the stream ecosystem can alter the timing, form, and size of the nutrients arriving downstream (Elwood et al 1983). Although total quantities of P in streams draining watersheds may be high, concentrations of dissolved P are generally low. Particulate material containing apatite P, sorbed P, or P incorporated in organic form predominates. In large fluvial systems, this has the opportunity of settling out as nutrient-rich sediment that is deposited in the fertile plains, along banks and bends in the river. These sediments may be used for food or fiber production, and the silty floodwater is frequently used for irrigation.

Under soil and streambed conditions, P sorption by sediments appears to predominate over desorption. Sorption processes are related to the sorption surface, position in or on the particle, and environmental parameters such as pH and redox potential (Syers et al 1973). In standing water, there is constant interchange between the P in sediments and the water column in lentic systems, but we are uncertain of their constancy in a moving stream. In large fluvial systems, the condition of P downstream may be little related to the condition of P at its source.

The Changjiang (Yangtze) River is the largest river in China, with a length of 6,300 km and a drainage area that exceeds $1.8 \times 10^6 \text{ km}^2$. It has a catchment of 26 million ha of farmland, and 7 million ha of forests in the upper reaches. Phosphorus losses are estimated as 0.22 kg P/ha per yr from forests and 0.16 kg P/ha per yr from farmland.

The rainwater contains a high concentration of dissolved CO₂ because of industry in the drainage basin. As water passes through the soils, the CO₂ content may be
augmented from plant and microbial respiration. Under such acid conditions, apatite P in soil materials and silts is released into solution and is available for plant uptake. The 10-yr seasonal averages (1970-80) of data collected from 2 stations on the Changjiang River show reduced pH levels and increased levels of P and CO₂ pressure as sampling progresses downstream from Chongqing to Datong. The highest P levels in summer and autumn are associated with higher temperatures, discharge rates, and CO₂ pressures at this time of year.

In contrast to such lotic systems with P in suspension, P in lentic systems is mainly in solution or in benthic deposits. Dissolved P or P derived from benthic sediments in seasonally anaerobic conditions may pass up the food chain into fish and other higher organisms. Dissolved P may be intercepted early to avoid loss to sediment or downstream so that it is quickly taken up by benthic, floating, or planktonic plants under natural or artificial systems manageable for aquaculture such as fish farming (see also Kajak 1989).

**Landscape approaches to phosphate management**

What happens in a small field site system or small catchment system will be reflected in some way in the larger landscape, but we have noted that the form of P exported from small systems may not persist in larger aquatic systems. The flexion point of system size is uncertain. Whether such P exports are seen as costs or benefits may depend on geophysics and the wider context of land use (Vitousek 1985).

Human experience in Aotearoa, New Zealand, is reflected in changes in vegetation and management (Fig. 2). This exemplifies in a few centuries what has happened elsewhere over human history. Despite substantial fertilizer P application for 70 yr, we hesitate to suggest a positive P balance for the land itself as an outcome of human use.

![Graph](image)

We recognize that pasture production is at its highest when soil fertility limitations are removed and pastures are grown in a forest climate. In pastoral as in agricultural systems, as topsoil fertility is raised, rate of returns diminishes and nutrient losses occur. There appear to be ecological limits to agricultural and pastoral development.

Increasing the temporal or spatial dimensions of pastoral systems may allow management of nutrient flows before such ecological limits of fertility are reached (O’Connor 1989). This may involve alternation of pasture systems with cropping systems on suitable terrains, or exploitation of deeper soil layers by planting trees, or using high-nutrient runoff for aquaculture. For recently deforested hill lands such as on North Island, New Zealand, and much of the humid tropics and subtropics of Asia, agroforestry in one form or another may be demanded to counteract mass movements or surficial erosion. On some terrains, such as those with immature soils in the glaciated interior of South Island, New Zealand, tree plantations apparently augment P in surface soils by litter return of nutrients drawn from deeper horizons (O’Connor 1986). Further research is urgently needed on this topic in New Zealand and other environments to determine at what rate such litter P becomes available to pasture or crop species growing under tree canopies of different densities.

Phosphorus is well named from the Greek as light-bearer or morning star, for its study in terrestrial and aquatic systems has illumined virtually every phenomenon from pedogenesis (Walker and Syers 1976), the seas around us (Redfield 1958), and our life on earth (Pierrou 1979) to soil microbial biochemistry (Tate and Salcedo 1988). It is also aptly named “lin” in Chinese, for its word history as fish scale, as “evil air” or phosphine, and later as mineral is an eloquent reminder of its cosmic universality and a lively stimulus for modern science to learn from ancient art and practice. If much of that learning is focused on riparian wetlands and their management, we shall all benefit in our different cultures.

Australia and New Zealand have each developed vigorous and resilient cultures from successive immigrations of forest-burning peoples. Not every impact has been benign to the land and its waters. The algal bloom devastation of the Peel-Harvey Inlet in western Australia as a consequence of P leaching through coastal sandy soils under pastoral development (Hodgkin et al 1980, Ozanne et al 1961) is a stern lesson that not all soils have sufficient depth of P-sorbing fine-textured horizons to retain P against subsurface loss. It is also witness to the significance of place in a series of systems. If such gross P losses from soil columns had occurred hundreds of kilometers upstream in the catchment, the stream-channel processing upon which Ryden et al (1973) and Elwood et al (1983) expounded and which we have examined here in small streams and great rivers would have brought greatly different effects.

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Notes

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Citation information: International Rice Research Institute (1990) Phosphorus requirements for sustainable agriculture in Asia and Oceania. P.O. Box 933, Manila, Philippines.
Utilization of phosphorus transported from uplands to lowlands and estuaries

E. Miwa

In Japan 9.03 × 10⁴ t P was estimated to flow into the estuaries in 1982—8.3 × 10⁴ t coming from food and feed, and 7.3 × 10³ t from forests and agricultural lands. Lowland rice cultivation uses the P transported to the lowlands from the uplands. As eutrophication of irrigation water increases, P uptake by rice and the use of rice by-products will contribute to the sustainability of both food production and the environment. Attempts to recover P have been made by growing water hyacinth in estuaries and eutrophied lakes. Using harvested plants for composting or cattle feed is promising, but their high water content causes difficulties.

Japan has 4.24 × 10⁶ ha of cropland, of which 3.01 × 10⁶ ha are ricefields, 6.0 × 10⁵ ha grassland, and 5.7 × 10⁵ ha orchards or other perennial tree crops. The geographical distribution of these lands is complicated by mountainous topography, but each small watershed has a certain regularity in land use: forests at higher altitudes and orchards, grassland, and ordinary crops like rice at lower altitudes.

To describe P transport from the uplands to the lowlands, I ignored the real geographical distribution of each land type and instead used a simplified model in which each island is considered one large watershed, and each land type falls into 1 of 3 categories: 1) forests at higher altitudes (2.52 × 10⁷ ha); 2) upland fields including ordinary crops, grassland, orchards, and other perennial tree crop gardens (2.4 × 10⁶ ha); and 3) lowland ricefields (3.0 × 10⁶ ha).

Flow of phosphorus from uplands to lowlands and estuaries

From several estimated values (Tabuchi and Takamura 1985). I took 5 kg P/ha per yr as the input from rainfall. With this value and the area of each land category, I estimated that annual rainfall adds 1.3 × 10⁴ t P to the forests, 1.2 × 10³ t P to upland fields, and 1.5 × 10³ t P to lowland ricefields. I also took 0.24 kg P/ha per yr as the flow out of the forests (Tabuchi and Takamura 1985). With this value and the area of the forests, I estimated that forests add 6.1 × 10³ t P to the streams annually.

Yatazawa (1978) estimated that 0.5 kg P/ha per yr is leached out of ordinary crop fields. With this value and the area of upland fields, I estimated that upland fields add 1.2 × 10³ t P to the streams annually, assuming as a simplification that all losses accrue in the streams.
From several estimated values (Tabuchi and Takamura 1985), I took 1.5 kg P/ha per yr as the input to ricefields by irrigation. With this value and the area of ricefields, I estimated that lowland ricefields receive $4.5 \times 10^3$ t P from streams as an annual input. I also took 1.5 kg P/ha per yr as the flow out of ricefields—the same as the value for flow in. With this value and the area of ricefields, I estimated that lowland ricefields add $4.5 \times 10^3$ t P to streams annually.

The P contained in agricultural products in 1982 is shown in Table 1: $4.7 \times 10^4$ t P was taken out of upland fields, and $3.1 \times 10^4$ t P from lowland ricefields.

Based on the P application rate for each crop group in 1981 (estimated by Soejima 1983), the amount of P added to each land type was calculated as shown in Table 2: $1.84 \times 10^5$ t P was added to upland fields, and $1.19 \times 10^5$ t P to lowland ricefields.

In 1982, $1.75 \times 10^5$ t P was estimated to be brought in with imports of food and fish for domestic consumption.

Based on the number of livestock and the estimated concentration of P in livestock feces (Matsuzaki 1980), I estimated the amount of P in the feces of all the livestock in Japan (Table 3). Assuming that about 90% of livestock feces is reused as manure (range grazing is not practiced), $1.58 \times 10^5$ t P was recycled to agricultural lands in 1982.

Table 1. P in agricultural products. Japan, 1982.

<table>
<thead>
<tr>
<th>Crop</th>
<th>Production (× 1000 t)</th>
<th>P content (× 1000 t)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Upland field crops</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Rice</td>
<td>58</td>
<td>0.16</td>
</tr>
<tr>
<td>Wheat and barley</td>
<td>436</td>
<td>1.42</td>
</tr>
<tr>
<td>Other cereals</td>
<td>12</td>
<td>0.04</td>
</tr>
<tr>
<td>Sweet potato</td>
<td>1,384</td>
<td>0.60</td>
</tr>
<tr>
<td>Potato</td>
<td>3,775</td>
<td>2.07</td>
</tr>
<tr>
<td>Beans</td>
<td>278</td>
<td>1.98</td>
</tr>
<tr>
<td>Vegetables</td>
<td>16,649</td>
<td>9.15</td>
</tr>
<tr>
<td>Forage crops</td>
<td>9,582</td>
<td>3.56</td>
</tr>
<tr>
<td>Industrial crops</td>
<td>6,577</td>
<td>2.79</td>
</tr>
<tr>
<td><strong>Subtotal</strong></td>
<td></td>
<td>21.77</td>
</tr>
<tr>
<td><strong>Upland orchards and tea</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mandarin orange</td>
<td>2,864</td>
<td>0.42</td>
</tr>
<tr>
<td>Apple</td>
<td>925</td>
<td>0.07</td>
</tr>
<tr>
<td>Other fruits</td>
<td>2,435</td>
<td>0.68</td>
</tr>
<tr>
<td>Tea</td>
<td>99</td>
<td>0.28</td>
</tr>
<tr>
<td><strong>Subtotal</strong></td>
<td></td>
<td>1.45</td>
</tr>
<tr>
<td><strong>Upland grasslands</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Grasses</td>
<td>31,706</td>
<td>23.8</td>
</tr>
<tr>
<td><strong>Subtotal</strong></td>
<td></td>
<td>23.8</td>
</tr>
<tr>
<td><strong>Lowland ricefields</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Rice</td>
<td>10,212</td>
<td>28.2</td>
</tr>
<tr>
<td>Wheat and barley</td>
<td>735</td>
<td>2.34</td>
</tr>
<tr>
<td>Other cereals</td>
<td>19</td>
<td>0.06</td>
</tr>
<tr>
<td><strong>Subtotal</strong></td>
<td></td>
<td>30.6</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td></td>
<td>77.62</td>
</tr>
</tbody>
</table>
Table 2. Padded as chemical fertilizer. Japan, 1982.

<table>
<thead>
<tr>
<th>Crop</th>
<th>P rate (kg/ha)</th>
<th>Land area (× 1000 t)</th>
<th>P added (× 1000 t)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Upland field crops</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Rice</td>
<td>48.4</td>
<td>27.3</td>
<td>1.313</td>
</tr>
<tr>
<td>Wheat and barley</td>
<td>34.9</td>
<td>110.5</td>
<td>3.857</td>
</tr>
<tr>
<td>Other cereals</td>
<td>33.1</td>
<td>9.82</td>
<td>0.325</td>
</tr>
<tr>
<td>Sweet potato</td>
<td>34.9</td>
<td>65.7</td>
<td>2.293</td>
</tr>
<tr>
<td>Potato</td>
<td>67.2</td>
<td>127.2</td>
<td>8.548</td>
</tr>
<tr>
<td>Beans</td>
<td>43.6</td>
<td>272.9</td>
<td>11.898</td>
</tr>
<tr>
<td>Vegetables</td>
<td>90.8</td>
<td>647.0</td>
<td>58.748</td>
</tr>
<tr>
<td>Forage crops</td>
<td>51.5</td>
<td>175.8</td>
<td>9.054</td>
</tr>
<tr>
<td>Tobacco</td>
<td>51.4</td>
<td>56.3</td>
<td>2.894</td>
</tr>
<tr>
<td>Other industrial crops</td>
<td>89.0</td>
<td>125.0</td>
<td>11.125</td>
</tr>
<tr>
<td><strong>Subtotal</strong></td>
<td></td>
<td></td>
<td>110.055</td>
</tr>
<tr>
<td><strong>Upland orchards and tea</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fruits</td>
<td>59.8</td>
<td>399.6</td>
<td>23.9</td>
</tr>
<tr>
<td>Tea</td>
<td>118.3</td>
<td>61.0</td>
<td>7.22</td>
</tr>
<tr>
<td>Mulberry</td>
<td>63.2</td>
<td>113.0</td>
<td>7.14</td>
</tr>
<tr>
<td><strong>Subtotal</strong></td>
<td></td>
<td></td>
<td>38.26</td>
</tr>
<tr>
<td><strong>Upland grasslands</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Grasses</td>
<td>43.6</td>
<td>808.4</td>
<td>35.246</td>
</tr>
<tr>
<td><strong>Subtotal</strong></td>
<td></td>
<td></td>
<td>35.246</td>
</tr>
<tr>
<td><strong>Lowland ricefields</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Rice</td>
<td>48.4</td>
<td>2230.0</td>
<td>107.93</td>
</tr>
<tr>
<td>Wheat and barley</td>
<td>45.4</td>
<td>240.1</td>
<td>10.90</td>
</tr>
<tr>
<td>Other cereals</td>
<td>33.1</td>
<td>15.9</td>
<td>0.526</td>
</tr>
<tr>
<td><strong>Subtotal</strong></td>
<td></td>
<td></td>
<td>119.356</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td></td>
<td></td>
<td>302.917</td>
</tr>
</tbody>
</table>


<table>
<thead>
<tr>
<th>Livestock</th>
<th>Animals (no. × 1000)</th>
<th>Amount of feces (raw wt × 1000 t)</th>
<th>P content (%)</th>
<th>Amount of P (× 1000 t)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beef cattle</td>
<td>2,383</td>
<td>14,351</td>
<td>0.25</td>
<td>35.9</td>
</tr>
<tr>
<td>Dairy cattle</td>
<td>2,103</td>
<td>20,940</td>
<td>0.25</td>
<td>52.4</td>
</tr>
<tr>
<td>Pig</td>
<td>10,044</td>
<td>7,409</td>
<td>0.45</td>
<td>33.3</td>
</tr>
<tr>
<td>Chicken</td>
<td>299,128</td>
<td>3,148</td>
<td>1.70</td>
<td>53.5</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td></td>
<td></td>
<td></td>
<td>175.1</td>
</tr>
</tbody>
</table>

The P concentration of sewage sludge is estimated at 2.26%. The amounts of various types of sewage sludge and amounts of P recovered are shown in Table 4. I estimated that 1.2 × 10⁴ t P was recovered from city wastewater in 1982.

Thus, 8.3 × 10⁴ t P was estimated to flow into streams in 1982 as a result of food and feed consumption. The estimates of P flow were arranged to make a generalized flowchart of P from the uplands to the lowlands (Fig. 1). The annual P flow into the estuaries was calculated to be 9.03 × 10⁴ t.

<table>
<thead>
<tr>
<th>Treatment</th>
<th>Dry weight (× 1000 t)</th>
<th>Amount of P (× 1000 t)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Land backfills</td>
<td>241.7</td>
<td>5.46</td>
</tr>
<tr>
<td>Foreshore deposits</td>
<td>137.3</td>
<td>3.10</td>
</tr>
<tr>
<td>Abandonment (dumps)</td>
<td>43.9</td>
<td>0.99</td>
</tr>
<tr>
<td>Reuse as manure</td>
<td>73.0</td>
<td>1.65</td>
</tr>
<tr>
<td>Industrial reuse</td>
<td>2.9</td>
<td>0.06</td>
</tr>
<tr>
<td>Others</td>
<td>39.4</td>
<td>0.88</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>538.2</strong></td>
<td><strong>12.14</strong></td>
</tr>
</tbody>
</table>


Utilization of phosphorus transported to lowlands

Growing rice in the lowlands utilizes the P transported there. Ricefields with ordinary drainage require $1.5 \times 10^4$ t/ha of river water for irrigation annually in Japan. The rice plant can take up P from the irrigation water, and the soil can retain additional P for later use.

The P concentration of ordinary irrigation water is below 0.1 mg/liter, mostly in the range 0.01-0.04 mg/liter. However, recent population increases in rural areas have resulted in eutrophication of irrigation water, and the water entering some ricefields contains as much as 0.4 mg P/liter. Rice can take up more P from...
such water, and the P concentration in the drainage water is usually lower than in the entering water. With better drainage, this “purification effect” is larger. As eutrophication becomes more common, the use of P transported to the lowlands for rice culture will increase, and its effect on sustaining local agricultural production and the environment will become more important.

The P content of rice by-products is also important. Table 5 shows how the P in rice straw was distributed in 1983 in Japan: $1.87 \times 10^3$ t P in manure, $2.08 \times 10^3$ t P in roughage, $1.34 \times 10^3$ t P in bedding for animals, and $6.86 \times 10^2$ t P in mulch (Ministry of Agriculture, Forestry and Fisheries 1984). The transport to and use of these by-products in upland fields or barns recycle P from the lowlands to the uplands.

Recovery and utilization of phosphorus from estuaries

Use of dredged mud on agricultural lands

The estuary of the Tikugo River (in Saga, Kyusyu) used to be famous for its mud deposits, which were dredged for fertilizing nearby ricefields. But chemical fertilizers and labor shortages have made such dredging very difficult. Moreover, river pollution has rendered the mud less desirable. Table 6 shows the elements found in the deposits of Tokyo Bay (Japanese Society of Ocean Science 1986). The deposits contain Pb, Cu, Cd, and Hg in much higher concentrations than the

<table>
<thead>
<tr>
<th>Usage</th>
<th>Amount of rice straw used (× 1000 t)</th>
<th>Amount of P (t)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Direct mixing with ricefield soil</td>
<td>5093.6</td>
<td>5761</td>
</tr>
<tr>
<td>Manure</td>
<td>1649.3</td>
<td>1865</td>
</tr>
<tr>
<td>Roughage</td>
<td>1836.4</td>
<td>2076</td>
</tr>
<tr>
<td>Bedding</td>
<td>1189.2</td>
<td>1344</td>
</tr>
<tr>
<td>Mulch</td>
<td>606.3</td>
<td>686</td>
</tr>
<tr>
<td>Straw matting and other craftwork</td>
<td>417.4</td>
<td>472</td>
</tr>
</tbody>
</table>


<table>
<thead>
<tr>
<th>Element</th>
<th>Analyses (no.)</th>
<th>Content in deposit (mg/kg)</th>
<th>Annual precipitation (t)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Range</td>
<td>Mean</td>
<td>1981</td>
</tr>
<tr>
<td>P</td>
<td>28</td>
<td>710-1000</td>
<td>840</td>
</tr>
<tr>
<td>N</td>
<td>29</td>
<td>2000-5500</td>
<td>3600</td>
</tr>
<tr>
<td>Pb</td>
<td>28</td>
<td>26-74</td>
<td>47</td>
</tr>
<tr>
<td>Cu</td>
<td>28</td>
<td>34-125</td>
<td>70</td>
</tr>
<tr>
<td>Cd</td>
<td>25</td>
<td>0.6-1.9</td>
<td>1.2</td>
</tr>
<tr>
<td>Hg</td>
<td>27</td>
<td>0.36-0.79</td>
<td>0.56</td>
</tr>
</tbody>
</table>
Table 7. Recovery of P and N by water hyacinth (*Eichhornia crassipes*) grown for 3 or 4 mo, Teganuma Lake and Sinkawa Estuary, Japan (Okuda et al 1983, Ibaraki Prefecture 1988).

<table>
<thead>
<tr>
<th>Location and year (growth period)</th>
<th>Raw weight (t/ha)</th>
<th>Dry matter (t/ha)</th>
<th>P taken up (kg/ha)</th>
<th>N taken up (kg/ha)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Teganuma, 1980 (Jul-Sep)</td>
<td>282</td>
<td>13</td>
<td>96</td>
<td>435</td>
</tr>
<tr>
<td>Teganuma, 1980(^a) (Jul-Sep)</td>
<td>1035</td>
<td>46</td>
<td>353</td>
<td>1596</td>
</tr>
<tr>
<td>Sinkawa, 1986 (Jun-Sep)</td>
<td>513</td>
<td>24</td>
<td>73</td>
<td>653</td>
</tr>
</tbody>
</table>

\(^a\) 75% of plants harvested at mean time of growth.

background (Pb=20, Cu=30, Cd=0.1, Hg=0.1 mg/kg). While the deposits contain appreciable amounts of plant nutrients, the existence of heavy metals prevents their full use on agricultural lands. The agricultural use of dredged mud is now exceptional, only when it has excellent quality and is available nearby.

**Recovery and uptake by aquatic plants**

The role of aquatic plants in the recovery of P from water has been of great interest. However, we have little quantitative knowledge of their role in the whole transport system. Water hyacinth (*Eichhornia crassipes*) is known to take up N and P from water. Some scientists have wanted to use water hyacinth for recovering and using P from eutrophied estuaries and lakes. Table 7 shows measured uptake of P and N by water hyacinth planted in Teganuma Lake (Okuda et al 1983) and in the Sinkawa Estuary (Ibaraki Prefecture 1988): 400-1600 kg P/ha was taken up. With appropriate management, the plant took up an amount of P equaling the P in city wastewater derived from 20,000-30,000 people.

There exist several problems in using aquatic plants. To harvest water hyacinth grown over $9 \times 10^3$ m$^2$ in Teganuma Lake required 30 d of labor and heavy cranes. Transportation of whole plants required 100-200 trucks. This experience teaches that it is not wise to use this kind of technology on a large scale. The harvested plants must be composted for agricultural use or processed into cattle feed.

In the Sinkawa Estuary experiment, 5 t (6.5%) of the harvested plants were composted with 30 t of rice hulls, 3 t of rice bran, 15 t of chicken manure, and 0.75 t of ferment accelerator. Due to the high water content (>95%) of water hyacinth, low-cost composting requires large amounts of materials that absorb excessive moisture, so that only a small part of the harvested plants may be composted.

Matsumoto (1981) reported that water hyacinth contains 10% crude protein, 2% crude fat, 38% soluble N, 19% crude fiber, and 14% crude ash, indicating possible use as cattle feed. But low palatability and difficulties in drying have prevented actual use.
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Citation information: International Rice Research Institute (1990) Phosphorus requirements for sustainable agriculture in Asia and Oceania. P.O. Box 933, Manila, Philippines.
Inorganic reactions influencing phosphorus cycling in soils

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Of the several inorganic transfer processes that control the concentration of P in solution in terrestrial ecosystems, those involving dissolution-precipitation and sorption-desorption reactions are the most important. Minerals of the apatite group dissolve by chemical weathering under acid conditions, but their formation in unfertilized soils seems highly unlikely. Although secondary Fe and Al phosphates may precipitate as transient reaction products in acid, fertilized soils, their importance as a controlling influence in P cycling seems limited. Sorption-desorption reactions provide a better description of P uptake and release by soils. Several factors that influence the sorption-desorption of P by soil components are briefly reviewed. The lack of reversibility of sorption is attributable to the diffusive penetration or absorption of initially adsorbed P. The mechanisms involved in the sorption of P on a hydrous metal oxide surface invariably involve ligand exchange and are reasonably well understood. Good progress has been made with modeling the sorption and desorption of P by hydrous metal oxides, but the applicability of this approach to soils has limitations. A better understanding of sorption-desorption reactions in soils will provide much of the required information on inorganic controls on P cycling.

The widespread use of P fertilizers, prepared by the chemical processing of naturally occurring phosphate rock (PR) materials, has had an enormous impact on agricultural production in many countries. This is particularly the case in tropical regions, where the soils are usually P deficient.

Substantial work has been directed toward increasing the efficiency of P fertilizer use, but progress has been limited because of the complexity of the soil-plant system.

In this regard, improved knowledge of P cycling in terrestrial ecosystems is required for the development of management strategies and policies for using this vitally important resource.

Syers and Curtin (1989) discuss the inorganic reactions involved in P cycling. Solution P is the focal point of this cycle, with several transfer processes operating to control the concentration of inorganic P in the soil solution. The most important reactions in the inorganic P cycle involve dissolution-precipitation and sorption-desorption. This paper reinforces the discussion by Syers and Curtin (1989) and includes additional material from China on the effect of liming and organic manures on P sorption.
Dissolution-precipitation reactions

It is convenient to consider systems in which Ca is the dominant controlling cation (neutral or calcareous environments) separately from those in which Fe and Al are the dominant controlling cations (acidic environments).

Ca systems

Minerals of the apatite group are by far the most dominant P minerals in rocks and sediments. These are Ca phosphates having the general formula $\text{Ca}_{10}(\text{PO}_4)_6\text{X}_2$, where $\text{X} = \text{F}, \text{Cl}, \text{OH}$, or $\frac{1}{2}\text{CO}_3$. Fluorapatite is the most stable and most abundant apatite (McConnell 1979), but, like all apatites, it dissolves under acid conditions. Information on the dissolution rate of apatite in soils has been obtained from chronosequence studies (Walker and Syers 1976) in temperate environments. Apatite contents of soils decrease during weathering, while other forms of P increase, at least initially. With time, there is an overall decrease in total P due to leaching and erosion. It is very difficult to predict the rate of disappearance of apatite in different environments. There is an acute shortage of information on this important first step in the P cycle.

Calcium phosphates precipitate following an initial adsorption of P onto calcite (Freeman and Rowell 1981, Griffin and Jurinak 1973). Freeman and Rowell (1981) showed that phosphate was initially reversibly adsorbed on calcite, followed by the rapid formation of dicalcium phosphate, and finally by a slow change to octacalcium phosphate, the reaction products being identified by x-ray diffraction analysis. The extent to which these reactions proceed under field conditions is not at all well established.

The use of ion-activity product data and solubility isotherms to indicate the formation of Ca and other metal phosphate compounds in soils was discussed by Syers and Curtin (1989). Dicalcium phosphate and dicalcium phosphate dihydrate form as reaction products in soils to which monocalcium phosphate (MCP) is added (Lindsay et al 1959). However, these compounds are unlikely to persist, even in weakly acid soils (Probert and Larsen 1970). It further seems doubtful that such compounds will form in unfertilized soils or in sediments, because P concentrations are not sufficiently high.

Fe and Al systems

Several short-range order Fe and Al phosphate compounds appear to form in soils when MCP is added (Taylor et al 1963). It has been suggested that the short-range order phosphate compounds may slowly crystallize to strengite ($\text{FePO}_4.2\text{H}_2\text{O}$) and variscite ($\text{AlPO}_4.2\text{H}_2\text{O}$).

It seems unlikely that such compounds persist, even if they form in soils, and thus their likely importance as a controlling influence in P cycling seems to be limited (Syers and Curtin 1989).

As with Ca phosphate systems, ion-activity data have been used to assess the formation of Fe and Al phosphates in soils, but available evidence suggests that the solubility of P compounds does not satisfactorily explain the observed soil solution P
concentrations (Bache 1963, Wild 1954). Ryden and Pratt (1980) showed that between pH 4 and 7 the P concentrations and pH values of soil extracts were independent, being undersaturated with respect to all P compounds between pH 5.5 and 6.5.

Although dissolution-precipitation theory is still used to describe the interaction of P with soil components, good evidence for the participation of such reactions in P cycling is rarely forthcoming. With the possible exception of recently fertilized soils, the uptake and release of P by soils can be described better by sorption-desorption reactions.

**Sorption-desorption reactions**

There is an important practical distinction between sorption and precipitation reactions in terms of the control over solution P concentrations. Whereas the sorption theory requires that the amount of P sorbed is determined largely by solution P concentration, the precipitation theory requires that the solubility product of the least soluble P compound control the solution P concentration. At high saturations of the sorption complex, the concentration of P maintained in solution is higher.

Sorption describes the removal of phosphate ions from solution by soil components. Adsorption (a surface reaction) may or may not be followed by absorption (Barrow 1990). Sorption isotherms are used to describe the relationship between the amount of P sorbed and that remaining in solution at constant temperature. The overall shape of these isotherms is usually remarkably similar, despite the often large differences in the amounts of P sorbed at a particular solution P concentration (Ryden et al 1977a).

Desorption is the reverse reaction of sorption and describes the release of sorbed P into solution. It is well established that P is not reversibly sorbed by soil components; that is, the sorption and desorption isotherms are not coincidental. The desorption isotherm is displaced to the left of the sorption isotherm; i.e., during the desorption phase, a lower solution P concentration is maintained for a given quantity of sorbed P.

The concept of irreversibility of P sorption has been questioned by Barrow (1985,1990). If desorption differs from adsorption, then either desorption is slower and insufficient time has been allowed, or a further process follows the initial adsorption so that a part of the “adsorbed” P is no longer in equilibrium with the solution. The diffusive penetration of initially adsorbed P, in fact an absorption process, explains the lack of reversibility of P adsorption (Barrow 1983b). and this can be modeled (Barrow 1983a), as discussed in the next page.

**Factors affecting sorption-desorption reactions**

Factors that influence the sorption and desorption of P by soil components include the amount and nature of the components involved, other ions, pH of the system, and kinetics of the reaction. These have been discussed in detail in recent reviews (Barrow 1985, Parfitt 1978).

Hydrous metal oxides of Fe and Al, and particularly short-range order components, are important in the sorption of P by soils (Bache 1963, Parfitt 1978). Even in
calcareous soils, it seems likely that small amounts of hydrous ferric oxide dominate the P sorption complex (Griffin and Jurinak 1973, Holford and Mattingly 1975).

Under reducing conditions in soils, P is released to solution, and this is related to the reduction of ferric iron to ferrous iron (Yu 1985) and the partial elimination of P sorption sites (Syers et al 1973).

Cations and certain other anions influence P-sorption to varying extents, and it is well recognized that more P is sorbed from a Ca system than from a Na system. Explanations for this range from the formation of insoluble Ca phosphates (Wild 1950) to the effect of the divalent cation on the screening of surface negative charge (Ryden et al 1977b) or of surface potential (Barrow 1985).

With the except of OH-, inorganic anions have a limited ability to compete with P for sites on hydrous ferric oxide gel (Ryden et al 1987), and no inorganic anion other than OH- is likely to be present in sufficient concentration to affect P sorption.

Certain organic anions can affect P sorption, either by direct competition for sorption sites or even by the elimination of sites by dissolution (Earl et al 1979). Extensive work in China has shown that adding organic manures to soil can decrease P sorption, probably through the competing effect of humic substances for P sorption sites. Effects on P sorption of adding three organic manures are shown in Figure 1.

1. Effect of adding organic manures on P sorption by soil.
Unpublished data from the Institute of Soil Science, Academia Sinica, Nanjing, China, indicate that some soils can sorb a very high proportion of the humic substances extracted from organic manures and added to soil.

Liming of soils can increase (Amarasiri and Olsen 1973), decrease (Woodruff and Kamprath 1965), or not affect (Reeve and Summer 1970) P sorption by soils. These contrasting effects have been attributed to differences in the soil incubation procedures used (Haynes 1982), the pH over which sorption is measured, the amount of desorbable P in the soil, the support electrolyte used, and the relationship between surface potential and pH (Barrow 1984). The varying effects of added lime on P sorption by two Chinese soils are shown in Figure 2, where sorption was increased (soil B) and decreased (soil A) when lime was added.

**Modeling**

Good progress has been made in recent years in modeling the sorption and desorption of P by goethite. The model, initially developed by Bowden et al (1977), has been extended by Barrow (1983a) to describe the reaction between divalent phosphate ions and a variable charge surface, and the solid-state diffusion of initially adsorbed P towards the interior of the particle. A difficulty in applying the model is that the electrostatic potential cannot be measured. Values have been assigned to it for well-defined materials, such as goethite, but this is not possible for soils, and an alternative approach (Poner and Barrow 1982) is required.

The mechanistic model extended and tested by Barrow (1983a) provides a close description of the effects on P sorption of P concentration, pH, contact time, and

2. Sorption of P by limed (+L) and unlimed samples of red earth (soil A) and a rice soil (soil B) from Jiangxi Province, China.
temperature. In particular, it accommodates the diffusive penetration or absorption of P into soil particles, which can explain the lack of reversibility of sorption and the continuing, slow removal of P from solution over time.

Rationalization of retention reactions

Although sorption-desorption reactions are considered to provide a better description of the chemistry of P in soils, the role of dissolution-precipitation reactions in certain situations must be recognized. In particular, the dissolution of apatite in unfertilized soils is clearly an important starting point in P cycling. Over time, apatite forms, as in marine phosphorites, through the phosphatization of calcium carbonate. Secondary Ca, Fe, and Al phosphates may form in fertilized soils, but their persistence seems unlikely, given their instability in most situations. Vivianite can form in strongly reducing environments in soils. However, it is with sorption-desorption reactions that the best prospects of understanding the inorganic controls on P cycling lie. These are by no means fully understood, because of the complexity of the systems.

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Citation information: International Rice Research Institute (1990) Phosphorus requirements for sustainable agriculture in Asia and Oceania. P.O. Box 933, Manila, Philippines.
Relating chemical processes to management systems

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This article reviews the characteristics of the reaction between soil and P, particularly the effects of concentration, time, temperature, repeated additions, pH, and electrolyte concentration on sorption. The characteristics of desorption are also discussed. A theory of the mechanism of reaction that is compatible with these observations is then outlined. It is proposed that phosphate ions are initially adsorbed onto variable-charge surfaces, that the surfaces are nonuniform, and that diffusive penetration of the adsorbing material follows. This information is then used to suggest ways in which P fertilizer could be managed more efficiently. Greatest improvement is likely to come from better understanding of the fate of previous P applications and appropriate adjustment of future applications.

The most important fact in managing any P fertilizer program is that P reacts with soil. That is, if we supply P in a soluble form, much of it reacts with the solid phase of the soil, and little remains in the soil solution. This is not entirely a bad thing; if it did not happen, much more P would be leached out of the soil and we would have even more pollution problems. Nevertheless, it has been frequently shown that the greater the reaction between soil and P, the more fertilizer we have to apply to get good growth. This is because the supply of phosphate to plant roots depends largely on diffusion; diffusion, in turn, depends on the proportion of the P that is in the soil solution. The smaller this proportion, the more P is needed to give an adequate rate of supply. Reduced to its simplest terms, management of P fertilization is aimed at maintaining an adequate concentration in the soil solution at least cost. Options that we might consider include modifying the environment or the method of application to decrease the amount of P in the solid phase; selecting an application schedule such that the concentration does not become too low or too high; and using a sparingly soluble P source in order to decrease the importance of the reaction with the soil. Before considering these, I will summarize the characteristics of the reaction between phosphate and soil and the possible mechanism. In this summary I have used references sparingly. The reader seeking more details will find them in Barrow (1980a, 1983, 1987).

Characteristics of the reaction

The reaction between soil and P is influenced by many factors, including concentration, time, temperature, previous additives, pH, and electrolyte concentration.
**Concentration effects**

Perhaps one of the most studied aspects of P chemistry is the relation between the amount sorbed by soil and the concentration in solution. I use the word “sorbed” in a nonmechanistic way, meaning merely that the P has been removed from the solution phase; it includes all of the possible mechanisms. Some of the sorbed P might be adsorbed, i.e., held by chemical reaction on the surface of the soil particles.

There is a very good reason for the interest in the relation between sorption and concentration; such relationship is very important in determining the rate of P supply to plants. It is also important in determining the point at which so much P has been applied that substantial leaching into drainage water occurs. A curved relation is always found between sorption and solution concentration, and much sweat and ink have been devoted to describing this relation. The Langmuir equation often describes the shape fairly well, but with large and consistent deviations. The Freundlich equation is usually better—for many purposes it is good enough—but if the range of data is large, modifications to the equation, such as that of Sibbesen (1981), may be preferred.

What do we gain from describing the relation between sorption and concentration? At best, we have an efficient summary of a large set of numbers. Such a summary can then be useful for comparing soils, for interpolating between observations, and for focusing our attention on the mechanism that gives rise to curves of this particular shape. The summary cannot, of itself, tell us much about the mechanism. One reason is that such curves are just the two-dimensional shadow of multidimensional curves, the other dimensions including time, temperature, pH, and electrolyte concentration.

**Effects of time**

The reaction between soil and P is rapid at first; it then becomes slower, but continues at an ever-decreasing rate for a very long time. Clearly this is also important. If the proportion of the P that is in the soil solution decreases through time, then the rate of supply to plants also decreases. The rate and extent of this reaction therefore influence both the effectiveness of a current application of P and the current effect of P applied many years ago. Yet it is a property that has not often been measured. Before we can discuss the relatively few results that have been obtained, we need a method to summarize the observations.

Several studies have shown that the following equation effectively summarizes the effects of both concentration and of time on P sorption: \( S = a c^{b_1} t^{b_2} \) where \( S \) is the amount sorbed per unit weight of soil, \( c \) is the concentration in solution, \( t \) is time, and the other symbols are coefficients. The dimensions of the terms in this equation sometimes cause confusion. It is usually considered that the dimensions of \( b_1 \) and \( b_2 \) are such that raising concentration and time to these powers renders the resulting terms dimensionless. The coefficient \( a \) therefore, has the same dimensions as \( S \). It is the amount sorbed per unit weight of soil at unit concentration in solution and at unit time.

Consider the coefficient \( b_2 \). If its value should be as high as one, then sorption would be linearly related to time. If, on the other hand, the coefficient should be as
low as zero, then sorption would be instantaneous. This number therefore tells us the shape of the relation: a small value means that the reaction is relatively fast at first but becomes very slow; a large value means that it is relatively slow at first but persists. The range of reported values for \( b_2 \) is large: for some Western Australian soils, Barrow and Shaw (1975) reported values that ranged from 0.16 to 0.3; for some North American soils, the range was 0.03 to 0.36 (Barrow 1980b); for a collection of soils from New Zealand, Thailand, Alabama, California, Hawaii, and Australia, the range was 0.07-0.27 (Barrow 1980c); for some Argentinian soils, 0.124.20 (Mendoza and Barrow 1987); and for some Mediterranean soils, 0.07-0.19 (Torrent 1987).

**Temperature effects**

The reaction between P and soil is a chemical reaction, albeit one that may have more than one step. Temperature may have two distinct effects on a chemical reaction: it may affect the rate of approach to equilibrium, and it may affect the position of the equilibrium. Both of these effects occur with P and soil. Increasing temperature greatly increases the rate of the reaction. If there is indeed more than one step, then we assume that this effect is on the slowest step—that is, the rate-limiting step. We can describe the effect by rewriting the rate equation as

\[
S = c^{b_1}(kt)^{b_2}
\]

where \( kt \) can be regarded as scaled time. In turn, \( k \) is related to temperature by the Arrhenius equation:

\[
k = A \exp(-E/RT)
\]

where \( E \) is the activation energy. The value of \( E \) is often about 80 kJ/mole. This has two important consequences. First, this value means that the rate increases roughly 3-fold for each 10-degree increase in temperature. By studying the reaction at, say 60 °C, we can therefore “compress” a year’s reaction into a week—an enormous advantage in studying the process. It is in the nature of science that we cannot prove that treatment at high temperature for a short time is identical with treatment for a long time at low temperature. We can only show that in important aspects—such as plant response, solution concentration, desorption, or isotopic exchange—they do not differ.

The second consequence of the large activation energy is that it gives us some clues about the mechanism. It shows, for example, that the rate-limiting step is not diffusion in solution, as this would require much less activation energy. Diffusion in the solid state would, however, require a large activation energy, because it involves atoms jumping over energy barriers in crystals. A further clue is that the activation energy for desorption is also about 80 kJ/mole. This suggests that the rate-limiting step is the same in both cases—as it would be for solid state diffusion.

Suppose we incubate soil with P for a long time, or at a high temperature. The rate of the continuing reaction then becomes so slow that, over short intervals (e.g., 15 min), it can be ignored. If we now look at the effect of temperature, we find that increasing the temperature increases the concentration in solution (Barrow and Shaw 1975). This is the effect of temperature on the *position* of the equilibrium.
between solution P and P on the surface of the soil particles—adsorbed P. This result shows that the adsorption step is indeed exothermic. It also shows that there are at least two steps involved: an initial exothermic adsorption step followed by a slow step, the rate of which is increased by temperature. Therefore, two separate soil properties should be considered in any management plan: the extent of the initial adsorption reaction and the rate of the subsequent slow reaction. These need not be correlated.

**Effects of application level**

The equation

\[ S = C^{b_1} (kt)^{b_2} \]

also describes a further important property of the reaction between soil and P. If we consider the reaction at any given value of time, then the relation between sorption and concentration in solution is clearly nonlinear. If we increase the concentration in solution, we do not produce a proportional increase in the amount of sorption. And if we increase the amount sorbed, we produce a disproportionate increase in concentration in solution. Nevertheless, the proportion changed to a firmly held form is independent of the application level. We have shown this to be the case in experiments involving plant response and in studies with isotopically exchanged phosphate. We can show that this is consistent with the above equation if we assume that the amount of adsorbed P is proportional to \( C^{b_1} \). Then the fraction that is adsorbed is proportional to \( C^{b_1} / S \) and to \( (kt)^{-b_2} \). That is, the fraction of the P that remains in the adsorbed form decreases with time but is independent of the amount. The management aspect of this result is that, no matter what the other advantages of banding fertilizer may be, it does not decrease the importance of the continuing reaction between soil and P.

**Effects of repeated additions and desorption**

The history of P chemistry in soil is replete with misleading terms. One of the most misleading is “irreversible adsorption.” This term has been used to describe the observation that plots of desorption against concentration do not follow the same track as plots of sorption against concentration. It is misleading because true adsorption must be reversible. This is because the reaction involved in true adsorption cannot go fully to the “right”—there must always be a substantial back reaction. If this were not so, we could not draw graphs of adsorption against concentration, for there would be no P remaining in solution. A reaction with an appreciable back reaction is, by definition, reversible. The observation that sorption is not reversible with respect to concentration does not mean that we have irreversible adsorption. It means that we do not have simple adsorption. It differs in two ways. First, as indicated above, a slow reaction occurs—removing some of the P from the adsorbed form. The longer the reaction has proceeded, the slower the subsequent desorption. Second, the electric charge on a soil particle that has reacted with P has become more negative. This change in the charge and in the electric potential of the surface affects both the desorption of previously added P and the
sorption of freshly added P. For these two reasons, we should not compare plots of desorption against concentration with plots of initial sorption against concentration. Rather we should compare desorption with sorption of newly added P. The slopes of such plots decrease with increasing time, because the properties of the reacting surfaces have changed; but plots of desorption remain consistent with plots of sorption of newly added P. This subject is discussed at greater length in Barrow (1987).

Effects of pH and electrolyte concentration

It is desirable to consider pH and electrolyte concentration together, because there is a large interaction between them. This has been a source of some of the controversy about the effects of pH on P sorption, but it also provides important clues about the mechanisms involved. When the effects of pH on P sorption are studied using Fe oxides as a model for soil, increasing pH always decreases sorption. This result has been contrasted with the less consistent effects with soil (White 1983). However, studies with Fe oxides have always used either Na or K salts as background electrolytes. The results with Fe oxide are, in fact, consistent with those of soil studies that also used dilute Na or K salts as background electrolytes (Obihara and Russell 1972, Lopez-Hernandez and Burnham 1974, Parfitt 1977). When Ca salts or concentrated solutions of Na salts are used, however, the decrease in sorption with increasing pH is not nearly as marked—and in some cases an increase in sorption above about pH 5.5 occurs (e.g., Barrow 1984). We should not find these results surprising. The reaction between P and soil is a reaction between charged particles (P ions) and variable-charge surfaces. Both the ions present and the charge on the surface vary with pH and, in addition, the charge and potential of the surface are affected by the electrolyte present. If the surfaces reacting with P are mainly negative—as they are for most soils at common pH values—then increasing the concentration of cations, or increasing the valence of the cation, makes the electric potential less negative and increases P sorption. The higher the pH, the greater this effect. Hence, if we want to realistically assess the effect of changing the pH on P sorption by a particular soil, we had better make the measurements in a solution of realistic concentration and composition.

A further source of controversy about the effects of pH on P sorption is the practical problem being investigated. Suppose we have a low-P soil and are contemplating applying P, we would want to know the effect of modifying the pH before applying the P. Suppose, on the other hand, we had a soil with appreciable available P. We might then want to know the effect of modifying the pH on the availability of that P. The two situations are quite different, and failure to distinguish them could lead to confusion. I found, for example (Barrow 1984), that P sorption tended to be higher at low pH. This, on its own, would lead us to think that decreasing the pH would decrease P availability. Yet decreasing the pH increased the desorption of P that had previously been added. This apparently puzzling result also occurs because changing the pH changes the electric potential of the surface, and the consequences of this change depend on the direction in which the phosphate is moving—whether away from, or toward the surface.
Explaining the characteristics of the reaction

Many mechanisms have been suggested to explain the reaction of soil with P. However, a satisfying explanation should be able to explain all of the above observations. It should do so with as few postulates as possible and these postulates should be realistic. It should be able to describe the observations precisely, and it should apply to nutrients other than P. That is, it should be comprehensive, efficient, effective, and realistic.

Such a model has three postulates: that phosphate ions are initially adsorbed onto variable-charge surfaces in soil; that these surfaces are not uniform; and that this initial adsorption is followed by a diffusive penetration of the adsorbing particle. These postulates can be expressed precisely in the form of equations, and these equations can then be included in computer programs that can be used to explore the consequences of the assumptions. These are dealt with in detail by Barrow (1987). Here we will confine ourselves to a brief overview of the way the model’s predictions match the observations.

The postulate that there is an initial adsorption reaction is needed to explain the observed effects of temperature on the position of the equilibrium between solution P and adsorbed P. That the reaction involves ions and that these react with variable-charge surfaces is indicated by the observations of the effects of pH and the interactions with electrolyte concentration. The postulate that the reacting surfaces are not uniform is needed to reproduce the observed shape of the relation between sorption and concentration and to explain certain observations on the point of zero charge (see later). The diffusion process that follows the initial adsorption is postulated to be very slow and to be the rate-limiting step. Because it is the rate-limiting step, anything that increases this step will increase the overall rate. It is here that the effect of temperature is postulated to work. Let us consider some aspects of the model in a little more detail.

In the normal range of soil pH values, P is present in solution mostly as HPO₄²⁻ and H₂PO₄⁻. Although both species could conceivably be adsorbed, the observed effects are best explained if it is assumed that the affinity of the reacting surface for the HPO₄²⁻ ion is much greater than that for H₂PO₄⁻. Then, at say pH 4, the concentration of HPO₄²⁻ ions is low, but it increases 10-fold for each unit increase in pH. This logarithmic increase holds until about pH 6, but then as the pK₂ is approached (at about pH 7), the rate of increase becomes much smaller. These effects, of themselves, would produce a large increase in sorption with increasing pH. However, they are opposed by an increasingly negative potential on the reacting surface, and this tends to decrease sorption. The outcome of these opposing tendencies depends on the background electrolyte. If this is dilute, and especially if the cation is monovalent, the effect of the decreasing potential dominates and sorption decreases with increasing pH. It is interesting to compare these effects on phosphate with those on borate. The concentration of the borate ion also increases with increasing pH, but the borate ion is monovalent. The increasingly negative electric potential, therefore, has less effect, and sorption increases with increasing pH.
One of the consequences of the interaction between pH and electrolyte concentration is that it is possible to locate a pH value at which changing the salt concentration has no effect on the amount of sorption. At this pH, the average potential of the reacting sites must be zero. At higher pH values, increasing the salt concentration increases sorption, and this indicates that the reacting surfaces are mainly negatively charged. At lower pH values, increasing the salt concentration decreases sorption, indicating that the reacting surfaces are mainly positively charged. These observations show that phosphate is indeed reacting with variable-charge surfaces. An intriguing aspect is that the point of zero salt effect on phosphate is at a higher pH value than the point of zero salt effect on pH. For example, at pH 4.3 for one soil, changing the salt concentration had no effect on the measured pH, and this was also the pH at which the measured value for the net charge was zero. Yet, at this pH, phosphate was apparently reacting with mainly positive sites, because increasing the salt concentration decreased sorption. It follows that the variable charge sites had a range of electric potentials and the phosphate was reacting with the positive end of the distribution of potentials. It was not until the pH had been raised to about 6 that the electric potential of the sites that reacted with phosphate decreased to zero.

The postulated diffusion mechanism is an effective way of explaining some of the puzzling observations on the effects of time. If the surface concentration of adsorbed P remains constant, then the amount diffusing into the solid in a given time is expected to be proportional to the surface concentration and to the square root of time, i.e., to $t^{0.5}$. However, the power for time is observed to be less than 0.5, partly because the diffusion step follows the initial adsorption step, and so we do not see pure kinetics, and partly because the rate of diffusion is slowed down by a feedback effect. Its mechanism is as follows. Penetrated P decreases the surface charge, and this means the surface is less attractive to P. Even if the solution concentration were constant, the concentration of adsorbed P would decrease. Consequently, the gradient of P into the solid is decreased and thus the rate of diffusion decreases.

If we accept that the slow reaction that follows adsorption does indeed involve diffusion, this has important consequences for our thinking about the availability of this P. It suggests that this P is not “fixed”—that is, it is never completely unavailable. Rather, the rate at which it can return to the surface of the soil particle decreases with time as the P becomes more deeply buried. It also suggests that it is wrong to try to divide soil P into two categories called “available” and “unavailable.” Rather, there is a continuum of rate of supply, ranging from almost instantaneous for freshly added P to a rate that is far too slow for adequate growth of plants. Where a previous P application stands in this continuum depends on the period that has elapsed since it was applied, and on the characteristics of the particular soil.

Management options

One of the most frequently considered options is that of changing the soil pH—usually to raise it with lime. However, when lime is beneficial, it may be for reasons not directly related to P supply from the soil. It may, for example, cure toxicities of
Mn or Al. Where the effects are on P, they may be on the plant component rather than the soil component. There are optimum pH values for P uptake by roots (Hagen and Hopkins 1955, Hendrix 1967). It would be surprising if this optimum were the same for all plants, but little attention seems to have been paid to this. Where there are effects on phosphate sorption by soil, they are not very large compared with the effects of pH on sulfate. As explained earlier, this is because of the dissociation behavior of phosphate ions. P contrasts with sulfate, which is already fully dissociated at, say, pH 4, and further increases in pH can only have the effect of decreasing sorption. Furthermore, any benefit due to decreased sorption of added P may be offset by decreased desorption of the P that is already there. In short, the benefits obtained from increasing the pH of acid soils are not as large as has sometimes been supposed and are not entirely due to improved supply of P from the soil. One would expect the benefits to be greatest on a soil that has a very low P status and that is about to be fertilized with P.

Another management option is to confine the added P to a band. This introduces a further complexity, because the precipitates that form when concentrated P solutions from fertilizer granules react with soil will be more important. It will take longer for the P to diffuse from them and therefore longer for them to dissolve than if the P were mixed through the soil. For this reason, and because the relation between the amount of P present and the concentration is nonlinear, the proportion of the added P in solution in the band will be higher. Diffusion to plant roots that penetrate the band will therefore be faster. However, the slow reaction is not affected by banding, for the proportion changed is independent of the local concentration. Of course, the overall effect of banding depends on more than soil chemistry. It is more likely to be beneficial if the P is placed so that a seedling root reaches it before the seed’s supply of P is too depleted. However, high concentrations of P may be, in fact, too high for efficient uptake by roots. Hence, in a very P-deficient soil, the net effect may be inefficient uptake by some of the roots and zero uptake by the remainder. This is consistent with the work of Fox (1980), who considered several experiments and concluded that major benefits could not be achieved from banding in such soils. Sanchez and Uehara (1980) also pointed out the disadvantages of banding P in soils of very low P status, but concluded it was more likely to be beneficial when P was reapplied to previously fertilized soils.

If it is difficult to make large improvements in the effectiveness of soluble P fertilizer, perhaps we can avoid the problems by using sparingly soluble sources, thus maintaining a steady, if slow, supply of P to the soil solution. The question is then whether it is possible to achieve an adequate rate of dissolution. All soluble materials dissolve by losing atoms from their surface. If these atoms are then removed from near the surface, dissolution will continue; if not, it will stop as soon as a certain concentration in solution has been reached. In the case of phosphate rock (PR), the surface loses phosphate, hydroxide, and calcium ions. If dissolution is to continue, the soil must be a good sink for these ions. For example, not only should the pH be low, but the buffering capacity for pH should be high. Thus, a good soil for dissolution of PR may be a poor one for plant growth. Sanchez and Uehara (1980) suggested the strategy of applying PR several months ahead of liming. If the soil is a
good sink for phosphate ions, PR will indeed dissolve quickly, but the availability to plants will not be high.

The factors that determine the rate of solution of PR have been included in a model by Kirk and Nye (1986). The model may be used to evaluate the conditions that give rise to rapid dissolution. Of the conditions that can be controlled by the experimenter, the two that have the largest effect are the size of the fertilizer particle and the uniformity of mixing through the soil. Small particles have a large total surface area and therefore dissolve faster, but only if they are mixed uniformly through the soil. If they are not uniformly mixed, the diffusion zones around each particle overlap and the rate of dissolution is decreased. This is one of the dilemmas with PR. To be effective, it needs to be finely ground and uniformly mixed with soil, which is difficult to achieve in agricultural practice. Even then, PR is not very effective—perhaps on average about a tenth as effective as soluble sources (although individual sources may be better or worse than this). This suggests the strategy of applying 10 times as much and expecting this application to be effective for a long time. However, as the application level increases, the diffusion zones around each particle are more likely to interact, and so the rate of solution decreases. One therefore has a situation like a dog chasing its tail—the more one applies, the slower it dissolves and the less effective it becomes relative to soluble sources. This is the reason for several reports that even very high applications of PR cannot reach the same maximum yields that soluble P can. Bolland and Barrow (1988) analyze this behavior.

This brief survey suggests there is no magic method by which the effectiveness of P fertilizer can be greatly increased. This should not surprise us. Phosphate fertilizer has been used for over a hundred years, and any easy solutions to the problems would surely have been found. Improvement in efficiency can come, however, from rational reapplication of P. This, in turn, requires rational consideration of the fate of previously applied P.

Some P may be lost by erosion, and some may be lost in drainage water. These losses are normally small. If the content of soil organic matter is increasing, then accumulation of organic P may, in effect, remove some P from circulation. Again, this is usually small. Large losses can, however, occur in produce removed from the land. Annual removal may be as high as 75 kg/ha for repeatedly cut, high-yielding, tropical pasture (Younge and Plucknett 1966). At the other extreme, if wool is the only product, the annual loss of P is trivial. Clearly, each case needs to be considered on its own merits. Often a very simple calculation involving approximate yields and P concentrations can give a value of adequate accuracy.

Very large decreases in effectiveness due to the continuing reaction between soil and P can also occur. As explained earlier, the extent of this can be summarized by the $b_2$ coefficients, which have been observed to range from 0.03 to 0.36. This range of values may have been important in causing some of the controversy about rational fertilizer policy. A scientist working on soils for which $b_2$ is small, and especially if the agricultural system is such that large amounts of P are removed in produce, might well conclude that one need do little more than replace the P removed in produce. This appears to be the case on the allophanic soils of the
Waikato region of New Zealand. On these soils, $b_2$ is small (Barrow 1980b) and P removal is large (Middleton and Smith 1978). Lines 3 and 4 of Figure 1 simulate this situation. They show, that even for a soil that sorbs P strongly and therefore needs high initial P applications, required applications soon decrease to low levels. On the other hand, a scientist working on soils for which $b_2$ is large, and especially on systems for which removal in produce is small, would conclude that merely replacing the P removed in produce would be quite unsatisfactory. Lines 1 and 2 of Figure 1 are meant to simulate this situation. They show that the required application is much higher than the P removed. However, they also show that, even for the unfavorable assumptions of these cases, the amounts of P required are much lower than the initial requirement. This is consistent with the conclusions of Fox (1980) that on soils that sorb P strongly, the initial P application should be regarded as a capital investment. On some tropical soils, the capital investment may be very large—but perhaps we should not make other capital investments unless we are prepared to also make this one. The differences between, on the one hand, lines 1 and 2, and, on the other hand, lines 3 and 4, emphasize the need for information on the rate of reaction of soil with P when planning fertilization strategy.

Figure 1 illustrates a very simple approach in which P applied several seasons ago and which has not been removed in produce or by other means is equated to units of fresh P. Thus, one might say, for example, that 100 units of old P produced as much yield as perhaps 30 units of fresh P and therefore the old P was 30% as good as fresh P. This is often a convenient summary, but it may hide important aspects. For example, the two P sources will have had different time trends through the growing season. The fresh P will have given a relatively high rate of supply soon after application, but this will have declined rapidly, whereas the rate of supply of the old

![Graph](image)
P will not have changed much during the growing season. The relatively high availability of the fresh P may be very important in providing adequate P to young plants.

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Notes

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Citation information: International Rice Research Institute (1990) Phosphorus requirements for sustainable agriculture in Asia and Oceania. P.O. Box 933, Manila, Philippines.
Phosphorus chemistry in relation to water regime

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The influence of water regime on reactions of P with soils and on plant P uptake is discussed, with particular emphasis on flooded rice soils and the effects on P reactions of the physicochemical changes following flooding. The major control on solution P in flooded soils is sorption by charged surfaces, particularly the surfaces of poorly crystalline hydrous Fe oxides, and the changes in soil Fe following flooding profoundly influence P reactions. Researchable items are suggested for developing ways of improving the efficiency of P fertilizer use, and for providing a rational basis for selecting rice varieties that are efficient at taking up P. Mathematical modeling should play a major role in future work because of the complexity of reactions of native and fertilizer P with flooded soils, and because the processes controlling P uptake by rice roots in flooded soils are experimentally inaccessible.

Water regimes strongly influence soil P chemistry, both directly through changes in water content and indirectly through changes in soil physicochemical conditions. But despite the enormous global importance of wetland rice soils and their very singular water regimes, their P chemistry has received scant attention compared with that of nonflooded soils. This is mainly because use of P fertilizers in rice production has been far less important than use of N. But P fertility is likely to be an increasingly important constraint as P is mined from soils under intensive rice production, and as attention is increasingly turned to improving rice production in less favorable environments. In the future, therefore, a much better understanding of flooded soil P chemistry will be needed.

This paper focuses on the P chemistry of flooded soils; reviews the current state of knowledge, indicating where we think the most important knowledge gaps are; and gives our recommendations for future research. Although we focus on flooded soils, many of the processes described also occur in localized spots in nonflooded soils subjected to wetting and drying cycles.

Physicochemical changes following flooding that affect phosphorus chemistry

The major physicochemical changes, consequent upon flooding, that influence P chemistry have been reviewed extensively by Patrick et al (1989, Ponnampuruma
212 Kirk et al (1985), and Yu (1985). Figure 1 illustrates the changes with time that are commonly found in neutral and acid soils. These are

- microbially mediated reduction of soil Fe

\[
\text{Fe(OH)}_3 + 3\text{H}^+ + e^- \rightarrow \text{Fe}^{2+} + 3 \text{H}_2\text{O}
\]
resulting in accumulation of exchangeable Fe\text{\textsuperscript{2+}} ions and consumption of exchangeable acidity with a concomitant rise in soil pH—reduction of other oxidants in the soil also consumes acidity;

- accumulation of CO\textsubscript{2} formed by organic matter decomposition, increasing soil acidity and thereby curbing the increase in pH brought about by the above changes, and causing an increase in the concentration of HCO\textsubscript{3}\textsuperscript{-} ions in solution; and

- an increase in the ionic strength of the soil solution as a result of a) the increase in exchangeable Fe\text{\textsuperscript{2+}} and b) the increase in concentration of HCO\textsubscript{3}\textsuperscript{-} in solution, which causes a further desorption of exchangeable cations (principally Fe\textsuperscript{2+}, Ca\textsuperscript{2+}, Mg\textsuperscript{2+}, and NH\textsubscript{4}\textsuperscript{+}) to maintain electroneutrality in solution.

1. Changes with time in pH, P\textsubscript{CO\textsubscript{2}}, and water-soluble Fe\textsuperscript{2+} following flooding of a moderately acid clay soil (after Ponnamperuma 1985).
In alkaline soils, reduction and accumulation of CO₂ following flooding cause a
decrease in soil pH to near neutral, concomitantly, Ca compounds dissolve.

We now turn to the forms of P in flooded soils and relate changes in them following
flooding to the preceding physicochemical changes.

**Solution phosphorus**

Soil solutions contain P principally in the form of orthophosphate: \( \text{H}_3\text{PO}_4, \text{H}_2\text{PO}_4^-, \) and \( \text{HPO}_4^{2-} \). The high concentrations of cations that develop in flooded soil
solutions favor formation of soluble metal-orthophosphate complexes, especially
with \( \text{Fe}^{2+}, \text{Ca}^{2+}, \) and \( \text{Mg}^{2+} \). The concentrations of such complexes can be calculated
using standard thermodynamic data. Metal-P complexes that are positively charged
may be more strongly adsorbed by charged surfaces than orthophosphate, which
complicates the effect of pH changes on P retention by flooded soils. Concentrations
of organically bound or organically complexed P may also be high in flooded soil
solutions because of the high concentration of dissolved organic compounds, but we
know of no quantitative data. In aerobic soils these soluble organic-P complexes are
typically much less significant.

**Solid phase phosphorus**

Opinions differ as to the importance of cycling of soil organic P in plant nutrition,
both in flooded and nonflooded soils (Neue 1988, Tate 1984). In flooded soils, easily
decomposable crop residues incorporated into the soil before flooding may release P
relatively quickly; but, by definition, the quantity of P released from crop residues
can only be a small part of the succeeding crop's needs. A much larger quantity of P
is contained in the soil organic matter—sometimes equaling the quantity of soil
inorganic P—but the part of this that is biologically active is small, and the net rate of
mineralization of the active part is very slow, although rates of mineralization in
flooded soils may be higher than in nonflooded soils (Islam and Mandal 1977). In
any case, the possibilities for manipulating soil organic matter as a source of P for
plant nutrition, by agronomic management, seem small—in this respect it is far less
interesting than inorganic P. Rather, we consider the importance of organic matter
in P dynamics in flooded soils to be due to its effect on microbial activity and thereby
on Fe transformations.

Studies on soil inorganic P have tended to dwell on identifying specific
crystalline phases. However, the future in this is limited because of the enormous
number of possible phases—pure crystalline forms often having variable surface
compositions—and because the rates of equilibration of solutions with crystalline
forms are typically very slow, and thus phases that are thermodynamically favored
are not necessarily kinetically favored. The physicochemical changes following
flooding occur sufficiently fast that many precipitated phases may be amorphous,
mixed-composition phases being the norm. In such circumstances, the distinction
between P that is precipitated in a solid phase, sensu stricto, and P that is adsorbed
on a solid surface with its charge balanced by another ion, is blurred. Most of the
observed characteristics of the reaction of P with soils, and its dependence on
measurable soil properties can be explained without distinguishing between precipitated and adsorbed P (Barrow 1987).

The solid phases that can sorb P, including metal- and organic-P complexes as well as orthophosphate, may be subdivided into 1) constant charge surfaces, especially crystalline clay minerals that interact with P primarily through their surface-held cations; and 2) variable charge surfaces, including the Fe and Al hydrous oxides, and organic matter, for which sorbed ions, especially H\(^+\) and OH\(^-\), determine the surface charge. There is considerable overlap between these two groups since clay minerals develop pH-dependent charges at their edges. Thus, for example, kaolinite and halloysite can have considerable variable charge and therefore high P sorption capacity, in spite of having very little constant charge developed through isomorphous substitution. Pure oxides rarely occur in soils, particularly in intermittently flooded ones; coprecipitated phases are the norm.

Clays and pure Al hydroxides are relatively stable under alternating redox conditions, although their surface charges may change; it is the transformations of the Fe-containing oxides under these conditions that dominate P chemistry. Discrete crystalline particles of Fe oxides have a relatively low capacity to sorb P. But in oxidized intermittently flooded soils, a large part of the Fe is in the form of discontinuous coatings of amorphous oxides on other clay minerals, and these have much greater P sorption capacities than the crystalline forms (Brinkman 1985). After a soil is flooded, reduced Fe may in part be reprecipitated as amorphous hydroxides and carbonates (Brinkman 1985, Ponnamperuma 1985, Van Breemen 1969). These poorly crystalline Fe(II) compounds also have higher surface areas than their crystalline counterparts, and consequently greater capacities for P sorption (Holford and Patrick 1979).

Changes in solution and solid phosphorus following flooding

The physicochemical changes following flooding influence both the amount of labile P in the soil and the nature of P sorbing surfaces, and consequently, the distribution of labile P between solid and solution. Many experiments have investigated these changes (Choudhury 1986, Khalid et al 1977, Ren 1987, Roy and De Datta 1985, Willett 1986). Such experiments often show that solution P increases to some extent following flooding, and continues to increase during the first half of the rice growing season; but it subsequently decreases, although not returning to the preflooding level by the end of the growing season. Figure 2 shows the changes in solution P found by Ponnamperuma (1985) for a range of flooded soils — there may be large differences in behavior among soils. Increases in solution P following flooding can be explained by

- reduction of Fe(III) oxides holding sorbed P on their surfaces and within their crystalline matrices, and reduction of Fe(III)-P compounds;
- displacement of sorbed P by organic anions;
- decrease in positive surface charge in acid soils as pH rises, resulting in desorption of P; and
- dissolution of Fe-P and Al-P compounds in acid soils as pH rises, and dissolution of Ca-P compounds in alkaline soils as pH falls.
Subsequent decreases in solution P can be explained by
- sorption by slowly precipitated solid phases;
- slow sorption by existing solid phases;
- microbial degradation of organic anions occupying sorption sites resulting in increased P sorption;
- microbial P uptake; and
- precipitation of Fe(II)-P compounds.

Changes in the tendency of the soil to sorb P from solution can be gauged with soil P buffer capacities—the slopes of plots of sorbed P concentrations versus solution P concentrations. Buffer capacities tend to be increased by flooding. Those calculated from the data of Ren (1987) and Roy and De Datta (1985) for sorption at low solution P concentrations (<1 µg/ml) by a range of soils when reduced and nonreduced nearly all increase following reduction; the increases are up to fivefold. In Figure 3, after Holford and Patrick (1979), the buffer capacity at P concentrations of a few µg/ml is about fivefold greater in the strongly reduced soil at pH 6.5 than in the untreated soil.

The changes in buffer capacity following flooding can be related to the changes in soil Fe. Figure 4 shows the changes in soil Fe consequent upon reduction, under controlled pH conditions, as measured by Gotoh and Patrick (1974). Fe(II) formed by soil reduction will be distributed between the solution, exchange sites, and poorly crystalline hydroxide or carbonate precipitates, which may adsorb P from solution. The increase in pH accompanying soil reduction favors precipitation of Fe(II) from solution, but it will also tend to make the electric potential of variable charge surfaces less positive, reducing P sorption, although the increase in ionic strength following

4. Distribution of soil Fe into water-soluble and exchangeable, reducible, and residual forms at various Eh-pH combinations (after Gotoh and Patrick 1974).

Reduction will moderate this effect (Fig. 5). A net increase in P buffer capacity means that the reduction in the affinity of exchange sites for P as a result of the changes in surface potential is outweighed by the increase in the number of exchange sites as a result of the changes in the surface area. The curves in Figure 3 demonstrate the complexity of the interaction among these effects. These curves and those discussed above were measured on soil at reduction equilibrium; however, since the changes in soil Fe are time-dependent (Fig. 1), one should expect the changes in buffer capacity to be time-dependent also; but we know of no experimental data on this. Also, increases in labile P following flooding may lag behind the onset of Fe reduction because P sorption appears to stabilize Fe oxides against reduction (Willett 1986), and thus Fe oxides holding sorbed P tend to be reduced later.
Effect of pH on the retention of P at indicated P concentrations in solution and at 4 ionic strengths (after Barrow 1987).

Increases in solution P with reduction occur, despite increased P buffer capacity, if reduction sufficiently increases the amount of labile P by the processes listed above. We explain this with the help of the idealized buffer curves in Figure 6. Linear-log plots often fit P buffer data well, because they allow for the fact that the affinity of an exchange surface for P decreases with the proportion of exchange sites already occupied by P. With more exchange sites, the reduction in affinity for added P with increase in the proportion of exchange sites occupied is more gradual; thus the buffer curve is less sharp, which is equivalent to a steeper logarithmic plot. The solution P concentration without P addition is greater in the reduced soil, because reduction has sufficiently increased the amount of labile P. Because this concentration and the slope of the buffer curve are both increased by reduction, the reduced and nonreduced curves cross over. This may complicate the interpretation of sorption data. Hence, to maintain the low solution concentration, A, in Figure 6 requires less added P in the reduced soil than in the nonreduced; but to maintain the higher concentration, B, requires more added P in the reduced soil than in the nonreduced. More profound than this, though, are the effects of changes in P buffer capacity and labile P on P uptake by plant roots; these effects are discussed in detail later.

With such a plethora of complex and interacting processes operating simultaneously, it is difficult to make precise predictions about the changes in P
Idealized linear-log P buffer curves under reduced and nonreduced conditions. The true, unamended soil \([P]_{\text{solution}}\) values are those for which P addition has resulted in no change in \([P]_{\text{sorbed}}\); the ratio of the buffer capacities at a particular \([P]_{\text{solution}}\) is given by the ratio of the slopes.

chemistry in a particular soil using readily measurable soil parameters alone. Experimental measurements of P sorption should be made with the soil parameters with which it interacts (particularly Eh, pH, and the nature and concentration of the supporting electrolyte) held constant, and the effects of varying the controlling parameters should be described mathematically so that quantitative models may be developed.

Reactions of fertilizer phosphorus

The initial reaction of water-soluble fertilizer P with soil solid phases is rapid, but often the concentration of P in solution continues to decline at a much slower rate for a seemingly indefinite period, even in the absence of changes in the nature of the solid phases (Fig. 7). Similarly, the release of sorbed P to solution when the solution concentration is lowered is initially rapid but continues at a lower rate for a long time. The mechanisms of these slow reactions and the factors governing their rates have not yet been characterized in flooded soils, nor in nonflooded soils, mainly because experimental investigation of the slow reactions is difficult; but a knowledge of the mechanisms governing slow reactions is important for predicting the long-term fate of native and fertilizer P. Also, we have very little quantitative information on the effect of soil drainage and reoxidation on soil P reactions, although it is often
reported that the availability of P to upland crops sown after wetland rice is reduced (Brandon and Mikkelsen 1979, Simpson and Williams 1970, Willett 1986). Midseason surface drainage and oxidation are the norm even in the so-called irrigated ricefields of Asia, but it is not known to what extent and how quickly this may influence soil P reactions.

In view of the paucity of experimental data, any discussion of the mechanisms of the slow reaction is necessarily speculative. A hypothesis that fits the slow reaction’s observed characteristics well is that it is controlled by the slow penetration of P into oxide crystals by diffusion. Barrow (1987) developed a model based on this mechanism that very successfully described the slow reaction in his experimental soil (Fig. 7). Diffusion within crystal lattices occurs because lattice defects provide vacancies into which diffusing ions can move with a relatively low activation energy; this process is distinct from diffusion along intracrystalline surfaces, which is very much faster. Defects may be caused by the presence of foreign ions within crystal lattices; this may explain the observed relationship between slow P reactions and the Al content of Fe oxides (Barrow 1987). Diffusion within noncrystalline materials should be expected to be very slow. Therefore differences in the crystallinity of reducible Fe from when a soil is flooded to when it is drained should affect slow P reactions. Thus, when the soil is flooded and the Fe is in a less crystalline form, slow P reactions should be less significant than when the soil is drained and the Fe reverts to a more crystalline form. However, we lack experimental data on this. In obtaining such data, we stress again the need for the development of quantitative models of the processes involved. Barrow (1987) gives an excellent review of approaches to describing P reaction kinetics in soils.

Phosphate rock (PR) fertilizers, which can cost, per unit of P, as little as one quarter the price of simple superphosphate, may have a large but as yet unrealized
potential in lowland rice production. They are not more extensively used because many factors determine the conditions under which their use is profitable, and there are as yet no simple means of assessing where these factors are satisfied. Two factors should be expected to enhance the rate of dissolution of PR under lowland rice. First, rice roots may greatly acidify the soil near them (see next section); Kirk and Nye (1986a,b) give the means of calculating the magnitude of such effects. Second, dissolved organic matter may chelate Ca and P in solution. The rates of change in soil chemical conditions following flooding will also have a bearing on the effectiveness of PR, particularly the changes in pH, ionic strength, and P and pH buffer capacities. Thus, in the majority of acid soils, the rate of PR dissolution should decline following flooding as the pH rises, but to what extent will depend on the rate of reduction. The pH of the soil shown in Figure I took 2 wk to rise from 5 to 6. Considerable amounts of PR could dissolve during this lag (Kirk and Nye 1986a); the lag may be several times this in more acid soils. Also, the residual value of PR compared with water-soluble forms is important, and hence an understanding of slow P reactions in flooded soils will be needed for assessing their effectiveness.

Plant uptake of phosphorus

The rate of P uptake by an absorbing root is determined by the concentration of P maintained in the soil solution at the root surface, and this concentration is controlled, at least in nonflooded soils, by the supply of P by diffusion across a narrow zone of depletion in the soil around the root. Thus, processes that cause changes in chemical conditions and hence diffusion in the soil near the roots have a large influence on P uptake. Diffusion processes in soils have been reviewed by Nye (1979). Soil P diffusion coefficients, from which P uptake rates may be found, may be calculated from the relation \( D_p = D_{LP} \theta - f/b_p \), where \( D_{LP} \) is the diffusion coefficient in water; \( \theta \), the moisture content; \( f \), the diffusion impedance factor; and \( b_p \), the buffer capacity, which is generally concentration- and other factor-dependent, as discussed earlier. Flooding will tend to increase \( D_p \) as it increases both \( \theta \) and \( f \)—this may be a twofold or threefold increase compared with soils at field capacity—but increases in \( b_p \) following flooding will offset this. The increases in \( b_p \) discussed earlier were up to fivefold. Therefore, contrary to accepted wisdom, overall P diffusion coefficients are unlikely to be increased much by flooding and in some circumstances may in fact be reduced. A decrease in P diffusion coefficients following flooding would offset the benefits to the plant of any reduction-induced increase in the amount of labile P. Because P diffusion coefficients are not greatly increased by flooding, the rate of diffusion to root surfaces is the rate-limiting step in P uptake from flooded soils, as it is in nonflooded soils.

But we must also consider, in addition to the effects of flooding on P chemistry in the soil bulk, the effects of rice roots on P chemistry in the rhizosphere. Chemical conditions in the rhizosphere of wetland rice, into which roots may be releasing free O\(_2\) and oxidizing materials, are complex, and we have as yet very little detailed experimental information on these conditions or on the processes influencing them. A theoretical model of rice rhizosphere chemical conditions developed by Kirk (unpubl.) shows that the pH in soil near roots may be at least two units lower than in
the surrounding soil as a result of 1) oxidation of mobile (i.e., exchangeable and solution) Fe(II) by the reaction

$$4 \text{Fe}^{2+} + \text{O}_2 + 10\text{H}_2\text{O} \rightarrow 4 \text{Fe(OH)}_3 + 8 \text{H}^+$$

and 2) proton release by roots to balance excess uptake of cations over anions, N being supplied in reduced soils chiefly as $\text{NH}_4^+$. The model allows for the complicated kinetics of the $\text{Fe}^{2+}$ oxidation reaction, and for the relatively high rate of dispersion of acidity away from the roots that is expected at high soil moisture content and pressure of CO$_2$. Such a large drop in pH, coupled with Fe(III) precipitation, would markedly affect P chemistry. Freshly precipitated, poorly crystalline Fe oxides would have a large P buffer capacity; and a decrease in pH and consequently more positive surface potential would increase the P buffer capacity of the new and existing soil surfaces (Fig. 5). However, it is generally found in nonflooded soils that a decrease in pH results in the net desorption of soil P. Barrow (1987) proposes that this is because the more positive surface potential also favors diffusion back to the surface of P held within crystals. Therefore, the net P desorption curve for oxidized rice rhizosphere soil, and consequently the diffusive supply of P to roots, would depend on the balance between the increase in surface sorption through precipitation of Fe oxides and decrease in pH, and the increased release of soil P through decreased pH. Clearly we need more information an these processes. The changes in rhizosphere chemical conditions occur within a distance on the order of 1 mm from the root. Because it is difficult to measure these changes experimentally with resolutions finer than 1 mm (Marschner 1986), theoretical models validated on simpler systems may be invaluable in investigating the processes at work.

The foregoing discussion focuses on the oxidized rice rhizosphere; however, not all of the rice rhizosphere is oxidized, and the characteristics of the root system change both with depth in the soil and with age. The root tips are nonoxidizing, but their total length per unit soil volume seems insufficient to account for much P uptake. The surface roots are more like those of upland crops and do not oxidize their rhizospheres, and it may be that much of the P is taken up there.

In short, with the current state of knowledge concerning chemical conditions in the rice rhizosphere and the consequences of those conditions for P chemistry, we do not know what plant characteristics favor ability to best exploit soil P, and therefore do not have a rational basis for the selection of P-efficient varieties.

Recommendations for research

We distinguish two main themes for future research on flooded soil P chemistry: 1) developing ways of improving the efficiency of P fertilizer use, and 2) providing a rational basis for selecting rice varieties that are efficient at taking up P. Researchable items for theme 1 are

- the factors that govern the kinetics of soil reduction and the fusion of models of soil reduction kinetics with models of P fertilizer reaction kinetics, especially for PR and PR/water-soluble P mixtures;
- slow reactions of P in flooded soils;
• the effects of midseason surface drainage and temporary oxidation on soil P reactions; and
• the effects of end-of-season drainage and prolonged oxidation on soil P reactions.

Researchable items for theme 2 are
• chemical conditions in the rice rhizosphere and the mechanisms of root uptake of P; and
• use of proven mathematical models of P uptake based on measurements of root geometries and soil diffusion characteristics, to account for measured uptake rates in flooded soils.

Because we are dealing with such a complex system, the only promising means of reaching definite conclusions about the mechanisms at work is to develop mathematical models of the linked processes involved. Therefore, as a guiding principle for future work, measurements should be made on individual processes in isolation from other processes (e.g., the effect of pH on P sorption at constant Eh) in such a way as to allow their mathematical description.

References cited

Notes

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Citation information: International Rice Research Institute (1990) Phosphorus requirements for sustainable agriculture in Asia and Oceania. P.O. Box 933, Manila, Philippines.
Chemistry of adverse flooded soils

H. U. Neue and Zhu Zhong-lin

About 24 million ha of adverse soils in South and Southeast Asia are suitable for rice cultivation. Largely because of multiple soil stresses such as salinity, alkalinity, strong acidity, and peatiness, these lands lie idle or are cultivated but with poor results. Good management of water (amount and quality) is the key to successful cultivation of adverse soils. Phosphorus deficiency is the most widespread and severe nutrient deficiency in adverse soils, and dramatic responses to P fertilization are common, especially in acid sulfate soils. Although P retention increases with increasing ionic strength, raising salinity enhances P availability in flooded soil because it decreases pH and Eh. Yield responses to P are more consistent at low salinity levels. Sodic soils may have high extractable P, but essential amelioration to replace Na by Ca lowers P availability. Application of P fertilizer becomes necessary after a few years of cropping. In acid sulfate soils, P fertilization is mandatory. The amount of lime is critical when phosphate rock is applied. Phosphorus fertilization is necessary on most Fe-toxic soils and on all peat soils. This paper discusses the chemistry of adverse soils and possible reclamation and amendments.

In Asia, population growth rates are high, and arable land for food production has become scarce. In some countries, 0.1-0.5% of good cultivated land is lost each year to nonagricultural use (Buringh 1979). Most cities, towns, and villages lie and expand on the best soils. Large areas of agricultural land are also lost because of soil erosion, soil salinization, alkalization, and desertification. The worldwide annual loss is estimated to be 5-8 million ha/yr (Buringh 1979).

Soil conditions often limit production. The main limiting soil factors are shallowness, high content of skeletal materials, low water-holding capacity, high groundwater table, poor internal drainage and aeration, slow permeability, low cation exchange capacity (CEC), low nutrient supplying capacity, and presence of toxic ions or highly soluble salts. Adverse soils are defined by their limited suitability for crop production. Submerged soils are classified as adverse soils for all crops except rice. Most upland soils are adverse soils for rice because of limited water supply.

Soils that yield <4 t rice ha because of soil stresses are classified as adverse soils in China. These are the gleied paddy soils, sticky paddy soils, calcified paddy soils, acid sulfate paddy soils, and mining-poisoned paddy soils.

- Gleyed paddy soils are wet for most of the year because of high groundwater or lateral seepage. They are difficult to drain and may be prone to Fe toxicity.
• Sticky paddy soils have clay contents of more than 50%. Because montmorillonite is the dominant clay, they are very plastic when wet and are prone to shrinking and swelling.
• Calcified paddy soils are enriched with CaCO$_3$ from Ca-rich irrigation water. The formation of these soils in karst areas of subtropical China started at least 300 yr ago (Gong et al. 1988).
• Acid sulfate paddy soils have developed in estuaries and tidal swamps where sediments of acid parent materials have accumulated.
• Mining-poisoned paddy soils have been polluted by mining effluents rich in coal pulp, S, Fe, Mn, or heavy metals.

This paper is limited to a discussion of soils that impose multiple stresses on rice, even if water is sufficient during the growing season. Thus, saline soils, sodic soils, acid sulfate soils, peat soils, and Fe-toxic soils are classified as adverse rice soils. Their relationships to Soil taxonomy (Soil Survey Staff 1987) are given in Table 1.

The estimated areas of adverse soils in South and Southeast Asia suitable for rice are given in Table 2. No reliable data are available for Fe-toxic soils. Iron toxicity has been recognized in many Asian countries, especially Sri Lanka, and is widespread in Africa and South America. Most saline and sodic soils suitable for rice are found in India and Pakistan, while the largest areas of acid sulfate soils and peat soils are located in Vietnam and Indonesia, respectively.

## Saline and sodic soils

The dynamics, processes, and management of saline and sodic soils have been reviewed recently (Bresler et al. 1982, Dargan et al. 1982, Shainberg and Shalhevet 1984).

### Saline soils

A saline soil contains sufficient salt in the root zone to impair the growth of crop plants. Such soils have an electrical conductivity of the saturation extract exceeding 4 dS/m at 25 °C, and the exchangeable sodium percentage (ESP) is less than 15 (United States Salinity Laboratory 1954). Saline soils vary widely in chemical,

<table>
<thead>
<tr>
<th>Adverse soils</th>
<th>Frequent$^a$ in Soil taxonomy (equivalents)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Entisols</td>
</tr>
<tr>
<td>Saline soils</td>
<td>+++</td>
</tr>
<tr>
<td>Sodic soils</td>
<td>–</td>
</tr>
<tr>
<td>Acid sulfate soils</td>
<td>+++</td>
</tr>
<tr>
<td>Peat soils</td>
<td>+</td>
</tr>
<tr>
<td>Iron-toxic soils</td>
<td>++</td>
</tr>
</tbody>
</table>

$^a$+++ = most frequent, ++ = frequent, + = less frequent.
Table 2. Estimated areas of adverse soils in South and Southeast Asia$^a$ suitable for rice (adapted from Boje-Klein 1986).

<table>
<thead>
<tr>
<th>Country</th>
<th>Area (million ha)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Saline</td>
</tr>
<tr>
<td>Bangladesh</td>
<td>0.8</td>
</tr>
<tr>
<td>Brunei</td>
<td>-</td>
</tr>
<tr>
<td>Burma</td>
<td>1.0</td>
</tr>
<tr>
<td>Kampuchea</td>
<td>0.1</td>
</tr>
<tr>
<td>India</td>
<td>2.8</td>
</tr>
<tr>
<td>Indonesia</td>
<td>ov</td>
</tr>
<tr>
<td>Pakistan</td>
<td>2.6</td>
</tr>
<tr>
<td>Sri Lanka</td>
<td>0.1</td>
</tr>
<tr>
<td>Thailand</td>
<td>0.3</td>
</tr>
<tr>
<td>Vietnam</td>
<td>0.1</td>
</tr>
<tr>
<td>Total</td>
<td>7.8</td>
</tr>
<tr>
<td>Whole adverse soil area in South and Southeast Asia</td>
<td>16.0</td>
</tr>
</tbody>
</table>

$^a$ Countries with less than 0.1 million ha not listed. ov = overlapping with other adverse soil types.

Physical, and hydrological properties. The salt content varies spatially, seasonally, and with the water regime. During the rainy season the salinity level may drop below the critical limit of 4 dS/m in most saline soils of Bangladesh. Salinity rises when the influx of salts is greater than the efflux. In arid and semiarid areas, salts accumulate in the soil because of the evaporation of rainwater or irrigation water. In coastal areas, salinity is caused by direct inundation with seawater or by lateral and upward movement of saline groundwater. The major salts in coastal saline soils are chlorides, while in arid areas sulfates and chlorides predominate. The pH ranges from 2.5 for saline-acid sulfate soils to 8.5 for alkali-saline soils. The organic matter content ranges from 1 to 50%, and the nutrient status from very low to moderately high (Ponnamperuma 1978).

Poorly designed and implemented irrigation systems have degraded soils by waterlogging, siltation, salinization, and alkalinization. Of the 40 million ha of irrigated land in India, about 6 million ha have become waterlogged or saline (Nangju 1986). Because climatic conditions, crops, and soils are diverse, several authors have set different critical limits for irrigation water quality (Table 3). Only class 1 irrigation water is regarded as safe and suitable for most plants under any soil and climate conditions.

Salinity thresholds for various crops at the seedling stage were established by Maas and Hoffmann (1977). In general, yields decrease linearly with increasing salinity (Fig. 1) except in the lower part of the relative yield curves, where yields are commercially unacceptable. Some crops approach zero yield asymptotically; others drop sharply to zero beyond specific salinity levels. Variability among cultivars of a crop is high.
Table 3. Qualitative classification of irrigation waters.

<table>
<thead>
<tr>
<th>Criterion</th>
<th>Classification system</th>
<th>Parameter</th>
<th>Irrigation water</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Parameter</td>
<td>Class 1</td>
</tr>
<tr>
<td>Salinity</td>
<td>United States Salinity Laboratory 1954</td>
<td>Electrical conductivity (dS/m)</td>
<td>&lt;0.25</td>
</tr>
<tr>
<td></td>
<td>Doneen 1975</td>
<td>Potential salinity = CI + 1/2 SO₄ (meq/liter)</td>
<td>&lt;5</td>
</tr>
<tr>
<td>Sodium</td>
<td>United States Salinity Laboratory 1954</td>
<td>Sodium adsorption ratio (meq/liter)</td>
<td>&lt;10</td>
</tr>
<tr>
<td></td>
<td>Doneen 1975</td>
<td>Sodium percentage</td>
<td>&lt;60</td>
</tr>
<tr>
<td>HCO₃⁻</td>
<td>Wilcox 1955, Eaton 1980</td>
<td>Residual sodium carbonate (meq/liter)</td>
<td>&lt; 1.25</td>
</tr>
<tr>
<td>Boron</td>
<td>Doneen 1975</td>
<td>Boron (mg/liter)</td>
<td>&lt; 0.5</td>
</tr>
</tbody>
</table>

Rice is moderately susceptible to salinity, since most rices are severely injured in submerged soils at an electrical conductivity (ECₑ) of 8-10 dS/m. Below an ECₑ of 4, rice growth is normal. Although rice is moderately susceptible to salinity, it is highly suited to saline soils because it tolerates standing water, which is necessary for reclamation.

Irrigation and salinity

The degree to which irrigation will cause salinization depends on the quality of the irrigation water and on the balance between supply and drainage. The change in ECₑ of the profile per unit time and soil depth can be expressed as

$$\Delta EC_e = \frac{(EC_{iw} \times A_{iw}) - (EC_{dw} \times A_{dw})}{A_{sat}}$$

(1.1)

where $$A_{sat} = (D \times B \times W_{sat})/100$$. $$A_{iw}$$ and $$A_{dw}$$ (in cm) represent the amount of irrigation water and drainage water, respectively, in cm during the period considered. ECₑ is the depth of soil (cm), B is the bulk density in g/cm³, and $$W_{sat}$$ is the water content of the saturation paste in weight percent of the dry soil. The denominator $$A_{sat}$$ expresses the amount of water (cm) in the soil at saturation. This salt balance equation indicates that, with a given annual supply of irrigation water of constant average EC, the rate of salinization is dependent only on the amount of drainage water removed.

In flooded rice soils, subsurface drainage may become almost zero because of a developed traffic pan or high groundwater table. Desalinization is done by surface flushing with fresh water. Since rice has a shallow rooting system, only the topsoil
Chemistry of adverse flooded soils

1. Divisions for qualitative salt-tolerance ratings of agricultural crops (adapted from Maas and Hoffman 1977).

(15-20 cm) has to be desalinized. During land preparation of a dry saline soil for flooded rice, the initial standing water is surface drained after puddling. If the subsurface drainage is estimated to equal the amount of unavailable water, the drainage water amounts to

$$A_{dw} = A_{iw} - A_{sat} \quad (1.2)$$

Substituting equation (1.2) for equation (1.1) and considering the EC of the drainage water to be equal to the EC, after flushing, and the EC of the irrigation water to be zero, the amount of water needed to reduce a given EC, to a critical level ($EC_c$) is calculated as

$$A_{iw} = \frac{(EC_e \times A_{sat}) - A_{sat}}{EC_e} + A_{sat} \quad (1.3)$$

which is simplified as

$$A_{iw} = A_{sat} \left( \frac{EC_e}{EC_e - 1} \right) \quad (1.4)$$

To lower an initial $EC_e$ of 16 to 4 in the top 20 cm of a clay loam ($A_{sat} = 8-9$ cm), about 40 cm of fresh water is required.

To prevent salinization, the drainage capacity and the subsurface leaching requirement have to be established to calculate the excess amount of irrigation water needed.

**Salinity and nutrient availability**

Inland saline soils are low in N and available P. Saline sodic soils and calcareous saline soils are deficient in available Zn. Thionic saline soils show Al and Fe toxicities
and P deficiency. Histic saline soils are deficient in N, P, K, Cu, and Zn and are prone to H₂S toxicity. Boron toxicity may be also a problem in saline soils (Dargan et al 1982, Stumm and Morgan 1981).

Salinity influences the magnitude of electrochemical and chemical changes brought about by submergence. It also increases the solubility of soil minerals and enhances the dissociation of acid and ionic complexes. Increasing salt concentrations decrease the pH and Eh of the soil solution, whereas the concentrations of Na⁺, K⁺, Ca²⁺, Mg²⁺, NH₄⁺, Fe²⁺, Cl⁻, BO₃⁻³, H₂PO₄⁻, and SO₄⁻² increase (Panaullah 1984).

Aside from their influence on the concentration of the soil solution, increasing salinity affects the ion exchange complex. Adding electrolytes to the soil solution leads to a progressive collapse of the diffuse double layer (Bolt and Bruggenwert 1978). As a result, colloid surfaces are no longer masked by the diffuse double layer, which enhances cation and anion exchange and decreases pH and Eh. The lower the surface density of charge of the colloids, the lower is the electrolyte level that affects these processes. Once the electrostatic field of the diffuse double layer has been reduced to negligible potentials, added electrolytes will no longer influence the pH except through small effects on the activity coefficients.

Quantifying interactive multiphase equilibria, which determine the chemical composition of the soil solution, can be successful only by using simulation models as done by Jenne (1979), Oster and Frenkel (1980), and Robins et al (1980).

Alkalization and sodication

When the carbonate concentration and/or the ratio of Na⁺to divalent ions of irrigation water becomes high, salinization may lead to alkalization (rise of pH) and sodication (Na saturation of the adsorption complex). The rate of both processes depends on the composition and amount of water supplied and the CEC of the soil. The high bicarbonate concentration of the deep-well water used on the farm of the International Rice Research Institute in the dry season has raised the pH from 5.5 to about 6.8 and has increased the relative proportion of exchangeable Na. Because Na carbonates have higher solubility than do Ca/Mg carbonates, irrigation with water high in carbonate and bicarbonate ions will cause soil sodication, even if the total salt content is not high.

The hazard of sodication can be derived from the sodium adsorption ratio (SAR) of the irrigation and drainage water according to

\[
\text{SAR} = \frac{\text{Na}^+}{\sqrt{\frac{(\text{Ca}^{2+} + \text{Mg}^{2+})}{2}}} \quad \text{(in mmol/liter)⁰⅔}
\]

where cation concentrations are in meq/liter.

The relationship between ESP and SAR is given by ESP/ 100 - ESP = 0.015 SAR (Bolt and Bruggenwert 1978).

If considerable amounts of HCO₃⁻ or CO₃²⁻ are present in the irrigation water, ESP will be higher than expected because of the precipitation of Ca and Mg carbonates. Reducing the concentration of (Ca²⁺ + Mg²⁺) equivalent to the concentration of (HCO₃⁻ + CO₃²⁻) has been proposed. But the assumption that all HCO₃⁻ and CO₃²⁻ will precipitate in the soil is not realistic in most situations. The SAR of the irrigation water has only limited applicability as a hazard criterion because of various interactions in the soil.
Sodic soils

Sodic soils contain sufficient exchangeable Na to impair crop growth. They have an ESP >15 and a pH >8.5 when dry. They contain free Na-carbonate or -bicarbonate, Ca/ Mg carbonates, and high concentrations of water-soluble Si. Clay and organic matter are dispersed, and the hydraulic conductivity is low. Sodic soils are deficient in N, Zn, and P.

High Na saturation (ESP) does not necessarily lead to high pH. If neutral Na salts like NaCl or Na₂SO₄ are dominant, the pH may be neutral. The strongly alkaline reaction of most sodic and saline sodic soils is caused by high HCO₃⁻ and CO₃²⁻ according to

\[
pH = \log (\text{HCO}_3^-) - \log P_{\text{CO}_2} + 7.81 \tag{3.1}
\]

\[
2pH = \log (\text{CO}_3^{2-}) - \log P_{\text{CO}_2} + 18.14 \tag{3.2}
\]

The pH of the soil solution is a function of the partial pressure of CO₂ \((P_{\text{CO}_2})\) and the alkalinity concentration. The pH may be modified by the solubility of mineral phases of carbonate and, conversely, \(P_{\text{CO}_2}\) and pH control the maximum concentration of cations. The relationship of pH, \(P_{\text{CO}_2}\), and alkalinity is shown in Figures 2 and 3. While in well-aerated soils the pH will rise above 8.5 if the alkalinity

2. pH as a function of the alkalinity concentration (mainly \(\text{CO}_3^{2-}\) and \(\text{HCO}_3^-\), in meq/liter) at 2 CO₂ pressures (after Van Beek and Van Breemen 1973).
is more than about 1.5 meq/liter, the increased $P_{CO_2}$ (up to 0.8 bar) under flooded conditions depresses the pH and increases the solubility of Ca, Mg, Fe, Mn, and Zn.

**Reclamation of saline and sodic soils**

For saline soils, reclamation is almost entirely by leaching and preventing salt intrusion, which has only few soil chemical aspects. For sodic soils, the adsorbed Na ions must be exchanged for other cations, especially $Ca^{2+}$. This can be achieved by irrigation water with low SAR and/or adding soluble Ca salts. The electrolyte concentration of water applied to sodic soils must be considered to avoid problems of infiltration and soil permeability due to dispersion of clays (Agassi et al 1982, Kazman et al 1983).

Applying lime is mostly useless because of its low solubility. Under flooded conditions, lime in combination with organic manures may be somewhat effective. The higher $P_{CO_2}$ will increase the solubility of $CaCO_3$ according to

$$-\log(Ca^{2+}) = 2 pH - 9.79 + \log P_{CO_2}$$  \hspace{1cm} (4.1)

which is simplified as

$$2(Ca^{2+}) = (HCO_3^-)$$  \hspace{1cm} (4.2)
Dissolved Ca\(^2+\) will exchange with adsorbed Na\(^+\), which causes further dissolution of CaCO\(_3\), providing excess carbonate and Na\(^+\) are leached. Because of impeded leaching capacity and low efficiency per unit of water application, manure and lime will effectively decrease ESP only in the surface soil and only after several years. Saline sodic soils frequently contain precipitated CaCO\(_3\) and CaSO\(_4\), which upon leaching may provide sufficient Ca to exchange Na.

The most effective amendment for sodic soils is gypsum (CaSO\(_4\)). Estimates of the amount of divalent ions to lower the ESP to a desirable level and depth may be estimated from the equation

\[
(M^{2+}) = (ESP_0 - ESP_d) \times CEC \times B \times D/100
\]

where ESP\(_0\) is the original and ESP\(_d\) is the desired ESP value, CEC is in meq/100 g, B is the bulk density (g/cm\(^3\)), and D is the depth (cm) to be reclaimed. Because of the complex interactive chemical, physical, and biological mechanisms, comprehensive simulation models are required to achieve reliable predictions about sodic soil amendments. Tanji and Deverel (1984) reviewed the strength and weaknesses of existing models.

**Fertilization of saline soils.** Soil salinity-fertility interactions occur, suggesting that some of the adverse effects of salinity may be overcome by fertilization. A wide range of fertility problems have been reported for saline soils. These include N, P, Zn, and Cu deficiencies; B and Fe toxicities, depending on physiographic position; proximity to the sea; and presence of calcareous, sodic, histic, or thionic material (Biswas 1981, Dargan et al 1979, Mondal 1981, Raskhit 1981).

Apparent decreases in rice salt tolerance after high N application were reported by Ogo and Morikawai (1965). Niane (1984) found that the amount and timing of N application significantly affected rice growth and yield. Topdressing at panicle initiation was more effective than basal application, because salinity stress is higher during early growth.

Selassie and Wagenet (1981) reported a negative effect on maize of high urea treatments when combined with salinity.

Bernstein et al (1974) intensively studied the salinity-fertility interaction on yields of some grain and vegetable crops in sand culture. Increasing the NO\(_3^-\)-N supply decreased Cl\(^-\) concentration in the leaves of maize.

When ammonium was taken up as a cation, it reduced Ca and Mg contents in tomato plants (Kafkafi et al 1971). According to the ionic balance in nutrient uptake, ammonium uptake should increase anionic uptake. When Cl\(^-\) is the dominant anion in solution, ammonium nutrition increases the Cl\(^-\) concentration in the plant (Weigel et al 1973).

Several studies reviewed by Champagnol (1979) reported positive effects of P application on the growth and yield of crops in saline soils. Responses to P are more evident and consistent at low salinity levels and have been related to increased solubility of P and reduced transpiration with higher P content in the plant tissue. Negative responses to P application have been attributed to increased Na\(^+\) and Cl\(^-\) and to decreased K\(^+\) accumulation in the plant tissue (Patel and Wallace 1975). Negative responses were reported for pea, tomato, onion, and barley, but positive
responses were observed with clover, sorghum, maize, and sesame; with other crops no effect has been observed (Kafkafi 1984).

For rice, Miah (1987) found that higher P rates (up to 100 mg/kg soil) suppressed Na, Mg, and Fe uptake under saline conditions. Regardless of salinity, P fertilization enhanced the growth and yield of rice and increased the P, K, Mn, and Zn contents of the plant tissues.

The availability of P may be modified by soil salinity. Taylor and Gurney (1965) observed that salts like KCl and NH₄NO₃ precipitated about 20% of soluble P of the Ca(H₂PO₄)₂·2H₂O in situ and decreased the availability of added P. Since P retention increases with increasing ionic strength (Ryden and Syers 1975), saline soils need higher P fertilization. Proper application of N and P fertilizer can also decrease toxic concentrations of Cl in plants (Chhabra and Abrol 1983).

Responses to fertilizer application in saline soils vary highly between crops, and also between cultivars (Miah 1987, Verma and Neue 1984). Because crops and cultivars differ in tolerance and tolerance mechanisms, no simple, general relationships concerning fertilization of saline soils can be established.

Fertilization of sodic soils. Sodic soils are generally deficient in N, Zn, Fe, and Ca but have high extractable P and Si. Because of the high amounts of Na₂CO₃ present in these soils, Ca phosphates are changed to more soluble Na phosphates. The high pH favors the formation of the PO₄³⁻ ion, which is unavailable to plants. But the lower pH in the rhizosphere results in H₂PO₄⁻ ions, so P may seldom be a limiting factor in sodic soils when the pH is above 9.

Reclamation of sodic soils decreases P availability. This is attributed to the formation of insoluble Ca phosphates by added gypsum or lime, leaching of soluble P to deeper layers, plant removal, and decreasing soil pH (Chhabra and Abrol 1983). Minimum availability of P is found at a pH of 8.5. Decreasing the pH even more increases P availability again.

In long-term field studies, Chhabra and Abrol (1983) observed that in the first 3-5 yr of reclamation, rice and wheat did not respond to P fertilizer. Thereafter rice, which has a shallow root system, started to respond, while wheat did not need P addition for another 3 yr because of its deeper rooting.

Sodic soils are highly prone to volatilization losses of 7% as well as to Zn and Fe deficiency. Split application of N (basal and two topdressings) is recommended for rice and wheat. Submergence and organic amendments increase Fe availability for rice, but Zn fertilization is mandatory, even after reclamation. Lowering the pH of sodic soils dissolves Zn precipitates based on given stability-pH diagrams, but it does not increase the availability of Zn (Gupta et al 1987). The chemistry of soil Zn and its antagonisms with P are still not well understood. Organic amendments intensify the reclamation of sodic soils by increasing $P_{CO_2}$ and decreasing pH.

**Acid sulfate soils**

Acid sulfate soils develop when sediments that are rich in sulfides, mainly pyrite (FeS₂), are drained. Most often, acid sulfate soils are found in tidal swamps, brackish lagoons, and inland valleys with an influx of sulfate-rich water. In the
Philippines, acid sulfate soils have also developed in sulfurous sediments of volcanic origin.

Pyrite is stable only under anaerobic conditions. When submerged and reduced, these soils are nearly neutral in reaction. But when the water recedes or the land is drained, the oxidation of pyrites generates $\text{H}_2\text{SO}_4$ and the soil becomes extremely acid. The genesis, characteristics, and reclamation of acid sulfate soils have recently been reviewed by Dent (1986). Acid sulfate soils pose numerous chemical, biological, and physical problems for cultivation of dryland crops:

- severe acidity that results in toxicity of $\text{H}^+$, $\text{Al}^{3+}$, $\text{Mn}^{2+}$, and possibly $\text{Fe}^{3+}$;
- low base status;
- nutrient deficiencies;
- salinity; and
- severe P deficiency caused by Fe and Al interactions.

When submerged for rice cultivation, the pH increases, but new problems include

- $\text{Fe}^{2+}$ toxicity,
- $\text{H}_2\text{S}$ toxicity, and
- $\text{CO}_2$ and organic acid toxicity.

**Nutrient kinetics in acid sulfate soils**

Soil reduction and pH increase after submergence are often very slow because of the high acidic buffer capacity that impedes the activity of most microorganisms.

The reduction of Fe(III) can readily produce concentrations (>300 ppm) toxic to rice in acid sulfate soils. The $\text{Fe}^{2+}$ concentration in the soil solution is controlled by FeS if the pH does not increase enough to result in FeCO$_3$ (Neue and Bloom 1989). The quantity of S$^{2-}$ produced by jarosite reduction is insufficient to remove all Fe$^{2+}$ released from jarosite and Fe(III) oxyhydroxides. If the acid sulfate soil is influenced by saline water, the sulfate ions may be sufficient to keep Fe$^{2+}$ concentrations low by FeS precipitation. But excess SO$_4^{2-}$ may lead to H$_2$S formation if the pH has been raised to about 5.

Since sulfate is reduced at a lower Eh than Fe(III) (Yu 1985), Fe$^{2+}$ may initially increase to very high concentrations. Ponnamperuma (1985) reported Fe$^{2+}$ concentration of more than 3,000 ppm. Manganese can also precipitate as MnS. If the initial Fe$^{2+}$-to-Mn$^{2+}$ ratio is low, Mn$^{2+}$ concentration may decrease below the solubility of MnS by coprecipitation with FeS, resulting in Mn deficiency (Neue 1988).

At pH values <4.5, Al$^{3+}$ is the principal hazard for crop growth. Since submergence raises the pH, rice is mostly unaffected by toxic levels of Al.

Phosphorus availability is usually restricted in acid sulfate soils, and added P is strongly absorbed. This is attributed to the high content of active Fe and Al. As pH drops below 8.34, depending upon which Fe oxide controls Fe and which mineral controls Al$^{3+}$, strengite (FePO$_4$2H$_2$O) and variscite Al (PO$_4$2H$_2$O) can be transformed to vivianite [Fe$_3$(PO$_4$)$_2$8H$_2$O] (Lindsay 1979). Vivianite precipitation can suppress P solubility in flooded acid sulfate soils to very low levels.

Phosphorus sorption varies widely in acid sulfate soils (Fig. 4, 5). Sorption is higher under oxidized than reduced conditions in the younger and less developed
4. P sorption under oxidized and reduced conditions in Sulfaquents and Fluvaquents (adapted from Ren 1987).

5. P sorption under oxidized and reduced conditions in Sulfaquepts and Tropaquepts (adapted from Ren 1987).
acid sulfate soils with easily reduced Fe (Sulfic Fluvaquents, Sulfaquents, Sulfic Tropaquents). Submergence of strongly developed acid sulfate soils hardly changes the P sorption pattern.

The sorption isotherm of the Sulfaquenet (Palehumic) in Figure 5 indicates that almost all added P precipitates. Saturation indices of the soil solution reveal the formation of vivianite. The response of flooded rice to P fertilization vanes according to P isotherm. If P is precipitated as vivianite, split application of P fertilizer becomes necessary.

The main limitations to crop production on acid sulfate soils are the depth of the sulfuric/sulfidic layer and the acidity potential based on features of Al, S, extractable Ca, and base saturation (Charoenchamratcheep et al 1988, Osborne 1985).

Reclamation of acid sulfate soils
Total reclamation of acid sulfate soils is economically feasible where the topsoil is only moderately acid and where adequate water, lime, and fertilizer are available. Water management is the key to reclamation and management. If fresh water is available for a minimum of 100 d, rice cultivation can be successful, even where sulfidic/sulfuric soils are present within 20 cm of the surface (Dent 1986). If the groundwater level can be maintained at the depth of the sulfidic layer and the non-sulfuric/ sulfuric topsoil is about 50 cm thick, even upland crops can be grown successfully on acid sulfate soils. If the topsoil is too shallow it can be raised with topsoil from shallow broad ditches that are constructed for irrigation and drainage.

Permanent flooding with fresh or saline water prevents oxidation of the sulfidic material. Acidity problems are severe in areas where waterlogging of the sulfidic sulfuric soil material cannot be maintained. Reclamation of these acid sulfate soils involves surface flushing of acids and soluble salts at the onset of the wet season, drainage, and incorporation of lime and fertilizer to remedy the residual acidity and nutrient deficiencies.

Lime requirements to neutralize all potential acidity of a 10-cm-thick soil layer may exceed 100 t/ha. Actual lime requirements are appreciably lower and dependent on the tolerance level of the crop. For flooded rice it is sufficient to increase the pH of the topsoil to about 5 to enhance microbe-mediated reduction of the soil. Less than 3 t lime/ha is usually sufficient for rice cultivation. The amount of lime is critical when phosphate rock (PR) is applied.

Nitrogen and P are always in short supply in acid sulfate soils. The availability of N is limited by slow mineralization. The low floodwater pH suggests that ammonia volatilization is not an important loss mechanism, but runoff loss may be serious (Satrusajang et al 1988).

Phosphate rock seems to be as effective as more soluble P fertilizer on acid sulfate soils. The response of rice to PR is inversely related to soil pH (Attanandana and Vachrotayan 1984). At low pH (<5) PR may even be superior to triple superphosphate (TSP). Liming to raise the pH to only 4.5 increased the efficiency of PR, while increasing the pH above 5 resulted in lower responses. Application of TSP
or fused magnesium phosphate gave highest grain yields when the pH was raised above 6. The most economical treatment is often a combination of lime and PR; its superior residual effect may last up to four successive crops. Placement or root dip of P fertilizer may be beneficial because of the high sorption capacity.

If the Fe$^{2+}$-to-Mn$^{2+}$ ratio is very high, application of MnO$_2$ at a rate up to 100 kg/ha depresses Fe toxicity induced through Mn deficiency.

**Peat soils**

Peat soils are organic soils that, in general, have high organic soil material in more than half of the upper 80 cm. The bulk density, bearing capacity, and content of all nutrients are very low in most peat soils. Nutritional disorders of rice on peat soils include deficiencies of both macro- and micro-nutrients, salinity, acidity, and H$_2$S toxicity. Sterility of rice occurs in areas with water-saturated deep peat soil and has been related to toxic concentrations of water-soluble polyphenols (Driessen 1978). Most peat soils in Southeast Asia are acid, and the pH is often <4. Many peat soil areas in Southeast Asia are underlain by acid sulfate soils and are influenced by tidal saline water.

The total N content of peat soils is usually high if expressed on a weight basis, but because of the low bulk density, wide C-to-N ratio, and low mineralization rate if saturated with water, the available N is low. The P- and K-supplying capacities of peat soils are high, but availabilities are low. Humic substances reduce P fixation by complexing Fe and Al, and the proportion of exchangeable Ca, Mg, K, and Na from the colloidal complex of peat is much higher than in mineral soils.

Aside from low contents, Zn and Cu are deficient in peat soils because of the strong fixing capacity of the organic matter, while Mo availability is limited by low pH. Deficiencies of Mn and Si in rice have been reported on peat soils in Japan (Takijima and Shiojiama 1955).

Drainage is required for growing upland crops, but irregular subsidence and rapid mineralization require careful design and management. Liming of peat soils may be recommended if appreciable amounts of mineral clays are present. Wetland rice cultivation is best suited for utilizing peat soils in their natural conditions, but the low bearing capacity, weeds, diseases, water management problems, and necessity of chemical fertilization greatly restrict productivity. Application of 50-100 kg N/ha, 25 kg/ha each of P and K, and adequate amounts of trace elements are needed to achieve rice yields of about 4 t/ha on peat soils.

**Iron-toxic soils**

Iron toxicity is a widespread nutritional disorder of wetland rice. It occurs with varying severity on flooded acid sulfate soils after drying, in poorly drained sandy soils in valleys receiving interflow water from adjacent acid highlands, and in clayey acid kaolinitic soils or sediments (Ultisols, Oxisols). In sandy soils, dissolved Fe may become toxic at concentrations of only 40 mg/liter (Van Breemen and Moormann 1978), but the concentration must normally exceed 300 mg/liter. Iron toxicity may
occur only at early growth stages or may last the whole season. If Fe toxicity appears early, plants suffer severe growth retardation; if late, yield is drastically reduced because of sterility. Iron toxicity may enhance stem rot at ripening, causing severe lodging. Benckiser et al (1984) suggested that Fe toxicity is induced by a multiple nutritional stress (insufficient supply of K, P, Zn, Ca, and Mg) rather than by a high level of water-soluble Fe under acid conditions. Apparently, a low pH and a relatively high concentration of ferrous Fe in the soil solution are not essential for Fe toxicity. The causal relationship between Fe toxicity and nutritional disorders is still not understood.

An Fe concentration of >300 mg/kg in the plant tissue has been established as the toxic level. Total Fe content is not a reliable discriminator for Fe toxicity. The orthophenanthroline-extractable ferrous Fe or the Fe(III)-to-Fe$^{2+}$ ratio seems to be more reliable.

Rice cultivars grown in China on Latosols (Oxisols, Ultisols) do not reveal Fe toxicity, although these soils are low in bases and available P. More than 80% of the inorganic P may be in the occluded P fraction in these soils. The P supply (A value) measured by $^{32}$P during tillering of wheat and rice was significantly correlated only with the unoccluded P and the Fe-P in acid soils (Zhu et al 1986). In calcified soils Ca-P also becomes important. The unoccluded P fraction, which increases upon flooding because of Fe(III) reduction, is the main P source for crops.

In acid sulfate soils and most Ultisols, Fe toxicity is more severe when the soil has been dried between cropping seasons. But in Madagascar, Fe toxicity in alluvial sediments derived from highly weathered Ultisols is less severe after a dry fallow period. In Sri Lanka, Fe toxicity is more severe in the wet than in the dry season. Iron toxicity in the latter two cases seems to be hydrology-induced (interflow of Fe-rich water and dilution or leaching of nutrients), while in the former case it is soil-induced. Since the intensity of the interflow and the concentration of dissolved Fe are highly variable in time and space, the occurrence and severity of Fe toxicity are highly variable, too.

Iron toxicity can be ameliorated by decreasing the dissolved Fe concentration in the root zone and correcting nutrient deficiencies. Decreasing dissolved Fe concentrations is achieved by liming, drainage, aeration, or prolonged submergence. The combination and amounts of fertilizers required may vary considerably among soils, but P and K applications are necessary on most Fe toxic soils. Organic matter amendments can be effective by increasing the availability of nutrients and by enhancing the initial reduction and subsequent precipitation of Fe.

Conclusions

Continued pressure on land resources demands further development of marginal lands that lie idle because of such soil problems as salinity, sodicity, strong acidity, and excessive organic matter. Extensive areas of adverse soils have been created by land reclamation and cultivation. Although we have accumulated a fair amount of scientific knowledge and expertise, there are still far more problems than solutions.
The main research targets for adverse rice soils are

- more efficient and effective water management practices to prevent or reduce salinity, sodicity, and acidity problems;
- better understanding of nutritional disorders in the context of soil nutrient kinetics, nutrient uptake, and physiological mechanisms of tolerance;
- enhancing knowledge on P kinetics and optimizing the use of P fertilizers;
- improving simulation models for quantifying interactive multiphase equilibria in and reclamation of adverse soils; and
- increasing the stress tolerance and yield potential of rice cultivars and promising upland crops.

Before marginal lands are brought under cultivation, policymakers should seriously consider the advantages and disadvantages of conserving or reclaiming adverse soils. The development of quantitative models to predict the environmental and socioeconomic impact of land reclamation is highly needed to establish a rational base for decisions.

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Notes

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Citation information: International Rice Research Institute (1990) Phosphorus requirements for sustainable agriculture in Asia and Oceania. P.O. Box 933, Manila, Philippines.
Chemistry of adverse upland soils

K. WADA, LI XUE-YUAN, AND P.W. MOODY

Chemically adverse upland soils fall into three categories: Ultisols and Oxisols in the tropics, Ultisols in the temperate regions, and Dystrandepts and Hydrandepts in the temperate to tropical regions. All these soils have formed in humid climates and differ in weathering and charge characteristics. The tropical Ultisols and Oxisols are highly weathered and low in plant nutrients. They have low constant and variable negative charges, and some are strongly acid but require relatively small amounts of lime to correct the acidity. The temperate Ultisols are higher in constant and variable negative charges and require larger amounts of lime if they are strongly acid. The Dystrandepts and Hydrandepts differ in depletion of plant nutrients, but both exhibit typical variable charge characteristics. The Ultisols and Oxisols grouped into the first two categories exhibit low to high P sorption, depending on soil texture and mineralogy and on whether the soils are derived from acid or basic parent materials. The Andepts exhibit extremely high P sorption in both the A and B horizons because of high activity of Al and Fe complexed with humus and associated with allophane and imogolite.

Adverse upland soils commonly have high and strong P sorption, and therefore require large inputs of P fertilizer. Some are highly weathered, low in organic matter content, and depleted of plant nutrients. Adverse upland soils have low effective cation exchange capacity (CEC) and hence limited ability to retain nutrient cations against leaching. They are often Al and/or Mn toxic or Ca deficient and require lime or gypsum to maintain productivity.

Adverse upland soils can differ widely in chemical, mineralogical, and physical properties. Chemically adverse upland soils are widely distributed and may be Ultisols, Oxisols, and some Alfisols in tropical and subtropical regions, and Ultisols in temperate regions. For example, in tropical and subtropical China, about 30% of cultivated upland soils have been classified as adverse upland soils (Cooperation Group of Utilization, Amelioration, and Division of Red-Yellow Soils 1985). Dystrandepts and Hydrandepts in the humid, temperate, and tropical regions comprise a unique category of adverse upland soils, although their distribution is more limited and they are different in extent of weathering.

This paper discusses the chemistry underlying the phenomena characteristic of adverse upland soils by examining the available information on charge characteristics, soil acidity and liming, and P sorption. It then relates this to an attempt to identify and alleviate the constraints of adverse upland soils.
Charge characteristics

The electric charges of soils are responsible for their ion exchange and retention. The difference in charge characteristics between the soils of the humid tropics and those of the temperate regions has been stressed by many investigators (e.g., Sanchez 1976, Uehara and Gillman 1981, Van Raij and Pech 1972). In tropical soils, positive charges exist, and positive and negative charges are generally pH-dependent; in the soils of temperate regions, negative, pH-independent charges predominate. However, adverse upland soils, in which leaching of nutrients is a problem, exist in both the tropical and temperate regions. Few data are available for comparison of the charge characteristics of these soils, particularly those based on separate evaluations of negative and positive charges.

Variable charges develop, depending not only on pH but on valence and concentration of ions that undergo ion exchange. This fact and the recognition that soils can carry variable charge as well as constant charge indicate the necessity for determining retention of exchangeable ions at pHs and electrolyte concentrations close to the soil solution in the field.

1. Electric charge characteristics of A1 or Ap and B2 or B horizons of That Ultisols and Oxisols, Korean Ultisols and Alfisols, and Japanese Dystrandepts, determined using NH$_4^+$ and NO$_3^-$ or Cl$^-$ as index ions at different pHs and concentrations (based on data of Okamura and Wada 1983, Wada and Okamura 1980, and Wada and Wada 1985).
Effects of pH and electrolyte concentration on charge development

Figure 1 illustrates features of the charge characteristics of upland soils in Thailand (tropical) and Korea (temperate). The soils differ in soil type, horizon, and major ion-exchange materials (Table 1). Figure 1 and Table 1 also contain data on Japanese Dystrandept A1 and B horizons. The measurement of electric charge was made by determining the retention of NH$_4^+$ and NO$_3^-$ or Cl$^-$. The soil sample was first saturated with NH$_4^+$ and NO$_3^-$ or Cl$^-$ by washing with 1 M NH$_4$NO$_3$ or NH$_4$Cl, and was then equilibrated with the same but more dilute solution at an appropriate concentration (0.005-0.1 M) and pH (4.5-8.0). The pH-charge curves in Figure 1 were drawn by “averaging” the ion retention data obtained for soil samples, which were grouped according to their location, soil type, and horizon. Constant negative charge was estimated by equating it with the cation retention at a pH of 4.0 and at a cation concentration of 0.005 M (Wada 1983). The difference in the effects of pH and electrolyte concentration on negative charge varied with soil and horizon. All soils except the Dystrandept B developed both constant and variable charges, but their magnitude and relative contribution varied with soil and horizon. The absence of constant charge was also reported for a Hydrandept B horizon (Wada 1983). The relative contribution of constant negative charge was least for the Japanese Dystrandept (A and B), followed by the Thai Ultisols and Oxisols (A and B) and the Korean Ultisols (A), and greatest for the Korean Ultisols (B) and Alfisols (A and B).

Table 1. Analytical data on soils different in ion-exchange materials (Wada and Ishimoto 1987, Wada and Wada 1985, Yoshinaga et al 1986, 1989).

<table>
<thead>
<tr>
<th>Soils</th>
<th>Horizon</th>
<th>Organic Clay (C (%))</th>
<th>Ion-exchange materia$^b$(H$^2$O)</th>
<th>pH</th>
<th>CEC Exchangeable</th>
<th>CEC Effective</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thai Ultisols and Oxisols (n = 13)</td>
<td>A1 or Ap</td>
<td>1.4 (± 1.0)</td>
<td>Kn, Al (Fe)-humus (± 0.4)</td>
<td>5.4 (± 1.9)</td>
<td>3.4 (± 1.3)</td>
<td>4.3 (± 1.8)</td>
</tr>
<tr>
<td></td>
<td>B2</td>
<td>0.5 (± 0.3)</td>
<td>Kn (± 0.5)</td>
<td>5.5 (± 1.5)</td>
<td>1.3 (± 1.1)</td>
<td>1.9 (± 1.3)</td>
</tr>
<tr>
<td>Korean Ultisols (n = 4)</td>
<td>A1 or Ap</td>
<td>1.4 (± 1.3)</td>
<td>Kn, Ch-Vt (± 0.4)</td>
<td>5.0 (± 1.0)</td>
<td>1.4 (± 2.2)</td>
<td>4.3 (± 1.7)</td>
</tr>
<tr>
<td></td>
<td>82</td>
<td>0.3 (± 0.1)</td>
<td>Kn, Ch-Vt (± 0.1)</td>
<td>5.5 (± 1.2)</td>
<td>2.1 (± 1.3)</td>
<td>6.0 (± 1.3)</td>
</tr>
<tr>
<td>Korean Alfisols (n = 4)</td>
<td>A1 or Ap</td>
<td>1.4 (± 0.3)</td>
<td>Ch-Vt, Vt, Kn (± 0.7)</td>
<td>5.5 (± 3.7)</td>
<td>10.5 (± 1.5)</td>
<td>1.2 (± 2.6)</td>
</tr>
<tr>
<td></td>
<td>82</td>
<td>0.3 (± 0.1)</td>
<td>Ch-Vt, Vt, Kn (± 0.9)</td>
<td>6.1 (± 10.7)</td>
<td>15.2 (± 1.4)</td>
<td>2.2 (± 10.0)</td>
</tr>
<tr>
<td>Japanese Dystrandept</td>
<td>A1</td>
<td>17.2</td>
<td>Al (Fe)-humus Ch-Vt (?)</td>
<td>5.0 (± 3.5)</td>
<td>4.6 (± 3.5)</td>
<td>4.9 (± 3.5)</td>
</tr>
<tr>
<td></td>
<td>B</td>
<td>2.0</td>
<td>A, Im (± 0.9)</td>
<td>5.7 (± 3.5)</td>
<td>3.3 (± 3.5)</td>
<td>0.1 (± 3.5)</td>
</tr>
</tbody>
</table>

$^a$Values in parentheses are standard deviations. $^b$A = allophane, Ch-Vt = chloritized Vermiculite, Im = imogolite, Kn = kaolin-group mineral, Vt = vermiculite.
The Japanese Dystrandept A and B horizons contained Al(Fe)-humus complexes and allophane and imogolite as major ion-exchange materials, respectively (Table 1). The Al(Fe)-humus complexes developed variable negative charge (Fig. 1), probably due to the interaction between ionized and negatively charged carboxyl groups and polymer hydroxy-Al and Fe cations with variable positive charge. A small amount of constant negative charge in the A horizon probably arises from the carboxyl groups ionized at or below pH 4.0. In allophane and imogolite, variable negative charge arises from ionization of Si-OH groups:

\[ \equiv \text{Si-\ OH} + \text{OH}^- \rightarrow \equiv \text{Si-\ O}^+ + \text{H}_2\text{O} \]

These Si-OH groups are present as “broken bonds” in the walls of hollow allophane spheres (diameter = 3.5-5 nm) and imogolite tubes (diameter = 2 nm) (Wada 1989).

The positive charge measured by NO$_3^-$ retention was very small on the average (<1 meq/100 g) in the Al or Ap horizons and did not exceed 2-3 meq/100 g in the B2 horizons (Fig. 1). The retention of NO$_3^-$ is usually lower than that of Cl$^-$. The K$^+$ or Na$^+$ and Cl$^-$ retention data for some Oxisols, Ultisols, and Alfisols in the tropics (e.g., Morais et al 1976, Van Raij and Peech 1972) showed that the A horizons were generally net negatively charged at or near the field pH, while the B horizons were either isoelectric or net positively charged. The Dystrandept B horizon containing allophane and imogolite developed variable positive charge comparable to negative charge, most probably due to protonation of Al-OH groups in the allophane spheres and imogolite tubes:

\[ \equiv \text{Al}\equiv\text{OH} + \text{H}^+ \rightarrow \equiv \text{Al}\equiv\text{OH}_2^+ \]

Note that the Al(Fe)-humus complexes in the Dystrandept A horizon did not develop positive charge.

**Effective cation exchange capacity**

Average soil pH ($\text{H}_2\text{O}$) and effective CEC values (Table 1) are also plotted in Figure 1. The effective CEC is defined as the sum of exchangeable bases (Ca, Mg, K, Na) and Al, and has been used as a measure of CEC under near-field conditions (Kamprath 1970). Comparison of the effective CEC and the amount of constant negative charge indicated that constant charge had primary importance, though variable charge more or less contributed to the cation retention in the field. The relative contribution of variable charge to the effective CEC was greatest in the Japanese Dystrandept (A and B), followed by the Thai Ultisols and Oxisols (A and B) and the Korean Ultisols (A), and least in the Korean Ultisols (B) and Alfisols (A and B).

The low effective CEC of the Thai Ultisols and Oxisols was due primarily to the low constant negative charge, which can be related to clay mineralogy, soil texture, or both. These soils contained fine-grained kaolin mineral(s) as major clay mineral species, and some were very low in clay (Table 1). In the B horizons, clays exhibited 5.7 ± 2.2 meq constant charge/100 g. The higher constant charge of 10.8 ± 7.4 meq/100 g of clay in the A horizons may indicate the contribution of humus.

The Korean Ultisols contained kaolin mineral(s) and/or chloritized vermiculites (Table 1). The latter contributed to the constant negative charge being higher in the
Korean Ultisols than in the Thai Ultisols. The higher proportion of variable charge in the A than in the B horizons of Korean Ultisols (Fig. 1) suggests the contribution of humus, but this was not indicated by the constant negative charge values of 9.9 ± 2.7 meq/100 g clay in the A horizons and 13.3 ± 2.2 meq/100 g clay in the B horizons. The distinctly high constant charge of Korean Alfisols probably reflected the higher relative content of vermiculite in the clays, which exhibited 33.8 ± 14.4 meq constant charge/100 g clay due to isomorphous replacement within the vermiculite layer.

**Soil acidity and liming**

Most upland soils under leaching conditions are acid, and Al$^{3+}$ is the dominant exchangeable cation. Soil acidity involves intensity and quantity aspects, which can be characterized using the pH-charge curve such as shown in Figure 1. When the soil is saturated with H$^+$, the constant negative charge sites, which can release H$^+$ at pH 4.0 or below, act as strong acid sites. The quantity of strong acidity is therefore equal to that of constant charge on the equivalent basis. Because H$^+$ reacts with layer silicate clays, resulting in the release of Al$^{3+}$, exchangeable Al$^{3+}$ is the dominant cation species in strongly acid soils. This is demonstrated for the acid Ultisols and Oxisols in Figure 1. On the other hand, variable negative and positive charge sites act as weak acid sites, which release H$^+$ above pH 4.0, buffering the rise of pH. These sites do not retain exchangeable Al$^{3+}$, as demonstrated for the Dystrandept.

It is now known that Al toxicity often associates with low levels of Ca and Mg and is the most common cause of acid soil infertility. In addition to exchangeable Al values, a useful measure of soil acidity is the percentage of Al saturation of the effective CEC (Sanchez 1976). The level of Al saturation can be used to designate lime requirements for specific crops or varieties, e.g., 10-20% for cotton, sorghum, and alfalfa, and 40-50% for maize. Juo (1981) proposed that 30% or more Al saturation in the diagnostic B horizon be used for separating Ultisols from Alfisols.

The pH-charge curves also give a good indication of the buffering capacity of a soil. Lime added to an acid soil is consumed, not only to interact with exchangeable Al$^{3+}$:

$$n\text{Al}^{3+} + m\text{OH}^- \rightarrow \text{hydroxy-Al polymer cations and Al(OH)$_3$}$$

but also to interact with H$^+$ released from variable charge sites:

$$\equiv \text{Si - OH + OH}^- \rightarrow \equiv \text{Si-O} + \text{H}_2\text{O}$$
$$\equiv \text{Fe} \equiv \text{OH}^+ + \text{OH}^- \rightarrow \equiv \text{Fe} \equiv \text{OH} + \text{H}_2\text{O}$$
$$\equiv \text{Al} \equiv \text{OH}_2^+ + \text{OH}^- \rightarrow \equiv \text{Al} \equiv \text{OH} + \text{H}_2\text{O}$$

Kamprath (1970) recommended that 1.5 meq Ca as lime/100 g soil or 1.65 t CaCO$_3$/ha per 1 meq exchangeable Al/100 g soil be used to eliminate Al toxicity. This practice has been used successfully in South America (Sanchez 1981), but cannot be used to correct the acidity of “weak acid” soils. The residual effect of liming depends on how fast the incoming H$^+$ replaces the Ca$^{2+}$ and Mg$^{2+}$ retained on negative charge sites. This residual effect would be more lasting for constant than
variable charge soils. It also depends on soil texture and structure, rainfall, and particularly on rate of residually acid N fertilizer used.

Overliming, i.e., liming at rates higher than necessary to eliminate Al toxicity and to pH values greater than 5.5, may or may not cause detrimental effects, depending mainly on soil type. Detrimental effects were most commonly noted in Oxisols and Ultisols in the tropics (Sanchez 1976), as expected from their low pH buffering capacity (Fig. 1). These soils are also low in available P, B, and Zn and high in P sorption capacity.

Phosphorus sorption

Phosphate shows a strong affinity for Al and Fe. Phosphate is adsorbed by replacing \( \text{H}_2\text{O} \) and \( \text{OH} \) groups coordinated to Al and Fe atoms (ligand exchange). These Al(Fe)-\( \text{H}_2\text{O} \) and \( -\text{OH} \) groups are present as “broken bonds” on mineral surfaces or in monomer and polymer cation forms adsorbed on mineral surfaces or complexed with humus. Chemically adverse upland soils generally have great P sorption capacities, because their clay mineralogy is dominated by oxides and hydroxides of Fe and Al or allophane and imogolite, and because their humus is complexed with Al and Fe.

To understand the forms of Fe and Al that are most important in determining the P sorption properties of soils, two approaches are generally adopted. The first is to measure P sorption before and after the removal by selective extraction of a particular form of Fe or Al. However, this approach is open to the criticism that the soil extraction process may appreciably alter the chemistry of the soil, and any change in P sorption may be an artifact. The second approach is to correlate P sorption properties with the amounts of Fe and Al extracted by selective dissolution. This approach avoids changing the chemistry of the soil but depends on the selective extractants causing the dissolution of only certain defined constituents (Parfitt and Childs 1988, Wada 1989).

Factors affecting phosphorus sorption

The most important factors governing P sorption are the surface area of the clay fraction and the types of constituents present. Many papers report a positive correlation between P sorption and clay content, which would be due simply to an increasing surface area for adsorption as clay content increased. However, soils of similar clay contents often exhibit a marked difference in P sorbing ability, and, using selective extractants, this can generally be traced to the amounts of different forms of Fe and Al in the clay fractions. Coefficients of multiple regression equations relating P sorption to the different forms of Fe and Al give estimates of their P-sorbing ability.

The quantity of P required to attain a standard P concentration of 0.2 ppm in the solution equilibrated with the soil has been measured as a good parameter of P requirement. Juo (1981) grouped soils into five categories according to their standard P sorption value and showed that the key factors affecting P sorption are mineralogy and the specific surface-area of oxides (Table 2). He also stressed the
importance of the difference between soils derived from acidic (e.g., granite) and basic (e.g., basalt) parent materials.

The relative importance of Al and Fe species in P sorption depends on the soils considered. For example, Udo and Uzu (1972) showed that Al was more highly correlated with P sorption than Fe for acid Nigerian soils. On the other hand, the regression indicated that noncrystalline Fe was more active than noncrystalline Al in some Oxisols from Australia (Moody and Standley 1979), and that Fe and Al were not different within each category in some soils from the southeastern coastal plain of the USA (Ballard and Fiskell 1974).

Tokashiki et al (1983) showed that the contents of Al and Fe oxides and hydroxides and P sorption values to attain 0.2 ppm P in the solution were comparable between upland soils in Thailand and those in Korea and Okinawa (Table 3). Multiple regression analysis of the data indicated that the P-sorbing ability of different forms of Al and Fe (P/Al or Fe molar ratio) decreased in the order:

$$\text{Exchangeable Al (0.49) > noncrystalline Al (0.07) > crystalline Al (0.018) > noncrystalline Fe (0.015) > crystalline Fe (0.004)}$$

The possible contribution of these different forms of Al and Fe to the P sorption was estimated using their P-sorbing ability and contents in the soils, and decreased in the order:

Noncrystalline Al (23-50%) > exchangeable Al (10-28%), crystalline Fe (14-25%), crystalline Al (15-19%) > noncrystalline Fe (24%)

Measurements of P sorption before and after the dissolution treatments indicated that the role of hydroxy-Al in 1.4 nm intergrade 2:1 layer silicates in P sorption was greater than Fe oxides in Ultisols (Red soils), while the opposite was true in Alfisols (Yellow Brown soils) of tropical and subtropical China (Li Xue-yuan, unpubl. data).

In Andepts, Al- and Fe-humus complexes, allophane-like constituents, allophane, and imogolite were related to P sorption (Wada 1985). The dependence of P sorption on the pH and P concentration was found to be different among the different groups of Andepts. Those containing allophane and imogolite showed

<table>
<thead>
<tr>
<th>P sorption (µg P/g)</th>
<th>Scale</th>
<th>Dominant mineralogy</th>
</tr>
</thead>
<tbody>
<tr>
<td>&lt;10</td>
<td>Very low</td>
<td>Quartz, organic materials</td>
</tr>
<tr>
<td>10-100</td>
<td>Low</td>
<td>2:1 and 1:1 layer silicates, quartz</td>
</tr>
<tr>
<td>101-500</td>
<td>Medium</td>
<td>1:1 layer silicates with “low specific surface” oxides</td>
</tr>
<tr>
<td>501-1000</td>
<td>High</td>
<td>“High specific surface” oxides, weathered ash</td>
</tr>
<tr>
<td>&gt;1000</td>
<td>Very high</td>
<td>Allophanes and desilicated amorphous materials</td>
</tr>
</tbody>
</table>

$^a$P sorption to attain 0.2 ppm P in the solution.
Table 3. Al and Fe contents and P sorption (mmol/100 g) of upland soils in Thailand, Korea, and Okinawa (Tokashiki et al. 1983).a

<table>
<thead>
<tr>
<th>Element</th>
<th>Thailand</th>
<th>Korea and Okinawa</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Al or Ap</td>
<td>B2</td>
</tr>
<tr>
<td>Exchangeable Alb</td>
<td>0.25 (±0.38)</td>
<td>0.54 (±0.36)</td>
</tr>
<tr>
<td>Noncrystalline Alc</td>
<td>8.2 (±10.6)</td>
<td>3.5 (±3.6)</td>
</tr>
<tr>
<td>Crystalline Ald</td>
<td>9.6 (±21.1)</td>
<td>11.2 (±12.4)</td>
</tr>
<tr>
<td>Noncrystalline Fe</td>
<td>2.5 (±1.9)</td>
<td>1.2 (±1.6)</td>
</tr>
<tr>
<td>Crystalline Fed</td>
<td>47 (±50)</td>
<td>64 (±54)</td>
</tr>
<tr>
<td>P sorptionf</td>
<td>0.79 (±0.96)</td>
<td>1.09 (±0.77)</td>
</tr>
</tbody>
</table>

a Values in parentheses are standard deviations. b1 M KCl-extractable. c0.2 M oxalate-oxalic acid (pH 3.0) extractable minus 1 M KCl-extractable Al complexed with humus and present as noncrystalline oxides. dDithionite-citrate-extractable minus 0.2 M oxalate-oxalic acid (pH 3.0)-extractable Al or Fe in crystalline oxides and hydroxides. e0.2 M oxalate-oxalic acid-extractable Fe complexed with humus and present as noncrystalline oxides. fP sorption to attain 0.2 ppm P in the solution.

appreciable pH dependence, whereas those containing Al- and Fe-humus complexes showed little pH and greater P concentration dependence (Gunjigake and Wada 1981). For some Andepts from New Guinea, Moody and Radcliffe (1986) suggested that allophane, crystalline and noncrystalline aluminum hydrous oxides, and Fe associated with humus account for the predominant P-sorbing sites.

Role of organic matter
The role of organic matter in P sorption is complex. There is some evidence that easily decomposable organic matter may produce carboxylic acids, which reduce P sorption by blocking Fe and Al sorption sites (Saunders 1965). Data also indicated that the presence of organic matter reduces the amount of P sorbed by Oxisols (Uehara and Gillman 1981). On the other hand, Udo and Uzu (1972) reported for Nigerian soils that organic matter had little effect on P sorption. Hinga (1973) and Moody and Standley (1979) reported close correlations between amorphous Fe and Al and organic matter content in several Kenyan soils and in basaltic soils in Queensland. For Andepts, the importance of Al- and Fe-humus complexes in P sorption was also indicated by positive correlations between organic C content and P sorption (Mizota et al. 1982) and between pyrophosphate-extractable Al and Fe (i.e., organically bound) and P sorption (Wada and Gunjigake 1979). Whether organic matter increases, decreases, or has no effect on P sorption apparently depends on how decomposable the organic matter is, and how much Al and Fe are associated with it.
Effect of liming on phosphorus sorption

Liming of adverse upland soils aims primarily at reducing Al and/or Mn toxicity, and also at improving P availability. However, the associated change in soil pH may increase, decrease, or have no effect on P availability (Haynes 1982). Numerous studies failed to show either reduction in P sorption or improvement in solubility in various extractants after liming (Pearson 1975).

The dominant P sorbing mineral surfaces of adverse upland soils comprise Al and Fe oxides and hydroxides (Oxisols, Ultisols, and Alfisols) and allophane and imogolite (Andepts). These surfaces exhibit variable charges depending on soil solution pH and electrolyte concentration (Fig. 1). The increase in negative charge with increasing pH would increasingly repel phosphates as they approach the surface, resulting in a decrease in P sorption (Parfitt 1978). However, in fertilized soils, P that is already sorbed is desorbed to a greater extent at low pH than at higher pH, and the net effect is an increase in P sorption as pH rises to about 5.5 (Barrow 1984).

Lime application leads to an increase in Ca concentration in the soil solution. The effect of the increase, with pH, of negative charge is partially counteracted by the specific affinity of Ca$^{2+}$ for the oxide surfaces causing the potential in the plane of adsorption to be less negative (Barrow et al 1980, Helyar et al 1976), and therefore less repulsive to phosphates.

Soil P solubility in an Oxisol from Colombia decreased sharply as pH was increased by CaCO$_3$ application up to about pH 6.5, and the limed soil had a higher maximum P sorption than the unlimed soil (Amarasiri and Olsen 1973). The authors suggested that the freshly precipitated Fe and Al oxides were responsible for the increased P sorption. On the other hand, P sorption decreased when an Oxisol from Panama was limed to pH 5.5, and less than half the P application rate was needed in the limed soil to approach maximum yields in relation to the unlimed soil (Sanchez 1976). The amount of P added to give different levels of P in soil solution was also decreased by adding lime or Ca silicate in an Oxisol from Brazil, but the effect was less marked at higher concentrations of soil solution P (Sanchez 1981). Sanchez and Uehara (1980) concluded that the decrease in P sorption by liming is considerable only in acid soils with high Al saturation. In acid soils with low Al saturation, the effect is negligible. Liming to pH values near neutrality may lower P availability because of formation of relatively insoluble Ca phosphates.

Conclusions

The chemistry underlying the phenomena characteristic of adverse upland soils is governed primarily by the nature and properties of clay constituents and humus complexes. The pH-charge and the electrolyte concentration-charge curves are useful for assessing not only the amounts of constant and variable charges but the intensity and quantity aspects of soil acidity. The effective CEC—defined as the sum of exchangeable Ca, Mg, K, Na, and Al—is a good measure of CEC under near-field conditions, and exchangeable Al is a useful parameter to estimate lime requirements for strongly acid upland soils where Al toxicity is a problem. The high P sorption capacity is due to various forms of active Al and Fe such as exchangeable Al,
noncrystalline Al silicates and oxides, Fe oxides, and Al and Fe bound with humus. The quantity of P required to attain a P concentration of 0.2 ppm in the solution equilibrated with the soil can be used as an indicator of P requirement.

References cited


Notes

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Citation information: International Rice Research Institute (1990) Phosphorus requirements for sustainable agriculture in Asia and Oceania. P.O. Box 933, Manila, Philippines.
Effects of liming on soil phosphorus availability and utilization

D.C. Edmeades, D.M. Wheeler, and R. M. Pringle

The effect of lime on soil P availability is examined. Evidence is presented to indicate that many of the commonly used criteria for assessing soil P availability—soil tests, absorption isotherms, incubation studies, and plant P concentration, and uptake—cannot necessarily be used as unequivocal evidence of the effects of liming. The P-sparing effect of lime is defined as the net effect of those lime-related soil processes that result in plant-unavailable P being converted to plant-available P. A method for identifying the P-sparing effect of lime is defined based on the effects of lime and P and their interaction on plant growth. This method, when applied to data from New Zealand and Australia, shows that liming does not generally increase soil P availability. On one soil where this effect did occur, the P-sparing effect was equivalent to 11-20 kg P/ha per yr. The "released" P was derived from mineralization of organic P (40%) and from decreased adsorption of inorganic P (60%). On soils where no P-sparing effect occurs, liming may increase the uptake and hence utilization of already available soil P by alleviating Al or Mn toxicity, increasing N availability through enhanced mineralization, or overcoming some micronutrient deficiency such as Mo. The importance of the effects of liming on enhancing mineralization of soil organic N is stressed. Results from field trials indicate that this effect is equivalent to 20-30 kg N/ha per yr. However, this effect of liming is generally ignored.

The persistent generalization that liming increases soil P availability and hence reduces fertilizer P requirements deserves close examination. This is especially relevant to New Zealand, where limestone is a relatively inexpensive indigenous resource but P fertilizer is imported at an annual cost of about US$123 million.

Haynes (1982), summarizing the literature on the effects of liming on P availability in acid soils, concluded that liming may increase or decrease the availability of soil P depending on circumstances. He also showed (Haynes 1982, 1983) that drying soils after liming can alter P sorption, which may explain some of the contradictory results in the literature on the effects of liming on P availability. This also has important implications for the interpretation of some laboratory-based measurements used to examine this effect of lime. Haynes (1982) also emphasized the effect of liming on increased mineralization of soil organic P and noted that this has been virtually overlooked by most workers. He stressed the need for further research in the area.
The purpose of this paper is to expand some of these ideas. The emphasis will be on the applied aspects, looking at the problem as an agronomist rather than as a soil chemist, and attempting to quantify some of the effects of liming on soil P availability.

**Measuring the effects of lime on soil phosphorus availability**

Many methods have been employed to measure the effects of liming on soil P availability.

**Laboratory measurements**

A wide range of laboratory tests have been used to measure the effects of liming on soil P availability, including adsorption isotherms, incubation and equilibration studies, and a variety of P extraction procedures. A number of the studies show that the observed effects of lime from laboratory tests are not always consistent (Curtin and Smillie 1984, Friesen et al 1980, Haynes and Ludecke 1981, Holford 1983) or do not relate in a meaningful way to plant P uptake (Amarasiri and Olsen 1973, Haynes and Ludecke 1981, Holford 1985, Rhue and Hensel 1983).

The evidence of Haynes (1982) on the effects on P sorption of wetting and drying after liming is one possible reason for these discrepancies. The point remains, however, that given current knowledge it is difficult and potentially misleading to place exclusive reliance on such tests when assessing the effects of lime on soil P availability.

A comprehensive review of the many discrepancies that have been reported is not within the scope of this paper, nor is a discussion of possible reasons for their existence. The point is that laboratory measurements of the type described are in themselves not particularly useful when attempting to examine the effects of liming on soil P availability.

A few examples from current New Zealand research will demonstrate these points.

The results in Figure 1 from a field trial on yellow-brown earth (Mahoenui) show the effects of liming and P application on the average annual Olsen P levels and pasture P uptake (Fig. 1b), together with the effects of pH on CaCl₂-extractable P and Olsen bicarbonate P from an incubation study on the same soil (Fig. 1a). In addition, P adsorption isotherms on soil samples collected from the respective treatments annually show no consistent effects of liming over time (D.C. Edmeades, unpubl. data).

These results reveal that the various laboratory tests showed inconsistent effects of liming on this soil, and furthermore that the test results do not relate in a meaningful way to the effects of liming on plant P uptake. Additional results from this field trial are discussed in a subsequent section of this paper.

Similarly, the data in Figure 2 from a glasshouse experiment (Edmeades et al 1983) show large decreases in Olsen P levels with increasing pH as a result of liming. These decreases were associated with increases in plant P uptake, indicating that the Olsen P test, under these circumstances, is not measuring the same pool of available P that the plant experiences. This anomaly has been reported elsewhere (Holford 1985). Furthermore, the decrease in Olsen P cannot be explained as a result of the
1. Effects of lime-induced changes in soil pH on indices of available P in an incubation study (a) and in the field (b) on a yellow-brown earth (Mahoenui). Soil pH 5.2; Olsen P, 10 µg/ml; 0.01 M CaCl₂-Al, 1.6 µg/g

2. Effects of lime-induced changes in soil pH on Olsen bicarbonate P and white clover P uptake on a yellow-brown earth (Marua) and a brown granular clay (Waitakere) (Edmeades et al 1983).
increase in plant P uptake. The reason for this apparent anomaly can be attributed to precipitation of P as Ca-P during extraction when the test is used on limed soils (Sorn-srivichai et al 1983).

It should be clear from these few examples that simple laboratory tests cannot be interpreted as unequivocal evidence of the effects of liming on P availability. At best they can be useful corroborative evidence.

**Plant phosphorus uptake and concentration**

Plant uptake of soil P, and plant P concentration are often used as indicators of the effect of lime on P availability (Haynes and Ludecke 1981, Holford 1985, Juo and Uzu 1977, Rhue and Hensel 1983, Sims and Ellis 1983, Soltanpour et al 1974). They should also be interpreted cautiously, as the following examples demonstrate.

It might be inferred from the P uptake data in Figure 2 and the plant P concentration data in Figure 3 that liming these soils increases soil P availability. However, Edmeades et al (1983) showed that the observed increases were due to the alleviation of Al toxicity, resulting in improved plant growth and plant P concentration, and hence P uptake. There was no evidence on either soil that liming increased the availability of soil P per se. Other examples of this can be found (Haynes and Ludecke 1981, Friesen et al 1980). A similar effect of lime on P uptake could occur on soils where Mn toxicity is the factor limiting plant growth.

Furthermore, even on soils where neither Al nor Mn toxicity limits growth, a lime-induced increase in P uptake cannot be assumed as categorical evidence that soil P availability is increased.

Results from a glasshouse experiment are given in Figure 4. The increase in growth of ryegrass *Lolium perenne* L. due to liming resulted from increased

3. Effect of lime-induced changes in soil pH on white clover P concentration.

mineralization of organic N (Edmeades et al 1981). Thus, the observed increase in P uptake was a consequence of improved plant growth resulting from increased soil N availability, not due to a lime-induced increase in soil P availability.

Similarly, all the evidence (see subsequent discussion) indicates that the observed lime-related increase in plant P uptake in the field trial (Fig. 1) was not due to an increase in soil P availability per se.

Definition of the phosphorus-sparing effect of lime

Given the preceding discussion, how can the effects of liming on soil P availability be measured and hence how can the beneficial effects of liming, if any, on reducing fertilizer P requirement be quantified?

To proceed, two types of lime-induced changes that affect soil P availability, uptake, and consequent utilization need to be differentiated:

- **Type A.** Those effects that alter the chemical availability of soil P, including changes in P adsorption, solubility of P minerals, and mineralization of organic P (c.f. Haynes 1982).
- **Type B.** Those effects that alter the ability of the plant to take up and utilize already plant-available soil P or applied fertilizer P, such as Al and Mn toxicity, mineralization of organic N, and changes in availability of trace elements such as Mo.
This distinction is important for several reasons. First, it is frequently the type A processes that are inferred in the generalization “liming increases P availability,” but it is often data relating to the type B processes that are used as supporting evidence. The widespread use of plant P uptake data as the definitive measure of P availability supports this proposition.

Also, it is important to differentiate between soil- and plant-related effects of lime. Type A processes are specific effects of liming on the soil and, assuming they are beneficial, result in otherwise plant-unavailable P becoming available. This is equivalent to what During et al (1960) called the “P-sparing effect of lime.” This term is useful to categorize these soil processes. In contrast, type B processes are plant-related in that they affect the ability of the plant to take up already available soil P. Looked at simply, in the absence of the plant, type A processes will result in an increase or decrease in the pool of available P, whereas type B processes will have no effect.

It is possible to differentiate between type A and type B processes by measuring the interactions between lime and P treatments in glasshouse or field experiments (see Munns 1965).

On a P-deficient soil, a negative interaction implies that the size of the response to applied P (i.e., a measure of P deficiency) is decreased by applying lime; liming releases unavailable soil P, thereby reducing P deficiency. This assumes that both lime and P application have a beneficial effect on growth. Negative interactions may also arise if liming decreases soil P availability (Haynes 1982), but these situations are characterized by an overall depression of plant growth by liming (Friesen et al 1980, Holford 1985, Lowther and Adams 1970).

Positive interactions on a P-deficient soil result when liming alleviates some limitations to plant growth not related to soil P deficiency per se. Common examples are Al and Mn toxicities, and Mo and N deficiencies. After alleviating the secondary limitation to plant growth, the plant is better able to respond to applied P. The size of the positive interaction will relate to some extent to the degree to which the secondary nutritional factor limits growth. It is possible that no interaction will occur if the degree to which the secondary factor limits growth is subliminal. The results in Figure 5 are an example.

5. Effect of lime in the presence and absence of applied P (50 kg/ha per yr) on total pasture production and the production of the grass (mainly ryegrass) and legume (mainly white clover) components on a yellow-brown earth (Mahoenui) (soil pH, 5.2; Olsen P, 10 µg/ml; 0.01 M CaCl₂-Al, 1.6 µg/g).
Both type A and B processes can occur on a given soil, and it is possible to identify both if the range of experimental treatments is wide enough. Munns (1965) provided an excellent example of this.

One point requires further emphasis. In the situation where there is a positive effect of time and P, and a positive or nil interaction between lime and P, it is possible to obtain the same yield at least in the short term by substituting lime for applied P. However, the pool of available P in the soil receiving lime and the reduced P inputs will in time decline, by definition, because lime is not releasing unavailable soil P (assuming that the rate of uptake of available P is greater than the natural release of stable components of the P cycle). Therefore, at some stage in the future a capital input of P will be required. This therefore does not represent a long-term saving in fertilizer P by the use of lime and is not regarded as a P-sparing effect.

With this background, Mansell et al (1984) proposed a definition of the P-sparing effect of lime based on the effects of lime and P and their interactions on plant growth.

The following conditions are necessary and sufficient to describe the P-sparing effect:

- There must be a negative lime × P interaction.
- There must be an overall response to P.
- There must not be yield depressions to lime.

The inclusion of the third condition takes into account the situation in which negative lime × P interactions occur because of decreased P availability in the soil due to liming. Thus, this definition of the P-sparing effect refers only to those type A processes that are beneficial in the sense that soil P availability is increased.

**Occurrence of the phosphorus-sparing effect**

The above definition has been applied to field trial results on the North Island of New Zealand to examine the long-term potential for reducing fertilizer inputs by liming (Mansell et al 1984). The results indicate that the P-sparing effect of lime does not commonly occur on North Island soils and, more importantly, when it occurs its practical effect in terms of reduced fertilizer P requirements appears small.

For example, of 25 trials, which included volcanic and sedimentary type soils, only 11 showed a P-sparing effect. Of these 11, in only 4 (Table 1) was the interaction large enough to indicate an economic saving in P fertilizer following liming. Pasture production data from two trials exhibiting the largest P-sparing effects are given in Figure 6.

**Table 1. Location of trials that showed large P-sparing effects due to liming.**

<table>
<thead>
<tr>
<th>Location</th>
<th>Soil group</th>
<th>Soil type</th>
<th>Soil pH</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wairarapa</td>
<td>Yellow-grey earth</td>
<td>Kokotau silt loam</td>
<td>5.4</td>
</tr>
<tr>
<td>Northland</td>
<td>Northern yellow-brown earth</td>
<td>Omanaia clay</td>
<td>5.1</td>
</tr>
<tr>
<td>Northland</td>
<td>Northern yellow-brown earth</td>
<td>Omanaia clay</td>
<td>5.2</td>
</tr>
<tr>
<td>Taranaki</td>
<td>Yellow-brown loam</td>
<td>Norfolk coarse sandy loam</td>
<td>5.6</td>
</tr>
</tbody>
</table>
6. Effect of lime in the presence and absence of applied P (50 kg/ha per yr) on total pasture production on Omanaia (yellow-brown earth) and Kokotau (yellow-grey earth) soils, showing the P-sparing effect of lime.

In addition, this study showed that, even on those soils where the P-sparing effect occurs, it is not consistent. Negative lime × P interactions in a 6-yr trial on a yellow-grey earth (Kokotau silt loam, pH 5.6) occurred 4 times in winter, 3 times in late spring, and once each in autumn, early spring, and summer. Not all negative lime × P interactions give rise to a P-sparing effect, and further analysis of this trial shows that the P-sparing effect of lime occurred in only 3 of the 40 seasons over the 6-yr period (Mansell et al 1984).

Mansell et al (1984) concluded that
• the P-sparing effect of lime does not commonly occur on soils on the North Island of New Zealand;
• even where the effect does occur, it is not consistent; and
• at present it is not possible to predict where and when this effect occurs, although it is associated with sedimentary-type soils at low pH (<5.5).

These conclusions are perhaps surprising, given how readily the notion that liming increases soil P availability has been embraced. The results of Holford (1985) are therefore pertinent. He examined the lime × P interactions in 15 Australian topsoils representing 8 of the great soil groups. Applying the definition of the P-sparing effect given earlier to his data shows that only three of these soils exhibited negative lime × P interactions, and on two of these it appears that the negative interaction was due to a depression in growth with liming in the presence of applied P. Thus, only one soil exhibited a P-sparing effect. The fact that soil P uptake and available soil P increased as a result of liming on most of the soils he examined is not inconsistent with this conclusion. As explained earlier, changes in these indices are not in themselves unequivocal evidence that liming increases the availability of P in the soil.

Accepting this means of defining the P-sparing effect of lime, we see that the generalization that liming increases soil P availability is not particularly useful, and that the scope for reducing P inputs by liming is not great, at least on many New Zealand and Australian soils.
Quantifying the phosphorus-sparing effect

Where the P-sparing effect does occur, how much fertilizer P can be saved? A subsequent field trial on the Kokotau soil quantified the size of the P-sparing effect on it. At this trial site, the initial pH was 5.3, with an Olsen P level of 9 µg P/ml soil, and 0.01 M CaCl₂-Al of 1-2 µg/g. The pasture production results (Fig. 7) show a classic P-sparing effect: a negative lime × P interaction with an overall response to liming and applied P.

A number of approaches can be used to analyze these data to quantify the P-sparing effect:

- Fit P-response curves. The difference in x-intercepts determined by extrapolation is a measure of P spared.
- Calculate the applied P required in the absence and presence of lime to obtain some target annual pasture yield. The difference in P required is a measure of P spared.
- Calculate the economically optimal rate of P to apply in the absence and presence of lime. The difference is a measure of P spared.
- Calculate the applied P required in the absence and presence of lime to obtain some target P concentration in herbage. The difference in P required is a measure of P spared.

The results (Table 2) indicate that 11-20 kg/ha of unavailable P was converted to available P annually as a consequence of liming. It does not particularly matter which method of analysis was used, although the estimate obtained by extrapolating the data and determining the difference in the x-intercepts was somewhat higher. This arises presumably because of the larger errors associated with extrapolating the data.

7. Effect of P applications on annual pasture production (mean over 4 yr) with and without applied lime (2.5 t/ha) on a yellow-grey earth (Kokotau) (initial soil pH 5.3; Olsen P, 9 µg/ml; 0.01 M CaCl₂-Al, 1-2 µg/g).
Table 2. Summary of the estimates of the amount of P spared by liming on Kokotau soil.

<table>
<thead>
<tr>
<th>Method</th>
<th>P spared (kg/ha per yr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Estimate from x-intercepts</td>
<td>30</td>
</tr>
<tr>
<td>P required for given yield</td>
<td>12-18</td>
</tr>
<tr>
<td>Maximizing economic outcome</td>
<td>15-19</td>
</tr>
<tr>
<td>P required for given herbage P concentration</td>
<td>11-17</td>
</tr>
</tbody>
</table>

Detailed analysis of the soils from this trial (Perrott and Mansell 1988), involving sequential P fractionation, showed that about 40% of the released P was derived from organic P, and the balance from a decrease in adsorbed inorganic P.

In a further field trial on a related sedimentary type soil, Quin et al. (1984) found that liming reduced the accumulation of organic P under pasture. They postulated that this was due to increased solubility, and therefore susceptibility to mineralization, of P monoesters. They found, in contrast to the results of Perrott and Mansell (1988), that liming also increased soil inorganic P. They attributed this largely to the precipitation of calcium phosphates and postulated that this effect did not occur in the Kokotau trial because the pH after liming was lower (5.9 vs 6.6).

It is not known from these experiments how long the P-sparing effect will last and hence how long the benefits of liming on reducing fertilizer P requirements will continue. One assumes that the fertilizer P requirements will increase to their former levels once the pools of unavailable soil P have been exhausted. It is also possible, in a semiclosed nutrient cycling system such as grassland farming in New Zealand, that the benefits of the P-sparing effect may last for several years after the beneficial soil processes giving rise to it have ceased.

Effects of liming on phosphorus utilization

Distinct from the P-sparing effect of lime (type A effect), it is axiomatic that liming will increase the uptake and hence utilization of existing reserves of available soil P or applied fertilizer P if timing alleviates some other limitation on plant growth (type B effects).

It is not appropriate to document in this paper all the possible mechanisms by which liming increases plant growth; interested readers should refer to comprehensive accounts of relevant New Zealand research (Edmeades et al. 1984, 1985; Jackson and Edmeades 1984). One aspect, however, requires further emphasis: the effects of liming on N mineralization.

Nyborg and Hoyt (1978) reported that, in 3 field trials (pH, 5.4-5.7; soil N, 0.13-0.83%), liming increased the uptake of soil N by oats by 15.42 kg/ha in the first year after liming. Their results indicated that this effect decreased with time. In these experiments, all nutrients except N were applied and, given the soil pH levels, it is reasonable to assume that the increased uptake was a consequence of increased mineralization of organic matter.
Effects of liming on enhanced N mineralization of a similar magnitude were reported by Edmeades et al (1986) on a productive legume-based pasture. Soil and plant analyses, together with adequate applications of all nutrients except N, ensured that N deficiency was the major factor limiting growth. The effect of liming (7.5 t/ha) on soil N uptake by the grass and legume components of the pasture was measured using $^{15}$N tracer. Liming increased growth of the grass, but not of the legume component (Table 3); this could be attributed to enhanced mineralization of organic N. Liming released an additional 50 kg N/ha over 2 yr (Table 4). These results are consistent with the effects of applied N on legume-based pastures, viz., stimulation of the grass component at the expense of the legume and hence decreased symbiotic N$_2$ fixation (Table 4).

The effects of lime and P applications on total pasture production and the production of the pasture components for the field trial referred to earlier (Fig. 1) are given in Figure 5. It is reasonable to conclude that on this soil the major mechanism by which liming increases plant growth is enhanced mineralization of soil organic N. This conclusion is consistent with

- no Al toxicity, indicated by the low level of soil Al and supported by the lack of positive lime × P interactions;
- no Mn toxicity, indicated by the fact that the legume Mn concentrations were much less (typically 100-200 ppm) than the levels required to reduce plant growth (Smith et al 1983);


<table>
<thead>
<tr>
<th>Treatment</th>
<th>Dry matter production (t/ha)</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Total$^b$</td>
<td>Grass</td>
</tr>
<tr>
<td>No lime</td>
<td>21.0</td>
<td>12.1</td>
</tr>
<tr>
<td>Lime</td>
<td>21.7 ns</td>
<td>13.1 +</td>
</tr>
<tr>
<td>SED</td>
<td>0.5</td>
<td>0.5</td>
</tr>
</tbody>
</table>

$^a$ns = not significant, + = significant at $P < 0.1$. $^b$Total of 20 harvests. $^c$Total of 17 harvests.

Table 4. Effect of lime on soil N uptake of total pasture and grass and clover sward components, proportional soil N uptake by clover, and symbiotic N$_2$ fixation from 17 harvests, Oct 1977-Oct 1979 (Edmeades et al 1986).

<table>
<thead>
<tr>
<th>Treatment</th>
<th>Soil N uptake (kg/ha)</th>
<th>Proportion of total soil N uptake in clover</th>
<th>Symbiotic N$_2$ fixation (kg/ha)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Grass</td>
<td>Clover</td>
<td>Total</td>
</tr>
<tr>
<td>No lime</td>
<td>443</td>
<td>95</td>
<td>538</td>
</tr>
<tr>
<td>Lime</td>
<td>493 +</td>
<td>98 ns</td>
<td>591*</td>
</tr>
<tr>
<td>SED</td>
<td>22</td>
<td>6</td>
<td>22</td>
</tr>
</tbody>
</table>

$^a$ns = not significant, + = significant at $P < 0.1$, * = significant at $P < 0.05$. Harvested in the plant tops only.
• no P-sparing effect, indicated by the lack of a negative lime × P interaction and consistent with the inconsistent soil chemical results (Fig. 1);
• no Mo deficiency (Mo was applied annually at 60 g/ha);
• lack of response to applied P at all lime rates in the grass component, indicating that available P was not limiting growth; and
• response to lime in the grass component but not in the legume, consistent with the known effects of N applications on legume-based pastures.

Taken together, these facts support the conclusion that the increase in plant P uptake due to liming was a consequence, not of an increase in soil P availability but of improved plant growth resulting from increased soil N availability.

From the grass N uptake we calculated that, on this soil, liming (10 t/ha) releases the equivalent of 25-30 kg N/ha annually. This is consistent with the results from other field trials discussed earlier.

Thus, there is good evidence to believe that not only does liming stimulate N mineralization, but, more importantly, this effect can be of sufficient magnitude to explain crop responses to liming. This may be especially important in glasshouse experiments, where the environmental conditions, together with the fact that the soils are “disturbed,” will act to enhance this possibility (Edmeades et al 1981).

The plea by Haynes (1982) for greater recognition of the effect of liming on organic P mineralization applies equally to organic N. Most authors completely ignore the potential effects of liming on N mineralization when discussing their results. This may be particularly important in interpreting results from glasshouse experiments.

Conclusions

The results presented indicate that liming does not generally increase soil P availability, suggesting that there is very little scope for using lime as a means of reducing P inputs in the long term. This should not be taken to imply that fertilizer P should be used at the expense of liming. There are valid and important reasons for liming, especially to reduce Al and Mn toxicity and to enhance N mineralization. However, liming should not be practiced in the expectation that fertilizer P inputs can be reduced in the long term.

References cited


Notes


Citation information: International Rice Research Institute (1990) Phosphorus requirements for sustainable agriculture in Asia and Oceania. P.O. Box 933, Manila, Philippines.
Effect of sulfur, silicon, and trace metal interactions in determining the dynamics of phosphorus in agricultural systems

G.J. Blair, J.R. Freney, and J.K. Park

Phosphorus, S, Si, and Mo occur in aerobic soils predominantly as oxy-anions, and the particular form of the ion present depends on pH and the oxidation-reduction potential. Differences exist in the affinity of these anions for positively charged surfaces, with phosphate having the greatest affinity. Phosphates undergo many reactions with other anions and trace metal cations, the most important being with silica, with Zn, and with Fe. Under low P-adsorbing conditions, applications of silicate have been found to reduce P requirements, but on highly weathered tropical soils, results have been more variable and are less promising. The incidence of Zn deficiency is increasing and is often associated with P application. There are several possible reasons for this interaction, including a higher Zn requirement resulting from greater plant growth as a result of P application, increased Zn retention in the soil due to a change in pH or a decrease in surface charge, changes in cell membrane integrity and selectivity, changes in Zn mobility within the plant, and reduced vesicular-arbuscular mycorrhizal infection. Interactions between phosphate and Fe are of considerable significance in flooded soils. As a soil is flooded and the redox potential decreases, insoluble ferric phosphates are reduced to more soluble ferrous phosphates, leading to an increase in the availability of P for plant growth. The decomposition of soil organic matter is of primary importance in controlling the cycling rates of P and S in terrestrial systems. Although similar amounts of P and S are taken up by crops, a greater proportion of the P is removed in grain. The higher S content of residues means that the recycling of S via crop residues is an important determinant of the long-term S requirements of a cropping system.

The macronutrients P and S occur in nature as oxy-anions and as such undergo many similar reactions. Phosphate also interacts with the various ions of Si, Se, and Mo and undergoes important reactions with the cations of Fe and Zn.

The cycling rates of P and S in agricultural systems show many similarities and some important differences. This paper discusses some of the major interactions between P and the other nutrients listed above.

Ion adsorption and interactions

The positive charges present on the surface of clays, oxides, and organic matter are sites for the adsorption of anions. Such adsorption may be beneficial in retaining
ions (e.g., sulfate) against leaching or may reduce uptake due to the strength of sorption (e.g., phosphate).

**Anionic species in soils**

The subject of P adsorption is discussed in greater detail in other papers in this volume, but it is prudent to discuss, in general terms, the adsorption of the anions of P, S, Si, and Mo because their similarities and dissimilarities are important. The major similarity of these elements is that all four occur as oxy-anions in soils. They differ in the charge on the anion and the extent of dissociation.

The pH of the system is a major determinant of the ionic species present, which in turn controls the adsorption reactions and hence the ability of the soil to retain the anion. Barrow (1987) gave a succinct explanation of the importance of soil pH in determining the ionic species present. For ions such as sulfate (SO$_4^{2-}$) and selenate (SeO$_4^{2-}$), the pK$_{a2}$ is near 2.0; hence under normal aerobic soil pH conditions (pH 4-8) all the ions are present as SO$_4^{2-}$ and SeO$_4^{2-}$ (Fig. 1). When a soil is flooded and the redox potential falls, the ionic species of both Se and S can change. Neal et al (1987) suggest that in neutral, aerobic soils, selenate (SeO$_4^{2-}$) and selenite (SeO$_3^{2-}$) will be present, whereas under acidic aerobic conditions biselenite (HSeO$_3^{-}$) will predominate. Under reduced soil conditions, immobile reduced forms of Se will predominate (White 1985).

Phosphate (PO$_4^{3-}$) dissociation is more complex, since it is a tribasic ion. The pK$_{a1}$ and pK$_{a3}$ occur at pH 2 and 12, which are beyond the limits of normal soil pH. The pK$_{a2}$ occurs near pH 7; hence the ionic species of HPO$_4^{2-}$ and H$_2$PO$_4^{-}$ are important in soil systems (Fig. 1).

The pK$_{a1}$ and pK$_{a2}$ of molybdc acid are both near 4. which means that the species H$_2$MoO$_4$, HMoO$_4^{-}$, and MoO$_4^{2-}$ are all present above this pH. As the pH increases, the proportion present as the plant-available MoO$_4^{2-}$ form increases. The differences in the ionic species present at a particular soil pH influence the extent to which they are specifically adsorbed.

**Anion adsorption**

Anions are specifically adsorbed on the surfaces of oxides of Fe and Al and on the weathered edges of clay particles. All of these contain metal atoms that are not fully coordinated, which leads to a positive surface charge. Anions are adsorbed to these positive surfaces. Some anions such as NO$_3^{-}$ and Cl$^{-}$ do not approach the surface closely and therefore do not form specific bonds, whereas anions such as phosphate, SO$_4^{2-}$, MoO$_4^{2-}$, SeO$_4^{2-}$, and SiO$_3^{2-}$ do.

In addition to differences in the amount of a particular ionic species present in the soil solution, differences exist among ions in their affinity for positively charged surfaces. Parfitt (1980) lists the affinity of anions for Fe and Al oxide surfaces as

\[
\text{phosphate} > \text{selenate} > \text{selenite} = \text{molybdate} = \text{fluoride} \\
> \text{sulfate} = \text{silicate} > \text{chloride} > \text{nitrate}
\]

An ion of higher bonding strength can replace an ion of lower bonding strength on the adsorption complex. The competition among ions for adsorption can be expressed in two main ways. The first is through the physical competition for
adsorption loci, and the second is through electrostatic competition resulting from a change in the electrostatic potential in a given absorbing plane following the adsorption of a charged species (Bowden et al 1980).

Soil pH has a major effect on anion adsorption. Hingston et al (1967, 1972) associated the adsorption of SiO$_3^{2-}$ on goethite with the pK$_a$ of silicic acid. In a later study (1972), they showed the importance of pH in determining the amount of anion adsorbed and the difference between anions (Fig. 2). Barrow (1970) showed a differential decline in the adsorption of MoO$_4^{2-}$ and SO$_4^{2-}$ relative to phosphate as pH increases (Fig. 3).

Hingston (1970) showed that, over the pH range 5-8, the presence of phosphate reduced SiO$_3^{2-}$ adsorption to a greater extent than the presence of SiO$_3^{2-}$ reduced phosphate adsorption onto goethite-B when SiO$_3^{2-}$ was added at 2.5×10$^{-3}$ M and phosphate was added at 8×10$^{-4}$ M (Table 1). On the other hand, phosphate and Zn$^{2+}$ adsorption onto goethite were found to be enhanced when both ions were added together (Bolland et al 1977). These competing and cooperating ion effects can have important agricultural and ecological consequences.

**Interactions between phosphate and other ions**

Phosphate interacts with many other ions in soils; the most important interactions are discussed here.
2. Sorption of a range of anions on goethite. Two samples of goethite were used, and the levels of addition differed for the differing anions (after Hingston et al. 1972).

Table 1. Effect of competing ions on adsorption of silicate and phosphate (after Hingston 1970).

<table>
<thead>
<tr>
<th>pH</th>
<th>Si</th>
<th>P</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>−P</td>
<td>+P</td>
</tr>
<tr>
<td>5</td>
<td>1.65</td>
<td>0</td>
</tr>
<tr>
<td>6</td>
<td>2.00</td>
<td>0</td>
</tr>
<tr>
<td>7</td>
<td>2.25</td>
<td>0</td>
</tr>
<tr>
<td>8</td>
<td>2.55</td>
<td>0.55</td>
</tr>
</tbody>
</table>

Phosphate and silicate. During the weathering process, silicate minerals are lost rapidly from the soil profile; the loss is most rapid from finely divided, poorly crystalline volcanic materials and from soils developed on basic igneous rocks. Fox (1974) found that SiO$_3^{2-}$ is lost rapidly from Andept soils and showed an inverse relationship between SiO$_3^{2-}$ content of a saturation extract of the soil and phosphate sorption over a weathering sequence (Table 2).

Variable results have been obtained with silicate fertilizers. In an experiment in Rothamsted, England, where 450 kg of sodium silicate per hectare have been added annually since 1862, yield differences between the control and treated areas were still being recorded in 1966 in the absence of P fertilizers (Table 3). However, when P was applied, no response to SiO$_3^{2-}$ was obtained at any time, suggesting that the application of SiO$_3^{2-}$ increased P availability to the barley crop, presumably by displacement of the P adsorbed onto the sesquioxide surfaces.

Table 2. Phosphate sorption and silicate content of a saturation extract of soil in a weathering sequence in Costa Rica (Fox 1974).

<table>
<thead>
<tr>
<th>Material</th>
<th>Rainfall (mm)</th>
<th>P sorbed at 0.2 µg P/g soil</th>
<th>Si in saturation extract of soil (µg Si/ml)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ash, 4- to 6-yr-old</td>
<td>2000</td>
<td>20</td>
<td>12</td>
</tr>
<tr>
<td>Umbric Vertisoliandep</td>
<td>2000</td>
<td>425</td>
<td>79</td>
</tr>
<tr>
<td>Typic Dystrandept</td>
<td>2000</td>
<td>1900</td>
<td>6</td>
</tr>
<tr>
<td>Oxic Dystrandept</td>
<td>3800</td>
<td>2500</td>
<td>2</td>
</tr>
</tbody>
</table>

Table 3. Influence of silicate fertilizer on barley grain yield in Rothamsted, England (Russell 1973).

<table>
<thead>
<tr>
<th>Treatment</th>
<th>1862-91</th>
<th>1932-61</th>
<th>19s64-66</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>−Si</td>
<td>+Si</td>
<td>−Si</td>
</tr>
<tr>
<td>Without P</td>
<td>1.92</td>
<td>2.45</td>
<td>1.85</td>
</tr>
<tr>
<td>With P</td>
<td>2.76</td>
<td>2.98</td>
<td>2.64</td>
</tr>
</tbody>
</table>
In contrast, the use of $\text{SiO}_3^{2-}$ on highly weathered soils in Hawaii has had variable results. Fox (1978) showed that adding $\text{CaSiO}_3$ reduced P sorption in a Typic Gibbsihumox soil in Hawaii, but that this effect was small compared with the addition of P. In an experiment on three soils from Hawaii, Fox (1978) obtained a response to $\text{CaSiO}_3$ at a low soil solution P concentration, and no response when P was adequate (Table 4).

Elward et al (1982a,b) found that increasing the application rate of silicate reduced leaf freckling in sugarcane, increased the P content of the leaves in the planted crop, and reduced the P content of the leaves in the ratoon crop. Silicate addition significantly increased water-extractable soil P in both crops. They attributed the increased P content of the leaves to the amount and solubility of the P applied in the silicate slag materials and not to any solubilization of soil P by the silicate.

Roy (1969) showed that $\text{SiO}_3^{2-}$ is most effective when placed in intimate contact with phosphate, which suggests a very localized effect. Roy et al (1971) suggested that adding $\text{SiO}_3^{2-}$ reduces the internal P requirement in sugarcane. These soil studies contrast with those in solution culture reported by Granssmann (1962), who found that the addition of $\text{SiO}_3^{2-}$ reduced P uptake, and that Si was unable to alleviate P deficiency.

Evidence suggests that silicate replacements are unlikely to be a feasible way of reducing P inputs to agriculture, especially on highly weathered tropical soils.

Phosphorus and zinc. Robson and Pitman (1983) divide the interactions between P and Zn into three main categories:

- **Direct effects of each nutrient on plant growth.** Fertilization with P can cause a Zn deficiency, because the increase in plant growth dilutes the Zn concentration in the plant (Loneragan et al 1982). This may occur because of a change in the shoot-root ratio as a consequence of P application (Loneragan and Asher 1967). Conversely, a Zn deficiency may reduce growth and cause P toxicity even though the total plant content of P is not increased (Loneragan et al 1982).

- **Interactions that affect uptake of each nutrient.** Application of P may result in decreased Zn uptake because of increased retention of Zn on the soil exchange complex (Bolland et al 1977). Saeed (1977) found that addition of P fertilizer decreased Zn retention in calcareous soils. Saeed and Fox (1979) found both increases and decreases in P retention, while Friesen et al (1980) found no

<table>
<thead>
<tr>
<th>Soil P status</th>
<th>Yield response (%)</th>
<th>Yield response (%)</th>
<th>Yield response (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Kahala soybean</td>
<td>Kailua soybean</td>
<td>Peanut</td>
</tr>
<tr>
<td>Low</td>
<td>+22</td>
<td>+15</td>
<td>+5</td>
</tr>
<tr>
<td>Adequate</td>
<td>0</td>
<td>-3</td>
<td>-1</td>
</tr>
</tbody>
</table>

$^{a}(\text{CaSiO}_3 - \text{CaCO}_3) \times 100.$
effect on the Zn activity in the soil solution. Barrow (1987) showed two possible mechanisms that could affect Zn sorption and, hence, the availability of Zn to the plant. Application of P fertilizer can result in either an increase, a decrease, or no change in soil pH. A decrease of one pH unit produces the same effect on Zn sorption as a 10-fold decrease in Zn concentration. The second mechanism is related to the decrease in surface charge brought about by the application of P, and the magnitude of the effect is related to the amount of Zn sorbed. Barrow (1987) suggested that the surface charge effect is likely to be important only when both Zn and P are applied in a band. Phosphorus addition to soils may reduce Zn uptake by reducing the infection rate of vesicular-arbuscular mycorrhizae (Lambert et al 1979); this can also result in reduced P uptake (Pairunan et al 1980).

- **Interactions within the plant.** Studies by Welch et al (1982) and Loneragan et al (1982) showed that Zn may play an important role in maintaining the integrity and selectivity of cell membranes, and that a deficiency of Zn may result in a loss in the control of P uptake. Olsen (1972) also noted an accumulation of Mn, NO₃⁻, Fe, Cu, and P in Zn-deficient plants. Evidence exists for interactions between P and Zn in the translocation of their ions within plants. Warnock (1970) found less Zn in the leaves of maize, relative to roots, at high P and low Zn levels. This is consistent with the conclusion of Sharma et al (1968) that the main effect of P addition is a physiological inhibition of the translocation of Zn from roots to tops.

**Phosphate and iron.** In aerobic upland soils, P is associated with Fe either as phosphate adsorbed onto iron oxide surfaces, or as crystalline or amorphous Fe-P minerals.

The interaction between P and Fe assumes major significance in flooded rice soils. When a soil is flooded and the oxidation-reduction potential falls, the concentration of water-soluble and available P increases (Ponnamperuma 1978). Ponnamperuma (1978) summarized the work of many authors and attributed the increase in water-soluble P upon flooding to

- release of occluded P and P sorbed on amorphic Fe and Mn oxides following soil reduction,
- increase in pH of acid soils,
- reduction of ferric phosphate to the more soluble ferrous phosphate,
- desorption following reduction of ferric oxides,
- desorption of P from clays and Al oxides following pH increase, and
- solvent action of inorganic acids.

In general, Fe phosphates contribute most to the higher availability of P when soils are flooded, with little contribution being made from Al and Ca phosphates (Kirk et al 1990).

Willett and Higgins (1978), monitoring changes in P sorptivity and oxalate-extractable Fe (Fe_{ox}) over a 220-d period, found that both increased substantially upon flooding and dropped sharply when the soil was drained (Fig. 4). Before flooding there was no relationship between Fe_{ox} and P sorptivity, but after 63 d of flooding a strong positive relationship existed.
Oxalate-extractable Fe (%) and P sorptivity in an unflooded soil and the same soil subjected to flooding and subsequent drainage (after Willett and Higgins 1978).

As the soil is reduced, the well-crystallized ferric hydrous oxides with low specific surface area and low P sorptivity are reduced to poorly crystalline ferrous hydroxides, ferrosoferric hydroxide, ferrous carbonate, and soluble Fe$^{2+}$ (Ponnamperuma et al 1967). This group of ferrous compounds contains a large number of sites capable of retaining P. Willett and Higgins (1978) suggested that this adsorbed P is available to the rice plant.

When the soils used by Willett and Higgins (1978) were drained and reoxidized, Fe$_{ox}$ and P sorptivity did not return to the levels before reduction, suggesting an overall decrease in crystallinity of the ferric hydrous oxides.

**Cycling of phosphorus and sulfur**

In contrast to the interactions between phosphate and the other ions in the preceding discussion, which are generally at the ionic level, and are very much related to
adsorption/desorption, interactions between P and S are more related to organic/inorganic transformations.

There are many similarities between the dynamics of P and S in agricultural systems; organic matter mineralization is a major source of plant available P and S, and, as indicated earlier, both nutrients are adsorbed as oxy-anions and hence undergo similar adsorption/desorption reactions.

While it is difficult to generalize across the wide range of agricultural soils found throughout the world, published data indicate broad similarities in the total P and S contents of topsoils (Freneny and Williams 1983). Stevenson (1986) reports an average native P content of 600 µg/g soil for U.S. topsoils, and Jordan and Reisenauer (1957) report a mean total S content of 540 µg/g soil for nonleached U.S. soils. A major difference between P and S contents is found on leached tropical soils. Under conditions of rapid mineralization of organic matter and high water percolation rates, sulfate may be leached down the profile or out of it, whereas phosphate is retained by adsorption in the topsoil layer. Little data are available on the P and S contents of soil profiles, but one profile from Thailand (Pongsakul 1987, Department of Agriculture, Thailand, pers. comm.) highlights some of the important similarities and differences between the two nutrients (Table 5). In the A, and B₁ horizons, the total S content is lower than the total P content; however, the reverse is true in the B₂ horizon. The lower sulfate adsorption capacity indicates a lower capacity to retain $\text{SO}_4^{2-}$ in the soil profile, which may be a reason for the lower total S content in the upper horizons.

Similarities have also been found in the reutilization rates of added P and S in white clover litter for *Axinopus affinis* swards (Till and Blair 1978). In these studies, the incorporation of P and S into the growing plant from the litter was rapid, with 28% of the applied P and 15% of the applied S being taken up in 56 d at a day-night temperature of 28/22 °C. Lower reutilization rates were recorded at 15/10 °C.

The knowledge obtained from various studies on P and S cycling rates in grazed pastures has been incorporated into a simulation model of C, N, S, and P cycling (McCaskill and Blair 1988). The model estimates similarities between P and S in rates of uptake by the pasture; rates of consumption, retention, and deposition in dung by the animal, and mineralization from the soil organic matter. Major

<table>
<thead>
<tr>
<th>Soil horizon</th>
<th>Total P</th>
<th>Total S</th>
<th>Extractable P</th>
<th>Extractable S</th>
<th>Sorbed P</th>
<th>Sorbed S</th>
</tr>
</thead>
<tbody>
<tr>
<td>A₀</td>
<td>442</td>
<td>310</td>
<td>27.5</td>
<td>8.3</td>
<td>178</td>
<td>21.5</td>
</tr>
<tr>
<td>B₁</td>
<td>442</td>
<td>359</td>
<td>6.7</td>
<td>7.4</td>
<td>205</td>
<td>30.0</td>
</tr>
<tr>
<td>B₂</td>
<td>315</td>
<td>367</td>
<td>6.7</td>
<td>7.6</td>
<td>220</td>
<td>11.0</td>
</tr>
</tbody>
</table>

*Phosphate and sulfate extracted from soil by either 0.05 M NaHCO₃ (Colwell 1963) or 0.01 M monocalcium phosphate, respectively. Phosphate and sulfate adsorbed at solution concentrations of 0.2 µg P/ml and 5 µg S/ml, respectively.
differences between the nutrients are found in sorption characteristics and losses from the system via leaching. The model predicts that 4.16 kg P/ha per yr would be transferred to the sorbed P pool, and this would be transferred back into the usable P pool at a very slow rate. All of the P would be retained in the topsoil of the profile by this sorption, whereas 7 kg S/ha per yr would be lost by leaching (McCaskill 1988).

Studies of P and S cycling in tropical cropping systems (Lefroy et al. 1988) have shown that in a maize - mungbean cropping system, similar amounts of P and S are taken up, large amounts of P are removed in the product (Table 6), and large amounts of S are retained in the crop residues. When P and S are not applied, there is a net loss of both nutrients in the straw-removed and straw-retained systems (Table 6). When 32 kg S and 32 kg P/ha were applied over a 3-yr period (no application in year 3), the S balance became positive in the straw-returned system but remained negative in the straw-removed system. The P balance, on the other hand, remained negative in both residue management systems.

These data again highlight the general similarities between the cycling of P and S and show the importance of crop removal and residue management in determining the long-term needs of the cropping system.

Conclusion

Marked differences exist between anions in their sorptivity, with phosphate having the highest affinity for positively charged surfaces.

Phosphate ions are involved in important interactions with Si, Zn, and Fe. Published reports show that application of silicates can reduce fertilizer P requirements in some situations, whereas in others no such effects have been found. The reasons for these differing results are not apparent.

The Zn-P interaction has been variously ascribed to reactions in the soil or within the plant, and no studies have been repeated where the soil/uptake/plant continuum has been adequately investigated.

Table 6. Pool sizes and flux rates of P and S in a maize - mungbean cropping system in Thailand.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>S</th>
<th>P</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Control</td>
<td>Fertilized</td>
</tr>
<tr>
<td>Input</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fertilizer</td>
<td>0</td>
<td>32</td>
</tr>
<tr>
<td>Rain</td>
<td>12.0</td>
<td>12.0</td>
</tr>
<tr>
<td>Total</td>
<td>12.0</td>
<td>44.0</td>
</tr>
<tr>
<td>Uptake</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Product</td>
<td>21.0</td>
<td>23.1</td>
</tr>
<tr>
<td>Residue</td>
<td>19.0</td>
<td>23.9</td>
</tr>
<tr>
<td>Balance</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Residue returned</td>
<td>-9.0</td>
<td>+s20.9</td>
</tr>
<tr>
<td>Residue removed</td>
<td>-28.0</td>
<td>-3.0</td>
</tr>
</tbody>
</table>
Iron-P interactions are important in flooded soils where solution levels of both ions generally increase upon flooding. While this increases their availability to plants during the flooded phase, it may lead to a P availability below that in the original soil when it is drained.

While phosphate is known to replace sulfate on adsorption surfaces, no field data exist to show this to be of agronomic significance. The major P and S interaction that occurs is increased removal of P in the harvested product, which can result from a crop response to S fertilization.

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Notes

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Citation information: International Rice Research Institute (1990) Phosphorus requirements for sustainable agriculture in Asia and Oceania. P.O. Box 933, Manila, Philippines.
Phosphorus as a factor limiting nitrogen fixation in flooded rice soils

I. Watanabe and Wisit Cholitkul

The P concentration in the floodwater of a ricefield and the P supply to the field limit the growth and N₂ fixation of blue-green algae (BGA) and azolla in the floodwater. Nevertheless, information on the chemistry of P in floodwater is limited. Not the concentration, but the supply from the soil limits P absorption by floating aquatic flora. Surveys of N and P concentrations of azolla grown in the Philippines and Thailand showed that at least half of the samples were deficient in P. Indigenous BGA blooming in the field also showed P deficiency. Azolla microphylla grew in soils higher in available P than those in which A. pinnata var. imbricata grew. This difference in P requirements was confirmed by water culture experiments. Under P-deficient conditions, A. microphylla showed less growth and N₂ fixation than A. pinnata. The effects of P application on BGA and azolla were examined in terms of the ratio of N gained to P applied. This ratio was generally higher in azolla than in BGA. Split application increased the ratio. Application of P to the azolla mat in the inoculum preparation field, followed by inoculation of the azolla thus enriched, was the most efficient way of applying P, giving a ratio higher than 8. The ratio of the price of P in superphosphate to the price of N in urea was 3 on the average in eight Asian countries. When the ratio of N gained to P applied is higher than 3, the use of P fertilizer to stimulate N gain can produce N costing less than the N in urea. When applying P to stimulate biological N₂ fixation, the ratio of N gained to P applied should be optimized.

To keep pace with the demands of escalating populations, rice yields should increase about 3%/yr. This increase is made possible by increasing the nutrient supply to rice plants. Nitrogen removed by rice plants can be replaced with fertilizer N, soil N and/or biologically fixed N. Nitrogen input by biological N₂ fixation (BNF) can substitute for or supplement chemical N fertilizers.

Wetland rice soils are suitable for BNF because of the presence of floodwater on the soil surface and anaerobic conditions in the soil. Photodependent BNF agents—free-living blue-green algae (BGA) and Anabaena azollae in symbiosis with azolla, an aquatic fern—grown floodwater and on the soil surface. In the anaerobic layer, anaerobic or microaerobic N₂-fixing bacteria grow on the crop residue and on living rice roots.

Requirements for encouraging the growth and N₂ fixation of BNF agents are an increased nutrient supply and the elimination of negative factors. Among nutrients for BNF agents, P has been studied most intensively. Okuda and Yamaguchi (1955)
showed that P added to a flooded soil in beakers increased photodependent N\textsubscript{2} fixation but not heterotrophic N\textsubscript{2} fixation, indicating that photodependent or aquatic N\textsubscript{2}-fixing agents are limited by the P supply more severely than are N\textsubscript{2}-fixing agents in soil (Table 1).

Long-term experiments without N fertilizers at three sites in Thailand (Chainat, Supanburi, and Klong-Luang) for more than 30 rice crops (Table 2) showed that in soils low in available P, P application increased rice yield by 0.8 t/ha in a moderately P-deficient Entisol (Supanburi) and by 1.5 t/ha in an acid sulfate soil (Klong-Luang) (Department of Agriculture [Thailand] Soil Science Division 1970-87). No yield decrease with time was observed in either no-fertilizer or PK plots. Application of P stimulated rice growth and increased N uptake. The N uptake was replaced, probably by N\textsubscript{2} fixation. Field acetylene reduction assays (Cholitkul et al. 1980) confirmed qualitatively that adding P fertilizer stimulated photodependent N\textsubscript{2} fixation in Klong-Luang.

Even with a sufficient P supply to wetland rice, the P supply to aquatic organisms in the floodwater, particularly floating flora, limits their growth and N\textsubscript{2} fixation. Because of the substantial effect of P application on photodependent N\textsubscript{2} fixation in the floodwater and the lack of data on the effect of P supply on heterotrophic N\textsubscript{2} fixation in soil, discussion in this paper is restricted to the effect of P on photodependent N\textsubscript{2} fixation in flooded rice soils.

**Phosphorus in floodwater**

The chemistry of P in floodwater has been studied less than that in flooded rice soils but was summarized by Watanabe and Roger (1985). According to E. Wada (Mitsubishi Kasei Life Science Institute, Machida, Tokyo, pers. comm.), the dynamics of P in floodwater after applying P is divided into three phases. Phosphorus content first decreases sharply because of chemical adsorption by soil (phase 1); then decreases slowly because of absorption by aquatic organisms (phase 2); and finally arrives at a constant concentration (phase 3, equilibrium) due to solubilization from the solid phase, release from aquatic organisms, and absorption by aquatic organisms. The equilibrium concentration is 1-2 × 10\textsuperscript{-6} M (0.03-0.06 ppm) P. Watanabe et al. (1980) showed that when 6.5 kg P/ha was applied to the surface of floodwater where azolla was inoculated, the P concentration was 1.5 ppm

| Table 1. Effects of various factors on N\textsubscript{2} fixation in a soil (mg N gained/100 g soil) (Okuda and Yamaguchi 1955). |
|-------------------------------------------------|-----------------|-----------------|-----------------|-----------------|
| Factor                                          | Illuminated     | Dark            |                 |                 |
|        | 7 wk | 12 wk | 7 wk | 12 wk |                 |                 |
| No addition                                    | 1.5  | 1.8   | 0.5  | 0.6  |                 |                 |
| CaCO\textsubscript{3}\textsuperscript{+} K\textsubscript{2}HPO\textsubscript{4} | 4.5  | 5.1   | 1.4  | 0.4  |                 |                 |
| Mannitol                                        | 4.7  | 4.7   | 5.2  | 5.5  |                 |                 |
| CaCO\textsubscript{3}\textsuperscript{+} K\textsubscript{2}HPO\textsubscript{4}+mannitol | 5.3  | 6.7   | 5.6  | 4.9  |                 |                 |
Table 2. Rice yields in long-term fertility experiments at 3 sites in Thailand (Department of Agriculture, Soil Science Division, Thailand [1970-87]).

<table>
<thead>
<tr>
<th>Variety</th>
<th>Chainat</th>
<th>Supanburi</th>
<th>Klong-Luang</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Crops (no.)</td>
<td>Rice yield (t/ha)</td>
<td>Crops (no.)</td>
</tr>
<tr>
<td></td>
<td>C</td>
<td>PK</td>
<td>C</td>
</tr>
<tr>
<td>RD1</td>
<td>11</td>
<td>2.6</td>
<td>3.8</td>
</tr>
<tr>
<td>RD3</td>
<td>11</td>
<td>3.1</td>
<td>3.3</td>
</tr>
<tr>
<td>RD5</td>
<td>16</td>
<td>3.4</td>
<td>3.6</td>
</tr>
<tr>
<td>RD7</td>
<td>8</td>
<td>2.7</td>
<td>3.1</td>
</tr>
<tr>
<td>RD9</td>
<td>8</td>
<td>2.5</td>
<td>2.9</td>
</tr>
<tr>
<td>RD21</td>
<td>10</td>
<td>3.8</td>
<td>4.2</td>
</tr>
<tr>
<td>RD23</td>
<td>10</td>
<td>4.0</td>
<td>4.3</td>
</tr>
<tr>
<td>RD25</td>
<td>7</td>
<td>2.8</td>
<td>3.0</td>
</tr>
<tr>
<td>Av</td>
<td>3.28</td>
<td>3.54</td>
<td>1.88</td>
</tr>
</tbody>
</table>

*Available P (Bray II): Chainat = 18.4 ppm, Supanburi = 4.6 ppm, Klong-Luang = 3.5 ppm. Dose of P$_2$O$_5$ and K$_2$O were 37.5 kg/ha each. Two rice crops grown/yr for 16 yr at Chainat, 18 yr at Supanburi, and 17 yr at Klong-Luang. C = control, no NPK.

P at 1 d after application; 0.36 ppm at 3 d; and > 0.05 ppm at 10 d. When 8.7 kg P/ha was applied to the azolla mat, the floodwater P concentration was 3.5 ppm at 2 d after application, 0.7 ppm on day 4, 0.2 ppm on day 6, and 0.03 ppm on day 14 (Watanabe et al 1988).

The P solubilized from soil enters the floodwater. It is therefore expected that P concentration in floodwater without P application will vary with solubility or availability of soil P. Ali and Watanabe (1986) showed a clear linear relationship between available soil P (Olsen P) and the P concentration in floodwater at 2 wk after flooding except in one soil (Fig. 1). Points above the linear regression line tend to be lower in P sorption capacity than those below the line—consistent with the concept that P sorption makes available P less soluble in floodwater.

Since P solubilized in reduced soil is the source of P in floodwater, it was expected that soil disturbance would increase the P concentration in floodwater by bringing reduced soil to the floodwater. The result (Watanabe et al 1988) showed no change in P concentration in floodwater due to soil disturbance. Disturbance probably oxidizes soil particles and traps solubilized P. The role of the oxidized zone in controlling P regeneration has not been fully elucidated in flooded rice soils. Mortimer (1971), who evaluated nutrient exchange between the sediment and the water, concluded that as long as the concentration of O$_2$ is greater than 2 µg/liter (in flooded rice soils, it is always so), nutrient release from the sediment is nil because of the oxidation of Fe, which occludes nutrients. Because in flooded rice soils the oxidized layer is thin and has reduced spots that are formed by soil faunal activities, the blocking of P diffusion to floodwater by the oxidized layer may not be as great as in lake sediments.

Phosphorus supply to aquatic nitrogen-fixing organisms

Even in eutrophic lakes, the P concentration available to aquatic organisms is usually low. The half saturation constant (Km) of initial P uptake rate by algae ranges from 20 to 80 µg/liter (Okada and Sudo 1982). The P concentration in the floodwater in nonfertilized fields falls within this range. Good algal growth response to P application in floodwater is therefore understandable. At 30 µg P/liter in continuous-flow water culture, azolla showed P deficiency, but not at 60 µg P/liter (Subudhi and Watanabe 1981). The Km of azolla P requirement may therefore fall within the same range as that of algae.

Greenhouse experiments using 11 Philippine soils showed how the P supply from the soil determines P uptake and growth of *Azolla pinnata* (Ali and Watanabe 1986). The P concentrations of floodwater at 1 wk after azolla inoculation or at 2 wk after flooding were highly correlated with the contents of N and P, and with P uptake by azolla. The critical level of floodwater P was 0.4 mg/liter (Fig. 2). This P concentration was higher than the Km of P uptake, because the volume of floodwater limited the P supply in small pot experiments. At 0.4 mg P/liter, azolla absorbed approximately 0.7 mg P/pot for 21 d (4.23 mg P/m² per d). In the pot used in this experiment the total quantity of water-soluble P in the floodwater (0.4 mg P/liter) was 0.16 mg P/pot. This indicates that floodwater P might have been replenished several times during the experiment. The P concentration is an intensity factor, and P supply from the soil to the floodwater is a capacity factor. In shallow floodwater, the P supply from the soil to the floodwater determines the P supply to azolla. In this experiment, at a P supply of 1.2 mg P/m² per d or lower, azolla
showed severe P deficiency. Parameters (Km, critical level of floodwater P, P supply speed) of the P requirements of BGA in floodwater have been less studied than those of azolla. Because some BGA grow on the soil surface during the night and float up during the day, the relationship of floodwater P to P uptake by BGA may be complex.

**Nitrogen and phosphorus concentrations in field-grown azolla**

Watanabe and Ramirez (1984) showed that the available soil P content determines the growth of azolla on soils. To estimate the frequency of P deficiency in azolla and the adaptability of azolla growth in national programs, N and P concentrations of azolla in fields were studied.

2. Relationship of floodwater P content at 2 wk after flooding to N and P concentrations and total P in azolla (Ali and Watanabe 1986). Symbols are same as in Figure 1.
Surveys in the Philippines. Azolla samples (232) were taken from ponds (33%) and ricefields (67%; 27% without rice and 40% with rice) in 11 regions of the Philippines. The dominant species, coverage, color, healthiness, fertilizer treatment, and use by farmers were recorded. Soils were sampled from about one-third of the sites. The N and P concentrations in azolla were expressed on an ash-free dry matter basis.

The average N concentration was 4.5% and the median 4.5%. The average P concentration was 0.385% and the median 0.332%. Region, species, color, and visual judgment of healthiness were correlated with P concentration. Phosphorus concentrations in Mountain Province, Bicol, and South Cotabato were higher than those in the other regions. Red *A. pinnata* var. *imbricata* had lower P content (n = 42, P = 0.245%) than green samples (n = 41, P = 0.46%). *A. microphylla* was always green and had significantly higher N and P concentrations than *A. pinnata* var. *imbricata* (Table 3). Nitrogen and P contents were highly correlated (simple correlation coefficient = 0.64, ranking correlation coefficient = 0.73). As the content of P increased, the content of N was likely to approach a plateau (Fig. 3). An exponential equation was therefore applied to regress N percentage on P percentage. For all samples,

\[
Y = 5.32 \left[1 - \exp\left(-6.29X\right)\right]
\]

where \(X\) = ash-free P%, and \(Y\) = ash-free N%. Values after ± are standard deviations, and \(R = 0.89\). At P% of 0.37, 90% of a plateau of N% (4.79) was obtained.

For samples dominated by *A. pinnata* var. *imbricata*, the simple correlation coefficient was 0.63 and the ranking correlation coefficient 0.68,

\[
Y = 5.22 \left[1 - \exp\left(-6.29X\right)\right]
\]

with \(R = 0.89\). At P% of 0.33, 90% of a plateau of N% (4.70) was obtained.

For samples dominated by *A. microphylla*, the simple correlation coefficient was 0.63 and the ranking correlation coefficient 0.81,

\[
Y = 5.75 \left[1 - \exp\left(-5.16X\right)\right]
\]

with \(R = 0.83\). At P% of 0.45, 90% of a plateau of N% (5.12) was obtained.

For samples dominated by *A. caroliniana* and *A. mexicana*, the simple Correlation coefficient was 0.77 and the ranking correlation coefficient 0.81,

\[
Y = 5.11 \left[1 - \exp\left(-6.71X\right)\right]
\]

with \(R = 0.76\). At P% of 0.34, 90% of a plateau of N% (4.60) was obtained.

For samples dominated by *A. pinnata* var. *pinnata*, the simple correlation coefficient was 0.74 and the ranking correlation coefficient 0.83. For this species, the application of the equation was not possible, because the N concentrations of all samples were below the plateau value.
The N concentration at the plateau and the P concentration to reach this plateau were higher in *A. microphylla*-dominated samples than in *A. pinnata* var. *imbricata*-dominated samples.

If the P concentration reaching 90% of the N% plateau in these equations is set as the critical concentration for P deficiency, 53% of azolla was judged to be P deficient.

From 66 of the azolla sampling sites, soil samples were taken and their chemical properties analyzed. There was a distinct difference in available soil P (Olsen P) between soils where *A. pinnata* var. *imbricata* was dominant and those where *A. microphylla* was dominant. The average of available soil P of the former (n = 51)
was 28 ppm and the median 12.5 ppm, whereas the average of the latter (n = 8) was 54 ppm and the median 47 ppm. No statistically significant differences were observed in other chemical properties. These results suggest that *A. microphylla* requires higher available P than *A. pinnata* var. *imbricata*. In soils where *A. pinnata* var. *imbricata* was dominant, the simple correlation coefficient between plant P concentration and soil available P content was 0.31 and the ranking correlation coefficient 0.34. The ranking correlation coefficient excluding the sites receiving P fertilizers was 0.54 (n = 43).

The survey of azolla samples grown in the Philippines thus showed that at least half were deficient in P and that *A. microphylla* required higher soil-available P than did *A. pinnata* var. *imbricata*.

**Surveys in Thailand and other countries.** Similar surveys were made in Thailand. Sixty-seven samples were taken, of which 88% were from canals and ponds near ricefields. *A. pinnata* var. *imbricata* dominated 91% of the samples. In five samples, *A. microphylla* was found. The average N concentration (ash-free) was 4.56% and the median 4.57%. The average P concentration (ash-free) was 0.311% and the median 0.282%. The average P concentration in Thailand was lower than that in the Philippines. The P concentration varied with region and color. Azolla from Region I (Northeast) had a lower P concentration (n = 4, P = 0.26%) than those from other regions (P = 0.31%). Red azolla had a lower P concentration (n = 13, P = 0.25%) than green (n = 38, P = 0.35%). The simple correlation coefficient between N and P concentrations was 0.70 and the ranking correlation coefficient 0.73 (Fig. 4).

\[ N\% = 5.5 \times [1 - \exp (6.09\ P\%)] \pm 0.24 \pm 0.82 \]

The P concentration to reach 90% of the N concentration plateau was 0.38%. This equation is similar to that of *A. pinnata* var. *imbricata* in the Philippines. If 0.38% is the critical value for P deficiency, 67% of the azolla were judged to be deficient. Soil samples were taken from 22 of the sites. The simple correlation coefficient between P concentration of azolla and Olsen P was 0.39 and the ranking correlation coefficient 0.51. The correlation coefficients between soil P content and P concentration of azolla were statistically significant but low.

From the limited number of samples in Thailand, it seems that azolla plants there are more deficient in P than those in the Philippines, as expected from surveys of Thai soils (Sangtong et al. 1987). More samples are needed from Thailand to make generalizations about azolla nutrition there.

Rother and Whitton (1988) reported the chemical composition of *A. pinnata* grown in deepwater ricefields in Bangladesh. The averages of seven locations were 4.23% N and 0.239% P (dry weight basis). Although N concentrations were high, azolla was moderately P-deficient. The P concentrations of floodwater at two sites on several dates ranged from 0.0176 to 0.176 ppm in total P and from 0.01 to 0.072 ppm in filtrable reactive P, indicating low P concentrations in the water.

### Nitrogen and phosphorus concentrations in blue-green algae

Roger et al. (1986) reported the chemical composition of BGA grown in laboratories, greenhouses, and fields (Fig. 5). At P concentrations (ash-free basis) higher than 1%, no increase in N concentration (ash-free basis) was found. The optimum level of P was obtained in laboratory culture only; natural samples and BGA grown on soil had concentrations < 0.5%. The maximum and minimum of 11 field samples were 0.48 and 0.07%, respectively. Further surveys of 400 field-grown BGA showed average of 0.45% P on an ash-free basis (P.A. Roger, IRRI, pers. comm.). These findings also confirm the P deficiency of BGA in natural samples.

### Azolla species differences in ability to grow in phosphorus-deficient conditions

Since *A. microphylla* grew in soils higher in available P than did *A. pinnata* var. *imbricata*, the former may require a higher P concentration in the medium.

An earlier study using continuous culture (Subudhi and Watanabe 1981) suggested a difference among species in the ability to grow in P-limited conditions. Water culture experiments were conducted to discern the difference among azolla species under P-deficient conditions (D.P. Kushari and I. Watanabe, IRRI, unpubl. data). Under quantity-limited conditions, azolla at full cover biomass level was treated with different rates of P supply (0.87-139 mg P/m² per d). At 7 mg P/m² per d or lower, azolla became P deficient, and the N concentration was proportional to P%. Above this level, an increase in P concentration did not accompany the N concentration increase, indicating luxury consumption of P. Under P-deficient conditions, *A. pinnata* (var. *imbricata* #5 and var. *pinnata* #7001) produced more biomass and fixed more N than did *A. microphylla* #4018 and *A. mexicana* #3010. The P concentration under P-deficient conditions was lower in *A. pinnata*. In P-sufficient conditions, *A. pinnata* strains produced less biomass. This clearly demonstrated a difference in the ability of azolla species or strains to grow under
Correlation between N and P contents (ash-free basis) in N\textsubscript{2}-fixing BGA. Data from the literature, laboratory mass cultures, artificial blooms on soil, and field samples (after Roger et al 1986).

P-deficient conditions. Growth in the field under P-deficient conditions confirmed this trend.

**Ratio of nitrogen gained to phosphorus applied**

**Effect of phosphorus on blue-green algae and azolla**

Because P deficiency prevails in azolla and BGA in flooded rice soils, the application of water-soluble P stimulates the growth of and N\textsubscript{2} fixation in these organisms. For BGA, many data are available since the first work by Shioiri et al (1944). There are many data for azolla as well. To know if the application of P fertilizer is economically feasible, the ratio of N gain stimulated by P to P applied is useful (P efficiency to N\textsubscript{2} fixation). Table 4 shows the ratio of N gained to P applied.

Nitrogen fixation by azolla responded better to P application, having generally higher N-P ratios than those of BGA. Split application of P increases the efficiency of P fertilizer. The data on split P application to BGA are limited. Bisoyi and Singh...
Table 4. Ratios of N gained to P applied in BGA and azolla grown in soils and fields.

<table>
<thead>
<tr>
<th>Condition</th>
<th>Agent</th>
<th>N gained/ P applied</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Soils (6) in laboratory with lime</td>
<td>BGA</td>
<td>1.7 -3.5</td>
<td>Okuda and Yamaguchi (1955)</td>
</tr>
<tr>
<td>Soils (6) in greenhouse with lime</td>
<td>BGA</td>
<td>0.63-4.2</td>
<td>De and Sulaiman (1956)</td>
</tr>
<tr>
<td>Soil in laboratory with lime</td>
<td>BGA</td>
<td>1.1 -1.6</td>
<td>Shioiri et al (1944)</td>
</tr>
<tr>
<td>Soil with FE-EDTA</td>
<td>BGA</td>
<td>0.51-0.8</td>
<td>App et al (1980)</td>
</tr>
<tr>
<td>Field</td>
<td>BGA</td>
<td>0.13-2.4</td>
<td>Bisoyi and Singh (1988)</td>
</tr>
<tr>
<td>3 splits of P</td>
<td>Azolla</td>
<td>2.4 -2.2</td>
<td>Watanabe et al (1980)</td>
</tr>
<tr>
<td>Field</td>
<td>Azolla</td>
<td>2.2 -4.3</td>
<td>Watanabe et al (1980)</td>
</tr>
<tr>
<td>Basal application of P</td>
<td>Azolla</td>
<td>8.5 -11</td>
<td>Watanabe et al (1988)</td>
</tr>
<tr>
<td>Split application of P</td>
<td>Azolla</td>
<td>8.7 -22</td>
<td>Watanabe et al (1988)</td>
</tr>
<tr>
<td>Field</td>
<td>Azolla</td>
<td>7-20</td>
<td>Watanabe et al (1988)</td>
</tr>
<tr>
<td>2 splits of P</td>
<td>Azolla</td>
<td>0.6 -1.5</td>
<td>Tuzimura et al (1957)</td>
</tr>
</tbody>
</table>

(1988) showed that three split applications of P at 0, 5, and 10 d after inoculating BGA gave higher N yields than one or two applications. The method of P application to BGA needs to be studied further.

Split application following the inoculation of P-enriched azolla gave the highest P efficiency (Watanabe et al 1988). The P source was applied to the inoculum production plot to enrich azolla with P. Azolla grown in one unit of area in an inoculum production plot is generally inoculated into 10-20 units of area in the main field. If 8.7 kg P/ha was used to enrich azolla in the inoculum preparation field and inoculated in a field 10 times larger, the P requirement of the main field was 0.87 kg P/ha. The high P efficiency from the inoculation of P-enriched azolla was therefore due to low P requirement expressed per area of the main field. Furthermore, when P was applied to the azolla mat, 50% of the applied P was absorbed by azolla, whereas when P was applied in the main field as a single dose, only 5-10% was absorbed.
Table 5. Farmers’ price of urea and superphosphate fertilizer and ratio of P price to N price in Asian countries (av of 1982-86) (FAO 1986).

<table>
<thead>
<tr>
<th>Country</th>
<th>Urea price (US$/1000 kg N)</th>
<th>Superphosphate price&lt;sup&gt;a&lt;/sup&gt; (US$/1000 kg P₂O₅)</th>
<th>Ps/N</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bangladesh</td>
<td>365.3</td>
<td>333.5</td>
<td>2.1</td>
</tr>
<tr>
<td>Burma</td>
<td>94.5</td>
<td>323</td>
<td>7.86</td>
</tr>
<tr>
<td>India</td>
<td>439</td>
<td>483</td>
<td>2.55</td>
</tr>
<tr>
<td>Indonesia</td>
<td>224.5</td>
<td>224.5</td>
<td>2.3</td>
</tr>
<tr>
<td>Japan</td>
<td>768.5</td>
<td>1164.3 (S)</td>
<td>3.49</td>
</tr>
<tr>
<td>Malaysia</td>
<td>419.5</td>
<td>216&lt;sup&gt;b&lt;/sup&gt;</td>
<td>1.14</td>
</tr>
<tr>
<td>Nepal</td>
<td>486.8</td>
<td>348</td>
<td>1.72</td>
</tr>
<tr>
<td>Pakistan</td>
<td>377.8</td>
<td>268.3 (S)</td>
<td>1.63</td>
</tr>
<tr>
<td>Philippines</td>
<td>633.3</td>
<td>762 (S)</td>
<td>2.8</td>
</tr>
<tr>
<td>Sri Lanka</td>
<td>256.5</td>
<td>282.3</td>
<td>2.55</td>
</tr>
<tr>
<td>Thailand</td>
<td>528.5</td>
<td>714.3</td>
<td>3.15</td>
</tr>
<tr>
<td>Av</td>
<td>333.5</td>
<td>323&lt;sup&gt;b&lt;/sup&gt;</td>
<td>2.79</td>
</tr>
</tbody>
</table>

<sup>a</sup>(S) = Single superphosphate. Otherwise, concentrated superphosphate. <sup>b</sup>Data available only for 1982-84.

Fertilizer price ratio

The ratio of the price of P as single superphosphate or triple superphosphate to that of N as urea in Asian countries is about 3 (Table 5). If the efficiency of P application to N₂ fixation is less than 3, the application of N fertilizer costs less. In many cases, the application of P to azolla is economically feasible. For BGA, an improvement in application methods is needed to make P application economically feasible. This consideration is not valid when the efficiency of biologically fixed N to rice production is higher than that of chemical N and the P used by BNF agents is re-used by rice for increased yield. This ratio, however, gives an estimate of the effect of P application on BNF. It is obvious that in this calculation, the costs of other inputs in growing the BNF agents are not considered.

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Notes

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Citation information: International Rice Research Institute (1990) Phosphorus requirements for sustainable agriculture in Asia and Oceania. P.O. Box 933, Manila, Philippines.
The role of phosphorus in nitrogen fixation in upland crops

M.J. McLaughlin, K.A. Malik, K.S. Memon, and M. Idris

Through the fixation of atmospheric N\textsubscript{2}, legumes offer the most effective way to increase the productivity of poor soils, either in monoculture, crop rotations, or mixed cropping systems. Where access to inorganic N fertilizers is limited by availability or cost, N\textsubscript{2} fixation provides the main pathway through which soil fertility can be improved. Phosphorus plays a key role in the buildup and maintenance of soil productivity through its effects on legume growth and on the growth and survival of rhizobia. Given the efficiency of the P uptake mechanism of rhizobia, the growth of free-living bacteria is limited by P only in the rhizosphere of very P-deficient soils, and only well after host plant growth has been affected by low P. Phosphorus has a specific effect on nodule function. Vesicular-arbuscular mycorrhizae (VAM) stimulate N fixation in legumes, mainly through their effect on host-plant P nutrition. VAM may also be able to stimulate N\textsubscript{2} fixation in legumes independent of the effect on host plant growth; the effect still appears to be related to P supply to the nodules. The specific effect of P supply on N\textsubscript{2} fixation, coupled with the often larger effect of P supply on growth of the host plant, requires that a successful production system based on legumes optimize P inputs either from soil reserves or from added fertilizer.

In terrestrial ecosystems, plants obtain C for metabolism and growth from CO\textsubscript{2} in the atmosphere through photosynthetic processes. Sulfur is derived from atmospheric and geologic sources, but N can be obtained in quantities sufficient to support vigorous plant growth only by adding fertilizer or through the action of free-living and symbiotic N\textsubscript{2}-fixing organisms. Thus, the cultivation of leguminous plants is one of the most important methods of adding N to the soil-plant system (Henzell 1962). Given adequate water and CO\textsubscript{2}, and with N supplied through N\textsubscript{2} fixation, the next major essential element for the growth of legumes is P. It has been suggested that P can be regarded as the "master" element in terrestrial ecosystems, regulating the accumulation of C, N, and organic S in soils (Walker 1964).

When dealing with the P nutrition of leguminous crops, we should consider all facets of the host-bacterial system. Loneragan (1972) conceptually divided the symbiosis into four interrelated main phases: host plant growth, rhizobial growth and survival, infection and nodule development, and nodule function. Vesicular-arbuscular mycorrhizae (VAM) can be added to the list through their interaction with host plant P nutrition. The overall response of a legume crop to P fertilization will be an
integration of the effects of P (and the associated cation) on each of these facets of the symbiosis. This paper first discusses the effect of P on each phase of the symbiosis, and then examines some observations on N, fixation response of legume crops to P fertilization in both pot and field experiments.

Host plant growth


- size, distribution, fineness, and efficiency of the root system;
- translocation, growth rate, response, and efficiency of P utilization; and
- interactions with other elements and water.

It is not within the scope of this paper to discuss the response of the host plant to P supply, even though host plant growth has an overriding effect on the rate and extent of N₂ fixation. The response of various plant species to P are adequately discussed in other papers in this volume.

Effects of phosphorus on growth and survival of *Rhizobium*

As early as the turn of this century it was noted that P is essential for the proper functioning of N₂-fixing bacteria (Gerlach and Vogel 1903, quoted by Truesdell 1917). Truesdell was one of the first investigators to realize that the effect of P on legume growth is more than a simple nutritional response of the host plant. Application of P with various complementary cations was shown to greatly increase the numbers of N₂-fixing bacteria in both media and soil cultures. More detailed work since then has elucidated many of the mechanisms of acquisition and utilization of P by N₂-fixing organisms. Unlike *Escherichia coli*, rhizobia contain only a single system for P uptake. Uptake is energy-dependent and can be repressed by high external P concentrations (Smart et al 1984b). While there are some differences among strains, P uptake is generally extremely efficient. Both Cassman et al (1981) and Smart et al (1984b) observed good growth rates in organisms exposed to external P concentrations as low as 0.06 µM. These results support the contention that microorganisms have much more efficient P uptake mechanisms than higher plants (Beever and Bums 1976). Low external P concentrations induce increased acid and alkaline phosphatase activity in some strains of rhizobium (Leung and Bottomley 1987, Smart et al 1984b), and certain strains produce increased quantities of extracellular polysaccharide (EPS) in response to low external P concentrations (Cassman et al 1981). Cunningham and Munns (1985) demonstrated that EPS produced by rhizobia reduces sorption of P to colloidal surfaces and can enhance desorption of previously sorbed P. The organisms therefore have the ability
to modify the external conditions of their immediate microenvironment. Leung and Bottomley (1987) suggested that rhizobia on the rhizoplane (root surface) could utilize inorganic P leaking from the root, or sequester organic P from the root through phosphatase activity.

In conditions of excess P supply, rhizobia have the ability to store P as polyphosphate granules, which can support the growth of subsequent generations of bacteria in P-deficient conditions (Beck and Munns 1984, Cassman et al 1981). This may be an important characteristic for successful colonization of P-depleted soil in the rhizosphere. But, given the efficiency of the P uptake mechanism of rhizobia, growth of the free-living bacteria may be limited by P only in the rhizosphere of very P-deficient soils, and only well after host plant growth has been affected by low P.

Effect of phosphorus on infection and nodule development

Little information is available on the role of P on infection and nodule development because it is difficult to isolate this effect from that of P on host plant growth. At the infection stage, the N2-fixing bacteria are located outside the host cells, either in an infection thread or intercellularly: in this period the bacteria presumably derive P from cell wall materials (O’Hara et al 1988) or from their own stored P reserves (Beck and Munns 1984, Cassman et al 1971). Following infection, the bacteria are completely enclosed by plant tissue, and therefore are almost completely dependent on the host plant for mineral nutrition. While storage P may provide for limited growth of rhizobia, it would be insufficient to provide for the many generations required in nodule development. The host plant seems to maintain the P concentration in the nodule at a higher level than in other tissues, even when P limits growth (Mosse et al 1976; Robson et al 1981; Smart et al 1984a,b). Although Gates (1970, 1974) claimed a specific effect of P on nodule initiation in *Stylosanthes humilis*—P application to a P-deficient solodic soil caused earlier nodulation of plants—the effect on nodulation was not isolated from stimulation of host plant growth. Recently, Bottomley and coworkers (Almendras and Bottomley 1988, Leung and Bottomley 1987) demonstrated a role for P in determining the competitiveness of rhizobia strains in forming nodules, with some serogroups dominating only when external P supply is low.

Effect of phosphorus on nodule function

The process of N2 fixation has a high energy requirement. In the reduction of atmospheric dinitrogen to ammonia, approximately 21 mol of ATP are converted to ADP per mol of N2 reduced (Shanmugan et al 1978). Thus, P supply is critical to the efficient functioning of the symbiosis. The specific effect of P on nodule function can be shown in a number of ways (O’Hara 1988):

- Rates of N2 fixation by free-living anaerobes have been measured and are dependent on P supply (Bergersen 1974).
- Concentrations of P in the nodules are higher than in the other tissues of the host plant and are less affected by low P supply than is the host plant (Smart et al 1984a).
• Rates of N₂ fixation by symbiotic organisms can be estimated using acetylene reduction activity (ARA), and changes in rates due to P addition can be compared on a nodule weight or bacterial concentration basis. Such changes must also be measured before there is a growth response by the host plant to added P (Robson 1978). While there are many reports of increased nitrogenase activity with increased P supply to the plant (discussed later), only a few distinguish between effects on the host plant and effects on nodule function (Carling et al 1978, Graham and Rosas 1979, Jakobsen 1985).

The role of vesicular-arbuscular mycorrhizae

VAM have the potential to increase plant growth through the acquisition of immobile nutrients such as P from soil. The main role of VAM in host-plant nutrition is the more effective exploration of the soil by the mycorrhizal root system rather than by the normal root system (Mosse 1977). This is particularly advantageous where soils are low in available P or where poorly soluble forms of P fertilizer are used (Munns and Mosse 1980; Table 1) Compared with graminaceous plants, most legumes have coarser and more restricted root systems (Barley 1970). Hence the growth response to mycorrhizal infection on P-deficient soils is often greater in legumes than in nonlegumes (Munns and Mosse 1980), particularly in legumes with coarse rooting habit (Table 2). The infection of roots by VAM and rhizobia appears to proceed simultaneously (Barea and Azcon-Aguilar 1983). However, the two endophytes do not appear to

<table>
<thead>
<tr>
<th>Soil</th>
<th>Available P (mg/g)</th>
<th>0</th>
<th>PR</th>
<th>M</th>
<th>PR + M</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ikenne, Nigeria</td>
<td>2.4</td>
<td>1103</td>
<td>1100</td>
<td>1103</td>
<td>1103</td>
</tr>
<tr>
<td>Merredin, Australia</td>
<td>3.0</td>
<td>215</td>
<td>215</td>
<td>215</td>
<td>215</td>
</tr>
</tbody>
</table>

Table 1. Response of *Leucaena leucocephala* to phosphate rock (PR) and mycorrhizal infection (M) (Munns and Mom 1980).

Table 2. Response of legumes to infection by mycorrhizae as related to rooting characteristics (Crush 1974).

<table>
<thead>
<tr>
<th>Legume</th>
<th>Length of root hairs (µm)</th>
<th>Diameter of roots (µm)</th>
<th>Roots (%) with hairs</th>
<th>Response to mycorrhizal infection</th>
</tr>
</thead>
<tbody>
<tr>
<td><em>Centrosema pubescens</em></td>
<td>106</td>
<td>288</td>
<td>17</td>
<td>Large</td>
</tr>
<tr>
<td><em>Stylosanthes guayanaeis</em></td>
<td>108</td>
<td>285</td>
<td>6</td>
<td>Large</td>
</tr>
<tr>
<td><em>Trifolium repens</em></td>
<td>213</td>
<td>221</td>
<td>79</td>
<td>Moderate</td>
</tr>
<tr>
<td><em>Lotus pedunculatus</em></td>
<td>809</td>
<td>229</td>
<td>99</td>
<td>Small</td>
</tr>
</tbody>
</table>
compete for infection sites, and nodule tissue is not invaded by the fungus (Smith and Bowen 1979). As early as 1944, the importance of VAM in the growth, nodulation, and N₂ fixation of legumes was recognized (Asai 1944). Smith and Daft (1977), Smith et al. (1979), Daft and El-Giahmi (1978), and Kucey and Paul (1982) suggested that VAM may be able to stimulate N₂ fixation in legumes independent of the effect of the VAM on host-plant growth, although the effect still appears to be related to P supply to the nodule. In general the growth, nodulation, and N₂ fixation response of legumes to VAM infection and to added P fertilizer, are similar (Munns and Mosse 1980, Robson et al. 1981).

**Nitrogen fixation by organisms other than *Rhizobium***

Apart from legumes, about 200 plant species covering 8 families and at least 17 genera are nodulated by the N₂-fixing actinomycete *Frankia*. These plants are termed “actinorhizal” (Dommergues et al 1988). There is, as yet, little information available on the P requirements for N₂ fixation by these organisms.

**Integrated effects of phosphorus on legume growth**

There are many ways of attempting to assess the relative P requirements for host plant growth and symbiotic N₂ fixation in the field (Robson 1978):

- **Interaction with inorganic N.** If the interaction between the effects of added N and P on legume growth is negative, then P may have a specific effect on N₂ fixation (Robson 1978). Timing of N application is critical in the study of interactions. As there is a time lag before nodulation and the start of N₂ fixation by a legume, N application at sowing may enhance growth even in effectively nodulated legumes with adequate P supply. It is therefore better to apply combined N at the start of N₂ fixation to see if the P supply is influencing N₂ fixation or host plant growth (Robson 1978). Unlike with such nutrients as Mo or Co, the interaction between P and N on legume growth has generally been positive (Gates and Wilson 1974, Zaroug and Munns 1979, Robson et al. 1981). Consequently, this approach does not provide evidence for a specific effect of P on N₂ fixation.

- **Examination of the effect of P supply on N concentration in the plant.** If P applications increase both plant dry matter and N percentage, then a specific effect on N₂ fixation can be proposed. The results of McLachlan and Norman (1961), Parsons and Davies (1960), Andrew and Robins (1969), Gates (1974), Andrew (1977), and Zaroug and Munns (1979) using this approach suggest a specific effect of P on N₂ fixation. For example, Andrew and Robins (1969) studied the effect of P supply on a range of tropical forage legumes and found a positive relationship between P percentage and N percentage in the tops (Fig. 1). However, changes in plant structure or metabolism due to improved N nutrition confuse the interpretation of these results (Robson 1983, O’Hara 1988).
1. Relationship between P and N contents in the tops of *Stylosanthes humilis* and *Macroptilium lathyroides* (after Andrew 1977).

\[ N(\%) \]
\[ P(\%) \]

- Examination of the effect of P fertilizer on nodule weight, nodule number, or rate of N\(_2\) fixation as estimated by ARA or \(^{15}\)N balance. Increased P supply has been shown to increase nodule number and weight, or rate of N\(_2\) fixation in a number of leguminous crops, e.g., clover (Lynd et al 1984, Robson et al 1981), *Medicago* spp. (Collins et al 1986, Dahmane and Graham 1981), stylosanthes (Gates 1974, Dradu 1974), soybean (DeMooy and Pesek 1966, DeMooy et al 1973, Cassman et al 1980, Sharpe et al 1986), common bean (Graham and Rosas 1979, Ssali and Keya 1986, Pereira and Bliss 1987), cowpea (Ssali and Keya 1980, Yadav et al 1984), pigeonpea (Ogata et al 1988), chickpea (Shukla and Yadav 1982), lentil (Dhingra et al 1988), and peanut (Turkhede and Giri 1982). Again, in most of these studies, the effect was not usually separated from the effect of P on host plant growth.

Clearly, P supply has a stimulatory effect on N\(_2\) fixation, although in most cases the enhancement can be attributed to improved host plant growth, and to the interaction of this with N\(_2\) fixation. Indeed, it is very difficult to isolate the effect of P supply on N\(_2\) fixation per se, particularly in field experiments. Nevertheless, irrespective of the fact that the effect of P is intimately associated with the stimulation of host plant growth, P is a vital requirement for N\(_2\) fixation. Successful production systems based on legumes therefore require P inputs either from soil reserves or from added fertilizer.

**Improved legume production using phosphorus**

The benefits from including legumes in a production system accrue not only from the production of high-protein material from the legume, but also from the improved productivity of the other crops grown in rotation with the legumes. Cycling of N\(_2\) fixed by rhizobia greatly improves the yield of cereals grown in rotation with legume-based pastures. In southern Australia, the improvement in wheat yield and the dramatic increase in pasture productivity over the last century can be attributed largely to the introduction of superphosphates and legumes (Fig. 2). There is little information
regarding the cycling of P in such systems, although it appears that P in legume residues carried over to the cereal phase of the rotation contributes little (in the short term) to the P nutrition of the cereal crop (McLaughlin et al 1988). Fertilization of the pasture phase of the rotation may enhance organic P accumulation, while fertilization of the cereal crop may favor inorganic P accumulation. Topdressing of P on pastures may make plants more susceptible to dry spells, while P application to cereals by drilling fertilizer at sowing depth may benefit both the cereal and the ensuing pasture crop: with drilled fertilizer the soil containing P remains moist for longer periods.

On many of the poor soils in South America, the possibilities offered by the introduction of legumes coupled with applications of P, Mo, and lime have been noted (Dobereiner 1975). In these areas, soybean grown in rotation with maize responds markedly to application of P to the preceding maize crop (Fig. 3).

In addition to improving the yield of legume crops, P application has the potential to modify the botanical composition of pasture swards. In pastures

![Graph 2](image2.png)

2. Mean (10-yr) wheat yields in Australia since 1870 (after Donald 1963).

![Graph 3](image3.png)

3. Relative fertilizer cost and effect of P applied to the previous maize crop on soybean grain yield (after Lobato et al 1967, quoted by Dobereiner 1975).
developed on nutrient-poor soils, P application often has a marked effect on the initial response of the legume component (compared with the grass component) of the sward; the legumes are not constrained by N supply (Andrew 1977). In later years, the grass component may dominate the sward once sufficient N is cycling within the system to support the requirements of the grass. At this stage the grasses have a competitive advantage over legumes because of their finer and more extensive root systems, which permit greater efficiencies of water and P uptake (Jackman and Mouat 1972), and their ability to shade out the legumes.

In Australia, stimulation of legume growth through P fertilization over long periods may lead to a gradual acidification of the soil under pasture (Williams 1980). This will ultimately have a detrimental effect on plant growth, as the lowered pH and increased availability of Al and Mn inhibit nodulation and root growth and function. Soil acidification by legume crops has been reviewed elsewhere (Haynes 1983, Edmeades 1990). In certain circumstances, however, it may be advantageous for plant growth, e.g., by increasing the dissolution of sparingly soluble Ca-based phosphate rock (Aguilar Santelises and Van Diest 1981, Bekele et al 1983, De Swart and Van Diest 1987).

Conclusion

By fixing atmospheric N\textsubscript{2}, legumes offer the most effective way of increasing the productivity of poor soils either in monoculture, crop rotations, or mixed cropping systems. Where access to inorganic N fertilizers is limited by availability or cost, N\textsubscript{2} fixation provides the main pathway through which soil fertility can be improved. Phosphorus plays a key role in the buildup and maintenance of soil productivity by legumes through its effect on host plant growth and through its specific effect on Rhizobium growth, survival, and nodulation capability.

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Phosphorus and nitrogen fixation in upland crops


Notes

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Acknowledgments: The authors thank A.H. Gibson and J.R. Freney for their useful comments on an early draft of this paper. The senior author thanks the Australian Phosphate Corporation for financial support.

Citation information: International Rice Research Institute (1990) Phosphorus requirements for sustainable agriculture in Asia and Oceania. P.O. Box 933, Manila, Philippines.
Phosphorus requirements and management for lowland rice

S.K. De Datta, T.K. Biswas, and C. Charoenchamratcheep

Large tracts of lowland rice soils in the tropics are P deficient. These include Oxisols, Ultisols, Vertisols, and certain Inceptisols, particularly Andepts and acid sulfate soils. Reduction of Fe-P, in which form P exists mainly in lowland rice soils, is the main source of available P in soil. More available P is released through transformation processes in lowland soils than in upland soils because of differences in their oxidation-reduction states. Furthermore, yield responses of lowland rice to P fertilization are not as common as those of upland crops. Results have shown that optimum rice yields in lowland soils cannot be achieved without P fertilization. For lowland rice, finely ground, moderately to highly reactive phosphate rock or partially acidulated phosphate rock are potential P sources. The Olsen method used on air-dry soils is the most universally acceptable method for estimating available P. Incorporating P fertilizer into the soil before transplanting rice is highly superior to split application. Dipping rice seedling roots into a P-soil slurry reduces the P fertilizer requirement by 50%.

Most tropical rice soils, particularly in upland areas, are low in P (Kawaguchi and Kyuma 1977). Phosphorus is commonly less deficient in flooded than in upland rice because higher levels of available forms of P are usually present in flooded soils. Nevertheless, P deficiency is still widespread in lowland rice, and response to P occurs in millions of hectares of the world’s riceland (De Datta 1981, Greenland and De Datta 1985).

Phosphorus deficiencies occur primarily on Ultisols, Oxisols, Vertisols, and certain Inceptisols, particularly Andepts and acid sulfate soils. Not only are these soils low in available P; they also fix P fertilizer into a highly insoluble mineral. Besides, the increased P availability brought about by soil submergence is low in these soils (Ponnamperuma 1977).

Plant nutrient removal from the soil by modern rice varieties is about three times that by traditional varieties. A single lowland IR36 crop that produced 9.8 t/ha took up 31 kg P/ha (De Datta and Morris 1984), where total nutrient removal of grains is estimated from 3 to 11 kg P/ha. Recent results show that P deficiency is widespread, particularly with modern rice varieties—where yields of up to 6 t/ha are common—and significant responses to P fertilizers have been noted.

Suboptimal and unbalanced P fertilizer use is often the main cause for not realizing the yield potential of modern rice varieties. This paper discusses the nature
Forms of phosphorus and their practical significance

After reviewing results from several Indian soils, Tandon (1987) concluded that total P in soils varies from less than 100 ppm (1% = 10,000 ppm) to more than 2,000 ppm (200-400 kg P/ha of plow layer). Figures for most rice soils vary within 200-800 ppm P (Khanna and Pathak 1982). Total P is rather poorly correlated with available P and is rarely used to describe the P fertility status of soils.

Although soil P occurs both in organic and inorganic forms, research has been focused on inorganic P. Inorganic soil P can be conveniently classified into four groups:

1. iron phosphate (Fe-P)
2. aluminum phosphate (Al-P)
3. calcium phosphate (Ca-P)
4. reductant-soluble or occluded Fe-P and Al-P

Phosphorus in all forms exists in all soils, but Al-P and Fe-P are more abundant in acid soils, while Ca-P dominates in neutral-alkaline soils. The highly mobile P in sodic soils is thought to be associated with Na. The reductant-soluble P fraction is too insoluble to be of any practical significance in upland rice, but this fraction is important in lowland rice.

Phosphorus exists mainly as Fe-P in rice soils (Cholitkul and Tyner 1971, Tandon 1987). Distribution of inorganic P fractions in Malaysian soils shows that Fe-P predominates in all soils, constituting an average of 79% of the inorganic P fraction (Table 1). Fe-P is followed by Ca-P, which is slightly more than Al-P (Bidin 1986). Sahrawat (1977) reported that in Alfisols of India, with pH ranging from 5.5 to 6.8, the order of soil P distribution was Fe-P > Ca-P > Al-P.

Perumal and Velayutham (1977) reported that Al-P and Fe-P constituted 55% of total P while Ca-P formed only 12%. The P forms were distributed as follows: unidentified-P > Fe-P > Al-P > Ca-P = reductant soluble P > saloid-P.

Basak and Bhattacharya (1962) found that organic P was dominant (42% of the total P) in alluvial rice soils of West Bengal, India. They observed a release of about 183 kg P/ha from the mineralization of organic P alone in a growing season.

<table>
<thead>
<tr>
<th>Soil order</th>
<th>Distribution (%) of inorganic P fractions</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Soluble P</td>
</tr>
<tr>
<td>Oxisol</td>
<td>0.15</td>
</tr>
<tr>
<td>Ultisol</td>
<td>1.9</td>
</tr>
<tr>
<td>Inceptisol</td>
<td>0.9</td>
</tr>
<tr>
<td>Entisol</td>
<td>0.7</td>
</tr>
<tr>
<td>Mean</td>
<td>0.9</td>
</tr>
</tbody>
</table>
further observed that Fe-P and Al-P constituted about 47% of the total P content of puddled soils. As the crop grew, the Fe-P and Al-P content of soil decreased by about 183 kg P/ha. The rate of decrease was apparently highest during the tillering to preflowering stage.

Khan and Mandal (1973) studied P distribution in typical rice soils of West Bengal (pH 4.9-6.6, 0.34-0.96% organic C). Organic P constituted about 35% of total P. Among the inorganic P fractions, Fe-P was 28%, Ca-P was 47%, and reductant-soluble Fe-P was 16%, while Al-P was 7% and occluded Al-P was 2% of total inorganic P. They concluded that, because the amounts of Fe-P were high, waterlogging would increase available P. They also suggested the application of organic matter for the release of P from Ca-P.

Several studies have shown that the Al-P and Fe-P fractions are the major contributors to plant-available P under most rice-growing situations. This is true even where Ca-P is much more abundant than Al-P or Fe-P. The value of a P fraction for plant growth depends not so much on its quantity as on its physicochemical qualities. Work with radioisotopes and chemical-statistical analyses has substantiated the importance of Fe-P and Al-P (Chang 1978, Verma and Tripathi 1982) in rice nutrition under submerged soil conditions.

**Phosphorus availability in flooded soils**

The behavior of P in flooded soils is markedly different from that in upland soils. Upon submergence, the pH values of acid soils increase, largely because of the reduction of Fe; but the stable pH of submerged soils is regulated by the partial pressure of CO$_2$ (Ponnamperuma 1972). pH values of submerged calcareous and sodic soils are lower than those of aerobic soils because of CO$_2$ accumulation. Ferric and Al compounds of P release P as pH increases, whereas Ca compounds of P liberate P as pH decreases. Generally, after soil submergence, concentrations of water-soluble P increase (Fig. 1). Marked increases in the availability of native and added P in flooded soils have been noted over those in well-drained soils (Patrick and Mahapatra 1968; Ponnamperuma 1965, 1972). Yield responses to P are not as frequent in flooded rice as in upland crops (De Datta and Gomez 1982).

Several investigators (Goswami and Banerjee 1978, Jones et al 1982) have attributed the increased P availability upon soil submergence to

- reduction of Fe$^{3+}$-P to more soluble Fe$_3$(PO$_4$)$_2$·3H$_2$O;
- release of occluded P and P sorbed on amorphous Fe and Mn oxides;
- hydrolysis of Fe-P and Al-P in acid soil;
- increased mineralization of organic P, particularly Fe-phytates in acid soil;
- increased solubility of Ca-P in calcareous soils; and
- the increased diffusivity factor of P.

Chang (1976) claimed that Fe-P reduction is the main source of available P for flooded rice soil. According to Turner and Gilliam (1976), enhanced P diffusion in water-saturated soils may be partly responsible for the greater P availability to plants in submerged soils than to upland crops.

Alva et al (1980) postulated that P mobilization was due to increased microbial activity in the presence of oxidized rice roots and P immobilization due to the rhizosphere during the later growing period. They suggested that lowland rice plants
have a mechanism for regulating the contrasting changes in P availability in the rhizosphere, depending on P requirement by the plants or P availability in soil. This in turn is responsible for the generally poor yield response to P fertilization.

Regardless of the chemical identities of soil P, the following release properties control the overall soil P supply to rice roots:

- **Quantity factor**—reserve P (P that is readily exchanged with soil P, i.e., labile P)
- **Intensity factor**—P potential (concentration of soluble P)
- **Capacity factor**—relative constancy of solution P concentration (buffer capacity) during P depletion

### Phosphorus fixation

The P-fixing capacity of soils is an important soil parameter in formulating adequate P levels for desired fertilizer response (Goswami and Banerjee 1978). When soluble P fertilizer is added to the soil, most of it is fixed initially as ALP, some as Fe-P, and the least amount as Ca-P except in calcareous soils. The initial fixation could be attributed to the greater P sorption from solutions high in P in submerged soil.

Patrick and Khalid (1974) observed that anaerobic soils released more P to solutions low in soluble P, and adsorbed more P from solutions high in soluble P than did aerobic soils. Khalid et al (1977) obtained similar results with two Alfisols and three Inceptisols from Louisiana. They found that, of the soil properties tested, oxalate-extractable Fe contributed most to P adsorption by flooded soils. They
suggested that $\text{Fe}^{3+}$-oxyhydroxide adsorbs P more firmly but has less surface area exposed to solution P than gel-like hydrated $\text{Fe}^{2+}$-oxides or $\text{Fe(OH)}_2$.

Willett and Higgins (1978) found results consistent with $\text{Fe}^{2+}$-hydrous oxides domination of P adsorption during the flooded phase, and poorly crystalline $\text{Fe}^{3+}$-hydrous oxides domination during the postflooding phase.

De Datta et al (1966) showed that within 4 d of equilibration, the added P remaining in solution was lowest in acid Ultisols (containing kaolin), moderately high in montmorillonite soils, and unchanged in calcareous soil.

Soluble P is fixed on the surface of the soil solid phase. Relative amounts of P fixed by Al, Fe, or Ca depend on the exposed, reactive surface area of the respective solid phases and the concentration of the reactive cations. Juo and Fox (1977) found a close relationship between soil sample surface area and standard P adsorption.

Soil mineralogy is the key factor affecting P fixation (Juo and Fox 1977). Bajwa (1982) ranked P fixation by Philippine rice soils according to mineralogy as follows:

- montmorillonite < vermiculite < halloysite < X-ray amorphous material < kaolinite

**Areas of phosphorus deficiency**

Phosphorus deficiency is next to N deficiency in importance. Most tropical rice soils are low in P.

Phosphorus deficiency is perhaps the most important factor limiting rice yields on Ultisols, Oxisols, Sulfaquepts, Andosols, and some Vertisols, which not only are low in available P but also fix large amounts of added P fertilizer. Furthermore, P deficiency is often associated with other limiting or retarding factors, as shown below:

<table>
<thead>
<tr>
<th>Soil class</th>
<th>Other growth-limiting factors</th>
</tr>
</thead>
<tbody>
<tr>
<td>Acid sulfate soils</td>
<td>Strong acidity, Fe toxicity, low nutrient status, base deficiency, salinity</td>
</tr>
<tr>
<td>Strongly acid Oxisols and Ultisols Vertisols</td>
<td>Fe toxicity, base deficiency</td>
</tr>
<tr>
<td>Zn deficiency, Fe deficiency, salinity, alkalinity</td>
<td></td>
</tr>
</tbody>
</table>

Phosphorus deficiency is widespread in the rice-growing soils of Asia. Kawaguchi and Kyuma (1977) reported that more than 60% of the soils in Thailand, Malaysia, and Kampuchea were P deficient at the lower limit of 13.2 mg Bray No. 2-soluble P/kg soil.

Bidin and Barber (1985), analyzing several Malaysian soils for available P using the Bray No. 1 method, concluded that the soils are P deficient, with available P ranging from 2 to 8 ppm. In the Philippines, a large group of rice-growing soils are P deficient (PCARR 1976). They are generally clay to clay loam in texture, with low pH; have high contents of active Fe, Al, and Mn; and show high P-fixing capacity. Cholitkul and Tyner (1971) surmised that the lowland rice soils of the northeast region and of the coastal areas of the southeast region of Thailand are P deficient.
These soils have low pH, low organic matter and cation exchange capacity, narrow C-N ratios, and low P adsorption coefficients.

Oxisols and coastal alluvial soils of Indonesia, acid sulfate soils of the Republic of Korea, Andosols of Japan, and black, red, and laterite soils of India have also been reported as P deficient (Goswami and Banerjee 1978). Similarly, Wang (1965) reported from Taiwan, China, that areas dominant in Oxisols or strong acidic soils and light-textured soils are deficient in P. In Nepal (Tamang et al 1986), about 28% of the soils have low available P, 61% have moderate amounts of available P, and the rest have high soil P status.

In India, Ghosh and Hasan (1979) and Tandon (1987) reported that P content was low in 45% of the soils, medium in 50%, and high in only 5%.

Thus, there is an urgent need for high to moderate doses of P along with judicial and balanced doses of other nutrients to produce and maintain high rice yields.

Soil test-based estimation of phosphorus fertilizer requirements

Soil tests measure the nutrient-supplying capacity of soil and estimate a part of the total soil nutrient reserve. Soil test values are of little use unless they are properly calibrated against crop response to applied fertilizer in the field. The objective of a soil test is to obtain a value that will help predict the amount of nutrients needed to supplement the nutrient supply in the soil.

Often, soil test calibration is complicated by the fact that many factors other than fertility level influence the response obtained (Tisdale et al 1985). Thus, many farmers lack confidence in fertilizer recommendations based on soil analysis (Cooke 1970). The introduction of new technology outdates calibration data, hence the need to regularly update soil test values.

There is a great deal of literature on tests for available soil P. Ideally, soil P tests should estimate plant-available forms from various soils and provide values correlated with crop response under various conditions. Soil P tests on submerged rice soils pose two problems: 1) tests on air-dry soil may not reflect the P status after submergence, and 2) P availability generally increases after submergence, with the increase depending on the soil characteristics.

In assessing P status by chemical tests, relationships among quantity, intensity, capacity, and diffusion, and factors influencing these components of P supply must be considered (Kamprath and Watson 1980). The quantity and intensity factors are functions of the amount and nature of hydrated-oxide of Fe and Al in acid and neutral soils, and of exchangeable Ca and CaCO$_3$ in calcareous soils. Chang and Juo (1963) showed that alkaline solutions and those containing NH$_4$F preferentially extract Fe-P and Al-P, whereas acid solutions preferentially extract Ca-P. Thus, soil tests characterize either the quantity factor (with strong extractants) or the intensity factor (with weak extractants) and limit their use in all soils. Nevertheless, numerous chemical extractants have been used to test available P in submerged soils.

The methods based on the type of extractant used may be grouped into four (Chang 1978):

- Solution of strong acid such as 0.002 N H$_2$SO$_4$ (Truog, Ayres-Hagihara), 0.13 N HCl (Spurway), and 0.05 N HCl + 0.025 N H$_2$SO$_4$ (Mehlich)
• Solution of an organic acid or acidified organic salt, such as NaOAc + HOAc (Peech, Morgan), 1% citric acid (Dyer), and CO₂ (McGeorge)
• Alkaline solutions such as 0.5 M NaHCO₃ (Olsen) and 0.1 N NaOH (Saunders)
• Solution of strong acid containing complexing radicals for Fe and Al such as 0.03 N NH₄F + 0.025 N HCl (Bray No. 1) and 0.03 N NH₄F + 0.1 N HCl (Bray No. 2).

Correlations of soil P, as determined by these methods, with rice response to P application have been extensively studied in most Asian countries. Studies by Indian workers during the early 1960s were summarized by Chang (1978), who concluded that none of the eight soil tests used gave good correlation between available P and rice response in the field. In pot studies, the Olsen method gave a high correlation and was far better than the other methods.

Goswami and Banerjee (1978) confirmed the superiority of the Olsen method to other methods in predicting rice responses to P fertilizer in the field based on 489 trials representing diverse soil and climatic conditions. Jugsujinda et al. (1973) found that when soils containing large amounts of Ca-P (phosphate rock [PR] experiments) were included in the calculation, available P determined by the Olsen and Bray No. 1 methods gave high correlation with rice response to P. Research in the Philippines reported that Olsen P correlated with grain yield and P uptake by rice at the 1% level. At present, the Philippine Bureau of Soils and many Indian soil laboratories recommend the Olsen method for routine soil P analysis.

Dabin (1980) found that with rice grown in pots with soils dominated by Fe-P, alkaline extractants gave the best correlation with crop response to P fertilizer. Verma and Tripathi (1982) found, by stepwise regression analysis, that Fe-P was the most important variable contributing to total variation in extractable P by Olsen, Bray No. 1, and Bray No. 2 methods in airdried and waterlogged Alfisols.

Cholitkul and Tyner (1971) and Mahapatra and Patrick (1971) drew similar conclusions: what is basically needed for air-dried samples of lowland rice soils is an extractant that is more Fe-P specific. This will allow P fertility evaluation of flooded soils by chemical analysis of air-dried samples. In this respect, the Olsen method was superior to Bray No. 2.

Ekpete (1976) evaluated several chemical methods for available P determination in 13 waterlogged soils (pH 4.2-6.1). He concluded that the Olsen method is better than all the other methods and that it could be used in air-dried soils to predict P availability and rice response to P fertilizer application in waterlogged soils. Likewise, Chang (1978) claimed that the Olsen and Bray No. 1 methods, but especially Olsen, are more universally applicable to all soil types.

Because P availability in the soil increases after submergence, it has been questioned whether calibrations made on dry soil samples are reliable when applied to the response of rice grown on submerged soils (Colwel 1971). However, Chang and Maleewan (1972) showed from 31 soils that 1) aerobic and anaerobic P determined by the Olsen method were highly correlated, regardless of soil pH, and were only slightly affected by a drop in Eh (Fig. 2); and 2) P determined by Bray No. 1 or No. 2 was moderately correlated when soil pH values were greater than 5.
2. Correlation between aerobic P and anaerobic P of soils, determined by the Olsen method and the Bray method (after Chang and Maleewan 1972).

Submergence and the addition of starch caused a decrease in Eh, which greatly increased P values as determined by the two methods.

In recent years, there have been attempts to use P adsorption isotherms to predict fertilizer P requirements. The amount of P adsorbed at standard supernatant concentration has been used as an estimate of the fertilizer P required.

Experiments at the International Rice Research Institute (IRRI) by Roy and De Datta (1985) showed that soil reduction by flooding decreases P adsorption by 28-70%. Subsequently, P adsorption isotherms for the reduced system were developed for four P deficient lowland rice soils in the Philippines. The external P requirement of rice was found to be 0.07-0.09 ppm (De Datta 1983, Greenland and De Datta 1985). A possible problem with this method, however, is that it does not account for differences in buffer capacity and diffusion rate in various soils. Diamond (1985) cautioned that it is too early to speculate on the possibility of using this approach to predict P fertilizer requirements for rice. Kamprath and Watson (1980) concluded that the method is not suited for routine analysis, but can serve to characterize soils and to group them for formulating fertilizer recommendations.

**Rice response to phosphorus application and phosphorus management**

Continuous submergence increases P availability. However, increased P availability under flooding does not remain once the soil is dry in the wet-dry cycle in rainfed lowland rice systems. Upon drying, the solubility of the soil and fertilizer P decreases. Management of P is largely dependent on soil characteristics such as soil
reaction, degree of weathering, kind of clay minerals, water regime, cropping intensity, and cropping patterns (De Datta 1981).

**Yield response to phosphorus application**

In some lowland rice-growing areas with highly P deficient soils, optimum crop yields are obtained only when P is applied with N. Results of experiments from different soil types show that rice generally responds to up to 26 kg applied P/ha. Results of 1,326 experiments in farmers’ fields under the AICRIP (1979) indicated that rice grain yield response to 26 kg P/ha ranged from 280 to 1,000 kg/ha with magnitude of response (kilogram of rice per kilogram of P) varying from 11 to 39.

Results from experiments in farmers’ fields have been increasingly used to compute the magnitude of yield responses to P. Table 2 summarizes yield responses to P in about 18,000 experiments in farmers’ fields, using modern varieties with irrigation or “assured” rainfall.

Crop variety, soil properties, initial available P, and seasonal conditions influence the response to P of flooded rice. Modern varieties respond more to P than do the tall traditional varieties, particularly in a cool and clear dry season. Higher responses to P generally reported in the dry summer season than in the wet season (Katyal 1978) have been attributed to higher yield potentials due to more sunshine, better water control, lower disease incidence, and lower soil P availability during the dry season.

Other experiments conducted for 3-10 yr report no or negligible seasonal differences (Nambiar and Ghosh 1984). When averaged over diverse soil-crop conditions and management levels, seasonal differences became nonsignificant; however, they may actually be significant in specific areas (Fig. 3).

**Rice response to phosphorus under intensive rice cropping**

Under intensive rice - rice cropping systems, demand for P increases, but often only after two or three croppings. Findings from long-term fertility experiments since 1968 at three experiment stations in the Philippines show that P response was observed only when N and K were applied (De Datta et al 1988). Phosphorus use efficiency in dry season rose from nil to as high as 210 kg rice/kg P at Maligaya, and to 109 kg rice/kg P at Visayas station (Fig. 4).

Monitored responses to soil fertility parameters suggest that available P was affected by successive P application (see Palmer et al 1990).

<table>
<thead>
<tr>
<th>Season</th>
<th>Trials (no.)</th>
<th>Yield without fertilizer (t/ha)</th>
<th>P applied (kg/ha)</th>
<th>Yield response kg/ha</th>
<th>Yield response kg/kg P</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wet</td>
<td>9634</td>
<td>3.0</td>
<td>26</td>
<td>620</td>
<td>23</td>
</tr>
<tr>
<td>Wet</td>
<td>2728</td>
<td>2.4</td>
<td>26</td>
<td>480</td>
<td>18</td>
</tr>
<tr>
<td>Cool (dry)</td>
<td>56863.2</td>
<td>26</td>
<td>26</td>
<td>740</td>
<td>28</td>
</tr>
<tr>
<td>Dry</td>
<td>3063.2</td>
<td>17</td>
<td>940</td>
<td>54</td>
<td></td>
</tr>
</tbody>
</table>

*Assured rainfall conditions.
Phosphorus management

Management practices for higher P use efficiency will depend on the P Source, timing, and application method to be used.

Sources of phosphorus fertilizer materials. Ordinary superphosphate, triple superphosphate (TSP), diammonium phosphate, and ammonium phosphate are most commonly used for lowland rice. However, fused Ca/Mg$_3$(PO$_4$)$_2$, urea ammonium phosphate sulfate, hyperphosphate, nitric phosphate, and PR have also been used in certain places.

The availability of P fertilizer to rice grown on waterlogged soil depends on the composition of the fertilizer and the time of fertilizer application (Porananond and Searle 1977). De Datta (1978) claimed that P availability to rice does not significantly differ among various kinds of fertilizers, except on very strongly acid or alkaline soils.

Phosphate rock has been evaluated as a P source for rice in many Asian countries (Hammond et al 1986, Khasawneh and Doll 1978). Ground PR costs less than acidulated phosphate and is easier to manufacture, moderately high in P content, and effective on P-deficient acid soils of the humid tropics. Increasing the use of ground PR may be one way of enhancing food production in tropical countries. Partially acidulated PR is intermediate in solubility between superphosphates and ground PR.

Two important principles must be remembered when testing PR: 1) PRs from various deposits differ in reactivity and thus must be characterized, and 2) PR dissolution in soil increases with decreasing pH and Ca and P concentrations. Thus, application of PR on lowland rice soils, unlike on upland soils, may trigger the following: 1) the pH of an acid rice soil may be raised to approximately neutral under submergence, which will decrease the solubility of PR applied to the soil; 2) the
ability of rice to use P will be very low. The PR available to other crops may often be unavailable to rice.

In 1977, the International Network on Soil Fertility and Fertilizer Evaluation for Rice (INSFFER)—a collaborative network among national institutions, IRRI, and the International Fertilizer Development Center (IFDC)—established a series of international trials on P sources in lowland rice (IRRI 1983). During 1977-82, 84 experiments were conducted at 24 sites in 10 countries. At each site, 10 treatments were tested, including a check, three positive rates of superphosphate, a highly reactive PR, and a less reactive PR. Phosphorus response was reported in only 58 of the 84 trials, and in those, all P sources behaved similarly.
Results with PR in flooded soils were highly encouraging because of differences in the chemical reactions of P in those soils. In general, the P-supplying capacity of flooded soils was superior to that of nonflooded soils.

These reactions tend to reduce the differences between the agronomic effectiveness of unacidulated PR and that of soluble P and thus suggest high potential for PR use in flooded rice. Nevertheless, it is clear from the results of INSFFER and IRRI collaborative research work with five Asian countries (De Datta 1988) that PR application rates must still be doubled to obtain yields equal to that with soluble P application (Table 3). This is a significant observation, because the PRs indigenous to Asian countries are generally less reactive. The relationship between the relative agronomic effectiveness of the PR as compared with TSP, and the ratio of the price of TSP to the price of PR (Fig. 5) is proposed as an index for source selection, but residual effects also need to be considered (Palmer et al 1990).

Again, because of the low reactivity of indigenous PRs, a number of modifications have been proposed and evaluated to improve PR effectiveness. Use of partially acidulated PR has resulted in yields comparable to those with completely soluble P. Table 4 illustrates the effectiveness of local PR and partially acidulated PR from Indonesia when used for irrigated rice.

Methods of phosphorus application. Field experiments with $^{32}$P-labeled P fertilizer in seven countries showed that surface broadcasting or incorporation of fertilizer before transplanting was more effective than the other methods such as deep placement of P at 10- or 20-cm depth either in planting hills or between rows (IAEA 1970).

Recent results in the Philippines showed similar responses of a short-duration variety to basal application of P whether surface broadcast or incorporated into the soil on each Vertisol, Alfisol, and Inceptisol (Diamond 1985).

Dipping rice seedlings into P fertilizer slurry before transplanting has attracted attention in some countries. Katyal (1978) reported that P application to roots in the form of a slurry before transplanting was an economical method of P use. Following


<table>
<thead>
<tr>
<th>P source</th>
<th>Grain yield$^a$ (t/ha) at P level of</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0</td>
</tr>
<tr>
<td>Check</td>
<td>3.9 d</td>
</tr>
<tr>
<td>Triple superphosphate</td>
<td>5.4 a</td>
</tr>
<tr>
<td>50% partially acidulated PR</td>
<td>4.8 abc</td>
</tr>
<tr>
<td>Local PR</td>
<td>–</td>
</tr>
<tr>
<td>Florida PR</td>
<td>4.4 bcd</td>
</tr>
</tbody>
</table>

$^a$Means followed by the same letter are not significantly different at the 5% level by DMRT. CV = 10%. A dash means data not available.
Phosphorus and lowland rice

5. Relationship between the relative agronomic effectiveness (RAE) values and price ratios of TSP and PR. RAE can be used in making a choice between these sources (after Engelstad et al. 1974).

this method, Katyal (1978) achieved a 50% reduction of P use without decreasing grain yield (Table 5). Lu et al. (1982), who reviewed P management practices in irrigated rice soils in China, concluded that a 40-60% savings on P fertilizer can be obtained by dipping seedlings before transplanting.

*Time of phosphorus fertilizer application.* Generally, P fertilizer for rice should be applied at transplanting, but it may also be applied later, before the vigorous tillering stage (De Datta 1978, 1981). Split application of P has not been effective because of the high mobility of P from old to young leaves, increased availability of

<table>
<thead>
<tr>
<th>P source</th>
<th>Grain yieldb (t/ha) at P level of</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0</td>
</tr>
<tr>
<td>No fertilizer</td>
<td></td>
</tr>
<tr>
<td>No P</td>
<td></td>
</tr>
<tr>
<td>Triple superphosphate</td>
<td></td>
</tr>
<tr>
<td>50% partially acidulated PR</td>
<td>6.6 bc</td>
</tr>
<tr>
<td>Florida PR</td>
<td></td>
</tr>
<tr>
<td>Local PR</td>
<td></td>
</tr>
</tbody>
</table>

*In a column, means followed by the same letter are not significantly different at the 5% level by DMRT. A dash means data not available.*
Table 5. Lowland rice response to P application to the root in the form of slurry (after Katyal 1978).

<table>
<thead>
<tr>
<th>Treatment</th>
<th>Grain yield (t/ha)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Check</td>
<td>0.0</td>
</tr>
<tr>
<td>Applied to soil</td>
<td></td>
</tr>
<tr>
<td>13</td>
<td>3.4</td>
</tr>
<tr>
<td>26</td>
<td>4.9</td>
</tr>
<tr>
<td>Applied to roots as slurry&lt;sup&gt;a&lt;/sup&gt;</td>
<td></td>
</tr>
<tr>
<td>SSP : Soil : Water</td>
<td></td>
</tr>
<tr>
<td>14: 1: 2&lt;sup&gt;b&lt;/sup&gt;</td>
<td>5.0</td>
</tr>
<tr>
<td>12: 1: 3&lt;sup&gt;b&lt;/sup&gt;</td>
<td>4.7</td>
</tr>
<tr>
<td>12: 1: 3&lt;sup&gt;c&lt;/sup&gt;</td>
<td>4.6</td>
</tr>
<tr>
<td>LSD (0.05)</td>
<td>1.2</td>
</tr>
</tbody>
</table>

<sup>a</sup>Proportions of SSP, soil, and water in slurry indicated.  
<sup>b</sup>Roots of individual seedlings were dipped.  
<sup>c</sup>Roots of seedlings in bundle were dipped together.

soil P with time during submergence, and low leaching losses (De Datta 1981). Experiments on P application methods for rice in 7 countries (IAEA 1970) showed that P applied 2 wk before panicle initiation is as effective as that applied at transplanting.

Patrick et al (1974) reported that grain yield, averaged over 3 yr, decreased as topdressing of P was delayed for 2, 4, or 6 wk after sowing. Lower yield response to P applied at 7 d after transplanting (DT) than from basal application on a Vertisol in India was reported by Katyal (1978). He found no significant yield differences among basal, and 7-, 14-, and 21-DT applications during the wet season. Late applications up to 63 DT resulted in lower yields.

Thus, applying the total dose as basal at transplanting is the best time and method of P fertilization for rice because

- more P is required by the rice during the early growth stages,
- available P from soil cannot meet the requirement at this early stage,
- adequate P supply may be conducive to better root development and tillering,
- particularly in low temperature areas, more P is required during the early growth stages, and application at transplanting is more convenient than topdressing during later growth stages.

Within a cropping system, addition of P to the preceding crop has been advocated by many authors for better P fertilizer use (Lu et al 1982, Patrick and Mahapatra 1968).

Generally, fertilizer P recovery by rice ranges from 8 to 20% (De Datta et al 1966, Goswami and Banerjee 1978), 80-90% of the applied P remaining in the soil for the succeeding crop. As P availability changes with alternating drying and submergence, the P applied to the upland crop may have greater residual effect on the succeeding rice, while P applied to rice may have less residual effect on the succeeding upland crop (Lu et al 1982).
In a study using eight lowland rice soils of varying physicochemical properties, Lu et al (1982) reported that, when all of P was applied to the upland wheat crop, total P uptake by rice and yield of wheat and rice were about twice the amount of that when all of P was applied to rice.

Rice yield responses to P fertilizer are becoming more frequent as soils are cropped more intensively and crop yields increase from greater use of modern varieties. Indigenous or imported commercial PR may offer low-cost P fertilizer, but the relative agronomic value of the materials must be determined to identify their potential role as P sources for rice.

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Notes

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Citation information: International Rice Research Institute (1990) Phosphorus requirements for sustainable agriculture in Asia and Oceania. P.O. Box 933, Manila, Philippines.
Phosphorus management in lowland rice-based cropping systems

B. Palmer, M. Ismunadji, and Vo-Tong Xuan

Some areas in Asia are giving lower responses to P fertilizers than were previously estimated. Data from Indonesia are presented to show that in Java and Madura the area considered highly responsive has decreased from 50 to 15% in the past 20 yr. Phosphorus balance sheets for lowland rice production at a number of locations in Southeast Asia show the low proportion of the applied fertilizer actually removed by the crop. Topics for further study are discussed, including improving our understanding of the type and timing of fertilizer application.

Before the early 1960s, the lowland rice grown in Southeast Asia had few fertilizer inputs other than N. With the introduction of the short-straw modern varieties (MVs), additional fertilizer inputs were required to realize the extra yield potential. In many locations, the addition of P and K was found to improve crop performance significantly, especially in the presence of N inputs (De Datta and Gomez 1975). In some countries, for example Indonesia, where triple superphosphate (TSP) is produced domestically and is heavily subsidized by the government, scientists, and advisers are now questioning the continued high application rates of acidulated P fertilizers to lowland rice crops.

Crop removal of P is in general much less than the P inputs to the system, giving a net accretion of this resource. After buildup of residual P, when the major purpose of applying P fertilizers is to satisfy a maintenance requirement, it should be possible to use less-available P sources, for example phosphate rock (PR). Perhaps, in the past, levels of P application were too high because of several factors that did not all have the same importance in every country. These include high subsidies, poor accuracy of empirical soil tests for P requirements, and poor understanding of the mechanisms of P turnover in flooded soils, together with the complexity of the farming systems used in the target areas.

Farming systems

The lowland rice-based farming systems of Asia and Oceania are diverse; the cropping patterns range from continuous flooded rice production through rotations including upland rice and other dryland food crops, to systems including nonfood crops, with aquaculture and the raising of other animals forming part of an integrated system. The selection of a particular system depends on many components
relating to national goals, edaphic and climatic factors, as well as the experience and traditions of the local farmers. All these factors influence decisions about the type, amount, and timing of P fertilizer inputs to support sustainable agriculture.

Dao and Vo-tong (1988) describe the existing farming systems for the slightly acidic and acidic soils of the Mekong Delta and discuss current research in this area. On the slightly acidic soils, MV rice is commonly followed by mungbean, soybean, maize, or watermelon. Alternatively, MV rice is followed by a photoperiod-sensitive rice cultivar with giant prawn or fish raised simultaneously in the ricefield. Fruit trees or green manure trees are grown on the dikes. Vo-tong and Ha (1976) found that the initial response to P was only moderate, but that P was depleted after the fourth rice crop if only N was applied. They concluded that P fertilizers must be applied as a basal dose at the beginning of each crop. On the more acidic alluvial soils (pH 4-4.5 in the dry season) it is recommended that the fertilizer be split into two doses. On acid sulfate soils, the first application should be immediately before planting to minimize fixation by Al-Fe complexes (Do et al 1986b).

Lowland rice-based cropping systems are dominant in Indonesian food crop agriculture. Where water is sufficient, farmers give priority to lowland rice as the major crop in the local cropping system. They try to achieve two lowland rice crops followed by a nonrice food crop (palawija) or a horticultural crop. Where water is limited, the farmers practice the gogo rancah system, wherein the rice is directly seeded into aerobic soil at the beginning of the rainy season and later flooded.

The Indonesian Government promotes rice production through intensification programs operating at several levels; they encourage, among other practices, the use of fertilizers to optimize production. Recommendations for fertilizer application, especially in the case of acidulated P, are being reevaluated by Indonesian scientists, as there are indications of marked reductions in yield responses. The role of other P sources is also being considered, especially in situations where only a maintenance application may be required to replace the P removed from the system by the crop.

With these complex farming systems, decisions must be made not only about the quantity and type of fertilizer to use but also about the phase of the rotation in which it is to be added. The P fertilizer applied to one crop can often meet the P requirement of the subsequent crop or crops in a cropping sequence. The efficiency of fertilizer use in a cropping system therefore can be greatly improved by the proper choice of crop sequence and crop to be supplied with the P. Jiang et al (1982) conducted a study in China on management strategies to make the best use of residual P in a soybean - lowland rice rotation; they concluded that when P fertilizer was applied to the upland soybean crop, the residual effect was sufficient to meet the requirement of the subsequent lowland rice crop. In contrast, applying P to the lowland rice crop gave a residual P insufficient to give maximum yield in the succeeding soybean harvest.

**Uptake of phosphorus**

The inputs of P available for crop removal come from the fertilizer applied, the soil, irrigation water, and rainfall, the last being at no cost to the grower. Phosphorus is removed from the farmer’s field in the form of grain, which usually has a P
concentration on the order of 0.25%, and sometimes in the form of straw. Results in the Annual Report of ACIAR Project 8328 (Lefroy et al. 1988) show P balance sheets for lowland rice crops at two sites, one in Malaysia and the other in Thailand.

At the Barenang site in Malaysia (Table 1), where no P was applied as fertilizer, the net loss to the system was 5.3 kg/ha and 6.9 kg/ha of P where straw was returned and removed, respectively. Where straw was removed, 25, 45, 72, and 86% of the P applied as fertilizer remained for the application rates of 8, 16, 32, and 64 kg P/ha, respectively. The highest level of application, equivalent to 320 kg TSP/ha, is almost certainly too high for any practical recommendation.

The data in Table 2, for the site in Ubon, northeast Thailand, include the P content of the plant material at three levels of applied P and at two levels of applied S. The P was applied as monocalcium phosphate and the S as gypsum. The P contained in rainfall is also included as an input. At this site, 2.2 kg of P was gained through rainfall; this P was predominantly in the organic and solid phase (G.J. Blair, University of New England, Armidale, Australia, 1989, pers. comm.). No information was given on the P input from irrigation water, nor were any data available in

Table 1. Phosphorus balance sheet for rice grown in Barenang, Malaysia, 1988.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>No P</th>
<th>8 kg P/ha</th>
<th>16 kg P/ha</th>
<th>32 kg P/ha</th>
<th>64 kg P/ha</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fertilizer input</td>
<td>0</td>
<td>8</td>
<td>16</td>
<td>32</td>
<td>64</td>
</tr>
<tr>
<td>Straw uptake</td>
<td>1.6</td>
<td>1.7</td>
<td>3.0</td>
<td>3.4</td>
<td>3.8</td>
</tr>
<tr>
<td>Grain uptake</td>
<td>5.3</td>
<td>4.2</td>
<td>5.8</td>
<td>5.4</td>
<td>5.2</td>
</tr>
<tr>
<td>P balance</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Straw returned</td>
<td>–5.3</td>
<td>3.8</td>
<td>10.8</td>
<td>26.5</td>
<td>58.8</td>
</tr>
<tr>
<td>Straw removed</td>
<td>–6.9</td>
<td>2.1</td>
<td>7.2</td>
<td>23.1</td>
<td>55.0</td>
</tr>
</tbody>
</table>


<table>
<thead>
<tr>
<th>Parameter</th>
<th>No P, no S</th>
<th>8 kg P/ha, no S</th>
<th>32 kg P/ha, no S</th>
<th>8 kg P/ha, 32 kg S/ha</th>
<th>32 kg P/ha, 32 kg S/ha</th>
</tr>
</thead>
<tbody>
<tr>
<td>Yield (kg/ha)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Brown rice</td>
<td>1231</td>
<td>1362</td>
<td>947</td>
<td>1348</td>
<td>1133</td>
</tr>
<tr>
<td>Stubble</td>
<td>2141</td>
<td>1757</td>
<td>1368</td>
<td>2816</td>
<td>2152</td>
</tr>
<tr>
<td>Straw + hulls + unfilled grains</td>
<td>1460</td>
<td>1433</td>
<td>1321</td>
<td>3115</td>
<td>1453</td>
</tr>
<tr>
<td>Fertilizer input</td>
<td>0.0</td>
<td>0.0</td>
<td>8.0</td>
<td>8.0</td>
<td>32.0</td>
</tr>
<tr>
<td>Rain</td>
<td>2.2</td>
<td>2.2</td>
<td>2.2</td>
<td>2.2</td>
<td>2.2</td>
</tr>
<tr>
<td>Brown rice</td>
<td>3.0</td>
<td>2.7</td>
<td>3.0</td>
<td>4.2</td>
<td>3.6</td>
</tr>
<tr>
<td>Stubble</td>
<td>2.3</td>
<td>2.8</td>
<td>3.3</td>
<td>6.3</td>
<td>4.8</td>
</tr>
<tr>
<td>Straw + hulls + unfilled grains</td>
<td>1.3</td>
<td>2.2</td>
<td>1.8</td>
<td>4.0</td>
<td>2.2</td>
</tr>
<tr>
<td>Stubble returned</td>
<td>–2.1</td>
<td>–2.7</td>
<td>5.4</td>
<td>2.0</td>
<td>28.2</td>
</tr>
<tr>
<td>Stubble removed</td>
<td>–4.4</td>
<td>–5.5</td>
<td>2.1</td>
<td>–4.3</td>
<td>23.6</td>
</tr>
</tbody>
</table>
the literature. However, the authors consider that important in some cases, especially at the bottom of a terraced system.

These data show at this nonresponsive site that where 160 kg of TSP was applied, only a small proportion of the nutrient was lost from the system. However, should no fertilizer be applied and if the stubble is removed, then the system will run down. In their study in Indonesia, Miyake et al (1984) (Table 3) supported these conclusions. In a study on a P-responsive acid sulfate soil, Do et al (1986a) showed grain removal of 5-14 kg P with an associated uptake of 5-11 kg P in the straw.

**Phosphorus status of the lowland system**

Most soils in Asia are low in native P. They are generally formed in highly leached situations from parent material having low P content. Both P and, to a lesser extent, K are required to support the high yields achievable with the use of MV rice cultivars and N fertilizers. In a recent study on a newly opened ricefield in Indonesia, responses to P were monitored over 7 rice crops, and the residual value in the final 2 yr was measured (Sismiyati, Central Research Institute for Food Crops, Bogor, pers. comm.). The data (Table 4) show responses to applied fertilizer in all seasons with no yield in three of the first four crops when P was not applied. All plots received a basal fertilizer application of N and K. Marked residual effects of the previously applied P were demonstrated by responses on the residual plots.

In some areas, however, with the increased use of P fertilizers in the past 20 yr, the P requirement appears to be declining, especially in areas of intensive production.

In a study of the chemical constraints to rice production in Java and Madura, the Centre for Soil Research (CSR), Bogor, Indonesia, produced the first (1970) edition of a map of the P requirement of rice soils (M. Sudjadi, CSR, pers. comm.). It was estimated that one-half of these soils required P fertilization. The revised edition of this map (Santosa and Sudjadi 1974) indicated that the P-deficient area had decreased to about one-third.

This decrease in the area of P-deficient rice soil is attributed to the result of accumulated fertilizer residues. Through the mass guidance programs practiced in Indonesia, at least 20 kg P/crop has been recommended since mid-1960. The continued practice of this management strategy will no doubt increase the P status of these soils even further. Field experiments conducted by the Soil Research Institute

### Table 3. Yield and P balance from field experiment in Tamanbogo, Lampung, Indonesia (Miyake et al 1984).

<table>
<thead>
<tr>
<th>Parameter</th>
<th>No P</th>
<th>13 kg P/ha</th>
<th>26 kg P/ha</th>
<th>44 kg P/ha</th>
<th>88 kg P/ha</th>
</tr>
</thead>
<tbody>
<tr>
<td>Yield (t/ha)</td>
<td>3.7</td>
<td>3.7</td>
<td>3.5</td>
<td>3.6</td>
<td>3.6</td>
</tr>
<tr>
<td>P uptake (kg/ha)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Grain</td>
<td>9.2</td>
<td>8.3</td>
<td>10.0</td>
<td>9.6</td>
<td>11.4</td>
</tr>
<tr>
<td>Straw</td>
<td>3.5</td>
<td>4.4</td>
<td>4.4</td>
<td>6.5</td>
<td>5.7</td>
</tr>
<tr>
<td>P balance (kg/ha)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Straw returned</td>
<td>−9.2</td>
<td>4.7</td>
<td>16.0</td>
<td>34.4</td>
<td>76.6</td>
</tr>
<tr>
<td>Straw removed</td>
<td>−12.7</td>
<td>0.3</td>
<td>11.6</td>
<td>27.9</td>
<td>70.9</td>
</tr>
</tbody>
</table>
Table 4. Effect of P application\(^a\) on grain yield of lowland rice in Tegalombo, Lampung, Indonesia, 1977-81 (Sismiyati, Central Institute for Food Crops, Bogor, pers. comm.).

<table>
<thead>
<tr>
<th>Season</th>
<th>TSP</th>
<th>HRP</th>
<th>LRP</th>
</tr>
</thead>
<tbody>
<tr>
<td>1977-78 WS</td>
<td>0.9</td>
<td>2.2</td>
<td>3.1</td>
</tr>
<tr>
<td>1978 DS</td>
<td>2.8</td>
<td>5.3</td>
<td>8.8</td>
</tr>
<tr>
<td>1978-79 WS</td>
<td>0.5</td>
<td>2.9</td>
<td>5.3</td>
</tr>
<tr>
<td>1979 DS</td>
<td>1.3</td>
<td>2.1</td>
<td>3.6</td>
</tr>
<tr>
<td>1979-80 WS</td>
<td>0.4</td>
<td>1.4</td>
<td>2.7</td>
</tr>
<tr>
<td>1980 DS</td>
<td>2.5</td>
<td>5.3</td>
<td>10.7</td>
</tr>
<tr>
<td>1980-81 WS</td>
<td>1.9</td>
<td>3.6</td>
<td>6.5</td>
</tr>
</tbody>
</table>

\(^a\)All treatments were provided with 80 kg N/ha and 30 kg K/ha in the wet season (WS) and 140 kg N/ha and 30 kg K/ha in the dry season (DS). TSP = triple superphosphate, HRP = highly reactive phosphate rock, LRP = low reactive phosphate rock.

during the 1987-88 rainy season showed the less frequent occurrence of P responses in rice soils. Analyses of soil samples taken throughout Java further support these findings.

In a recent study in Java and Madura, Moersidi et al (1988) estimated that only 15% of the area has a low P status, whereas 45% and 40% have medium and high status, respectively. These data are presented on a province basis in Table 5; 125 kg of TSP represents the previously recommended rate. In a study on three sites in West Java, three sites in Central Java, and two sites in East Java, Adiningsih et al (1988) showed no increase in yield of lowland rice when P was applied (Table 6). High yields of 5.0-7.8 t of grain were harvested where no P was applied. Of a further five sites in West Java that had been part of the “Supra Insus” or highest intensification scheme, only one site (Karawang) gave a marked response to applied P (Table 7) (Makarim, Central Research Institute for Food Crops, Bogor, pers. comm.).
Table 6. Lowland rice grain yield from P rate trials in Java, Indonesia, 1988 (Adiningsih et al 1988). a

<table>
<thead>
<tr>
<th>P application (percentage of currently recommended rate)</th>
<th>Grain yield (t/ha)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>West Java sites</td>
</tr>
<tr>
<td></td>
<td>1</td>
</tr>
<tr>
<td>0</td>
<td>6.6</td>
</tr>
<tr>
<td>50</td>
<td>6.7</td>
</tr>
<tr>
<td>75</td>
<td>6.5</td>
</tr>
<tr>
<td>100</td>
<td>6.4</td>
</tr>
<tr>
<td>150</td>
<td>6.5</td>
</tr>
<tr>
<td>LSD 0.05</td>
<td>0.3</td>
</tr>
<tr>
<td>CV (%)</td>
<td>3.4</td>
</tr>
</tbody>
</table>

a ns = not significant.

Table 7. Effect of P application on grain yield of lowland rice in the Supra Insus area (5 sites) of West Java, Indonesia, 1987-88 (Makarim, Central Research Institute for Food Crops, Bogor, pars. comm.).

<table>
<thead>
<tr>
<th>Treatment a</th>
<th>Grain yield (t/ha)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Kaliasin</td>
</tr>
<tr>
<td>NK</td>
<td>7.2</td>
</tr>
<tr>
<td>NKP</td>
<td>7.6</td>
</tr>
</tbody>
</table>

a N = 115 kg/ha, K = 40 kg/ha, P = 25 kg/ha.

These data from Indonesia support the hypothesis that there is a reduction in response to applied P after P fertilizers have been used for many years in the lowland cropping system in Java and Madura.

Conclusions

Phosphorus-containing fertilizers have been a major contributor to the increased rice production in Asia. Only a small proportion of the applied P is removed by the rice crop. Methods must be devised to utilize the residual resource. In addition, methods are required to delineate those areas or systems where lower input levels can be recommended without reducing the economic returns to the farmer. Alternate, cheaper fertilizer sources such as PR or partially acidulated PR need to be tested in lowland cropping systems.

More detailed information is required on the level of input through rainfall and irrigation, together with data on any losses through water runoff at inopportune times. A cost should be placed on straw removal, as this results in losses of both mineral nutrients and organic matter.

Ideally, an accurate and inexpensive empirical soil test for fertilizer recommendations is needed.
References cited


Notes

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Citation information: International Rice Research Institute (1990) Phosphorus requirements for sustainable agriculture in Asia and Oceania. P.O. Box 933, Manila, Philippines.
Phosphorus requirements and management in upland rice-based cropping systems

D.P. Garrity, C.P. Mamari, and Goeswono Soepardi

Upland rice is grown predominantly as a subsistence crop on strongly acid Ultisols and Oxisols throughout the humid tropics. The crop's widespread cultivation on acid soils is consistent with its high tolerance for Al toxicity and low P requirement relative to other major cereals. Fertilizer P uptake is generally 5-20% of applied P. Because of these factors and the modest yields usually expected (2-3 t/ha), fertilizer P recommendations for P-deficient Ultisols are often 1520 kg P/ha. On acid soils, rice blast epidemics are promoted by improvements in N and P nutrition. Many studies indicate that phosphate rocks are suitable replacement sources of P for upland rice-based cropping systems on acid soils. Banding P fertilizer with seed has been more effective than broadcasting in some environments. On high P-fixing soils, however, dense banding may be disadvantageous. Crop rotation is critical to the sustainability of upland rice-based systems. The development of acid-tolerant cultivars of all component crops will reduce P requirements. Much more work is needed to integrate legumes, including hedgerow tree legumes and forages, into the cropping system, with attention to their effects on P cycling to the cereal crop.

The accelerating rate of ecological degradation in the humid tropics is generating a growing wave of global concern. The tropical uplands are a development frontier witnessing the rapid immigration of large numbers of settlers and the expansion of indigenous populations. Most are small-scale farm families with few resources, but with a fundamental subsistence food requirement that can be met only from their own farming efforts.

Upland rice fits into prevailing agricultural systems as a dominant source of carbohydrate for subsistence. The crop is grown predominantly for home consumption, and very little is sold for cash, except in Brazil. Upland rice production systems span the humid and subhumid tropics. Of the total estimated area of 20.4 million ha (Van 1986), more than half is in Asia (11.5 million ha), 10% in Africa, and one-third in Latin America.

The vast majority of upland rice is grown on strongly acid Ultisols and Oxisols. Thus, the management of P for upland rice-based cropping systems is largely a matter of coping with the problems of highly P-deficient soils, most of which also have a high P-fixing capacity.
Some of the best minds in agricultural science have long been baffled by the challenge of developing ecologically and economically sustainable permanent food-crop farming systems in the acid P-deficient uplands of the tropics. Fortunately, there has been a substantial increase in research attention in this domain during the past decade.

A number of recent reviews have dealt with the overall management considerations for P in acid humid tropical soils (Arca 1985, Fox 1988, Sanchez 1985, Sanchez and Uehara 1980). We will review P management as related specifically to upland rice-based systems on soils considered typical of the acid infertile upland production zones. This includes about two-thirds of the world area. Because upland rice is a commodity that fills a subsistence niche, we will focus on the ways in which P nutrition and cycling can be enhanced with modest external fertilizer input.

The upland rice soil environment

The vast majority of the world’s upland rice is found on Ultisols, Oxisols, and Andepts. In Southeast Asia (4.7 million ha of upland rice), a correlation between soils and production zones indicates that upland rice is confined mainly to these soils (Garrity 1984). This is also largely true for Latin America (6.1 million ha). Brazilian upland rice (>5 million ha) is grown predominantly on the Oxisols and Ultisols of the acid savannas (cerrado) and the Amazon basin.

In West Africa, most upland rice occupies the belt of Ultisols that stretches from the Ivory Coast to Guinea (Moormann and Veldkamp 1978). Significant areas of production also occur on Alfisols derived from acidic rocks, which are P deficient but may have low P-fixing capacity. In South Asia, the crop occupies considerable areas of P-deficient Alfisols in addition to Ultisols (Garrity 1984).

Table 1 compares soil chemical properties for a number of sites throughout the tropics that were used for the discussion of P management in upland rice-based systems in this paper. Very low P availability is a common feature of these locations, often associated with strong acidity and high levels of exchangeable A1. Multiple macro- and micronutrient deficiencies such as Ca and Mg are also indicated in many cases.

The widespread cultivation of upland rice on acid infertile soils is consistent with our knowledge of the crop’s nutrient requirements. Among the major cereals, rice is the most tolerant of high concentrations of exchangeable A1. Tolerance for A1 toxicity and for low soil P are strongly1 related. Upland rice requires much less P than maize, sorghum, or millet (Sanchez and Uehara 1980). The external requirement for P in the soil solution that enables upland rice to produce 85% of maximum yields was reported as 0.03 ppm in an Oxisol, compared with 0.06 ppm for maize. Recommended P application rates for upland rice are often much lower than those for maize. Farmers in southern Philippines indicate that upland rice and cassava are grown when unfertilized acid soils can no longer produce maize (Fujisaka and Garrity 1988). Cassava and sweet potato also have low external P requirements.
Table 1. Topsoil chemical properties of several acid upland research locations in Asia, Latin America, and Africa.

<table>
<thead>
<tr>
<th>Acid upland site</th>
<th>pH (H₂O)</th>
<th>Organic C (%)</th>
<th>Bray II P (ppm)</th>
<th>Exchangeable cations (meq/100 g)</th>
<th>Exchangeable Al (meq/100 g)</th>
<th>Effective CEC (meq/100 g)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>K</td>
<td>Ca</td>
<td>Mg</td>
</tr>
<tr>
<td>Way Abung, Sumatra, Indonesia</td>
<td>4.71</td>
<td>–</td>
<td>4.8</td>
<td>0.11</td>
<td>0.46</td>
<td>0.31</td>
</tr>
<tr>
<td>Sitiung Sumatra, Indonesia</td>
<td>5.11</td>
<td>2.70</td>
<td>0.8</td>
<td>0.08</td>
<td>1.29</td>
<td>0.30</td>
</tr>
<tr>
<td>Cavinti, Luzon, Philippines</td>
<td>4.40</td>
<td>3.63</td>
<td>5.8</td>
<td>0.44</td>
<td>1.05</td>
<td>1.27</td>
</tr>
<tr>
<td>Claveria, Mindanao, Philippines</td>
<td>4.10</td>
<td>1.84</td>
<td>9.8</td>
<td>0.10</td>
<td>2.74</td>
<td>0.69</td>
</tr>
<tr>
<td>Yurimaguas, Peru a</td>
<td>4.20</td>
<td>–</td>
<td>14.0</td>
<td>0.15</td>
<td>1.30</td>
<td>0.40</td>
</tr>
<tr>
<td>CPAC, Planaltina, Brazil</td>
<td>4.6</td>
<td>2.10</td>
<td>&lt;1.0</td>
<td>0.03</td>
<td>0.31</td>
<td>–</td>
</tr>
<tr>
<td>Onne, Nigeria</td>
<td>4.7</td>
<td>1.42</td>
<td>11.1</td>
<td>0.10</td>
<td>0.44</td>
<td>0.16</td>
</tr>
<tr>
<td>Suakoko, Liberia</td>
<td>4.5</td>
<td>–</td>
<td>–</td>
<td>0.40</td>
<td>0.70</td>
<td>0.20</td>
</tr>
</tbody>
</table>

a Immediately after clearing; P is modified Olsen procedure.

Some form of fallow rotation is commonly employed in upland rice-based cropping systems on acid infertile soils. Crops grown as intercrops with rice or in sequence with rice vary greatly, but the dominant systems include cereals (maize) and root crops (e.g., cassava, sweet potato, or yam). Many studies have confirmed the wisdom of cropping for only limited periods of time and shifting to new fields to allow the land to undergo a fallow period. Available soil P increases after the burning of fallow vegetation but may rapidly fall to low levels after one or more cropping cycles. Inability to control the invasion of grass weeds in these systems may be an even greater spur to eventually allow a fallow period.

The average upland rice yield in Africa is only 0.5 t/ha (Van 1986). The average is 1.0 t/ha in Asia and 1.1 t/ha in Latin America. Risk is an important element of upland rice production systems. Drought stress is a common threat present even in high rainfall zones because the plant’s root system is shallow. In high-Al soils, this problem is exacerbated by even shallower root penetration. Therefore, water is often the most limiting nutrient, even when more than 2,000 mm of rainfall is received during the growing season. Rice blast disease caused by *Magnaporthe grisea* (*Pyricularia oryzae*) is a dominant threat, for which adequate genetic or management control is still unavailable in most environments. Epidemic blast infection is strongly promoted as crop N and P nutrition are improved (Fig. 1), often reversing the benefits of fertilization.

Given these uncertainties, it is unrealistic in most cases to target high yields in upland rice-based farming systems. But there is a strong imperative to develop
practical means to sustain productivity as farmers undergo the transition to permanent cropping, and to raise and stabilize yields substantially when permanent husbandry is practiced.

Phosphorus removal and cycling

The P uptake requirements of upland rice and of the annual cropping sequence are not large under prevailing conditions, but recovery of applied fertilizer P in the biomass is very low. Fageria et al (1982) observed a total P uptake of 4-5 kg in upland rice crops yielding 4 t/ha on a Brazilian Oxisol. Garrity and Tamisin (unpubl. data, 1986) found that the P uptake of unfertilized upland rice averaged 2.8 kg P/ha on a high P-fixing Ultisol in the Philippines (Table 2). This increased to 5.3-7.0 kg P/ha uptake with a 40 kg P/ha application, or with 20 kg P/ha plus lime and manure. The apparent recovery varied between 5 and 16% (Table 2), consistent with results from several other crops (Malavolta and Neptune 1977).

In long-term experiments with a rice - rice - cowpea sequence in Yurimaguas, Peru, Sanchez and Benitez (1987) observed that P appeared to be particularly...
Table 2. Cumulative P uptake and productivity of upland rim grown over a 4-yr period (1985-88) on a high P-fixing Ultisol,\textsuperscript{a} 1 crop per year, Cavinti, Laguna, Philippines (Garrity and Tamisín, unpubl. data).

<table>
<thead>
<tr>
<th>Treatment</th>
<th>Total P applied (kg/ha)</th>
<th>Total P uptake (kg/ha)</th>
<th>Apparent P recovery (%)</th>
<th>Total dry matter (t/ha)</th>
<th>Total grain yield\textsuperscript{b} (t/ha)</th>
<th>Extractable soil P\textsuperscript{c} (Bray II) (ppm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 Control</td>
<td>0</td>
<td>11.24</td>
<td>0</td>
<td>14.18</td>
<td>4.6</td>
<td>4.4</td>
</tr>
<tr>
<td>2 35 kg N/ha</td>
<td>0</td>
<td>9.29</td>
<td>0</td>
<td>12.21</td>
<td>3.5</td>
<td>4.5</td>
</tr>
<tr>
<td>3 70 kg N/ha</td>
<td>0</td>
<td>8.90</td>
<td>0</td>
<td>11.39</td>
<td>3.1</td>
<td>4.2</td>
</tr>
<tr>
<td>4 70 kg N/ha + 20 kg K/ha</td>
<td>80</td>
<td>15.94</td>
<td>5.9</td>
<td>19.31</td>
<td>5.4</td>
<td>6.6</td>
</tr>
<tr>
<td>5 35 kg N/ha + 10 kg P/ha</td>
<td>40</td>
<td>16.19</td>
<td>12.4</td>
<td>20.35</td>
<td>6.0</td>
<td>5.6</td>
</tr>
<tr>
<td>+ 10 kg K/ha</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>6 70 kg N/ha + 20 kg P/ha + 20 kg K/ha</td>
<td>80</td>
<td>20.18</td>
<td>11.2</td>
<td>22.23</td>
<td>6.1</td>
<td>6.6</td>
</tr>
<tr>
<td>7 35 kg N/ha + 40 kg P\textsuperscript{d}/ha + 20 kg K/ha + 0.5 t lime/ha</td>
<td>120</td>
<td>21.21</td>
<td>8.3</td>
<td>21.99</td>
<td>7.2</td>
<td>7.0</td>
</tr>
<tr>
<td>8 70 kg N/ha + 20 kg P/ha + 20 kg K/ha + 4 t lime/ha</td>
<td>80</td>
<td>23.40</td>
<td>15.2</td>
<td>24.74</td>
<td>7.0</td>
<td>6.8</td>
</tr>
<tr>
<td>9 T8 + 3 t manure/ha</td>
<td>180</td>
<td>27.95</td>
<td>9.3</td>
<td>29.09</td>
<td>6.4</td>
<td>13.0</td>
</tr>
</tbody>
</table>

\textsuperscript{a} Soil chemical properties in Table 1. \textsuperscript{b} Severe panicle blast in T3-T9 in all years. \textsuperscript{c} After 3 crop years. \textsuperscript{d} 20 kg P/ha applied during first 2 yr.

Problematic, because about two-thirds of the crop uptake was removed in the harvested grain. The amounts of nutrients accumulated by seven consecutive crops were determined. When crop residues were returned to the field, 54% of the N, 70% of the Mg, 89% of the K, and 95% of the Ca were recycled, but only 38% of the P was. The difficulty of maintaining adequate available soil P in a highly P-deficient agroecosystem without significant external input is readily apparent because P has the lowest recycling percentage among the major crop nutrients.

Application of small or moderate amounts of P appears to be a realistic strategy with a high marginal return for low-cash-flow farming. Fertilizer P recommendations for upland rice range from 15 to 20 kg P/ha on P-deficient Ultisols in a number of Asian countries (Santoso et al 1988) and in West Africa (Kang 1987).

Inexpensive phosphorus sources

The economic attractiveness of P fertilization on strongly acidic soils can be greatly enhanced by the direct use of phosphate rock (PR) in place of ordinary superphosphate. A considerable body of research in a number of countries points consistently to the economic advantage of PR as a P source for upland rice and other field crops. The findings are significant because PR usually costs one-third to one-fifth the price of superphosphate per unit of P applied.

Several PR sources were compared with triple superphosphate (TSP) over four growing seasons on upland rice at several locations on Ultisols and Oxisols in Sumatra (Adiningsih et al 1988). The yield response with Indonesian PR was
85-114% of that with TSP. Yields with Tunisia ground PR were higher than with TSP in 3 of 4 yr. The superiority of PR was also observed on soybean. Sediyarso and Suharto (1984) found that the response of both peanut and upland rice to PR was the same as that to TSP or diammonium phosphate (DAP) in greenhouse studies on Ultisols from three other locations in Indonesia.

Briones and Vicente (1985) observed the response of upland rice and maize to a Philippine source of apatite PR and to single superphosphate (SSP) at various P levels on a P-deficient (1.1 ppm Bray II) Dystrandept soil in the Philippines. The response of upland rice to P applied as SSP, partially acidulated phosphate rock (PAPR), finely ground PR, and minigranulated PR did not significantly differ. The maize response was similar, except that SSP was superior at 40 kg P/ha.

In Leyte, Philippines, the yield response of upland rice and maize (Atienza 1989) to indigenous deposits of PR containing 30% P and to superphosphate was significant and very similar.

Even in zero-tillage systems in the Amazonian tropics, PR is an efficient P source for upland rice and cowpea in rotation (Gicheru and Sanchez 1988). In a zero-tillage system, fertilizer P must be surface applied without incorporation. Sechura PR was as effective as superphosphate in supplying available P over seven crop seasons, with or without tillage and incorporation. Belcher and Ragland (1972) earlier observed that superphosphate surface-applied in a no-tillage system was as effective as P incorporated into the soil.

Low-solubility PRs have shown poor performance even in strongly acid soils (Sanchez and Uehara 1980). They often exhibit substantial residual effects on succeeding crops but cannot supply the P demand of the crops grown immediately after application. In such cases, these materials may be successfully used if initially combined with superphosphate (Smyth and Sanchez 1982).

On the farm, the effectiveness of PR is disappointing if it is not finely ground. Reactivity increases with fineness of particles down to 100-mesh size. Maintaining quality control in this aspect is crucial to sustaining interest among farmers in the use of PR.

Partial acidulation of PR is an intermediate alternative to direct application. Sudjadi et al (1984) found that PAPR was more effective than TSP across a range of P application levels. Yield responses were also observed in India (Panda and Misra 1970) and elsewhere. However, the poor physical properties of PAPR are a distinct limitation to their use (Engelstad and Russel 1975).

The accumulated evidence on the utility of PR leads to the question of how tropical countries with indigenous PR reserves can best utilize them commercially. Enough data may exist for defining extrapolation domains for PR use; however, much more research is needed to fine-tune application recommendations.

**Optimum methods of phosphorus placement**

In limited-cash-flow, upland rice-based farming systems. P application rates will necessarily be modest, usually less than 40 kg P/ha. Thus, there is much interest
in the possibility that more concentrated placement of the fertilizer will reduce P fixation rates and improve P recovery by the crop.

Crops require more P during the early growth stages than toward maturity. Maize, for example, requires 0.2 ppm P in the soil solution during the initial phases, but only 0.06 ppm P later on. Banded P may be accessible to the plant earlier and at greater concentrations. But in soils containing very low levels of P, the roots may be confined to a smaller soil volume than would be the case if the P were spread more diffusely. Singh et al (1988) observed that 95% of the root system of upland rice was confined within a 125-cm³ volume of soil when P was banded on a soil of very low available P.

Wade et al (1987) conducted several studies comparing broadcast and banded P (with the seed, near the seed, and between rows) at rates up to 80 kg P/ha in Situng, Sumatra, Indonesia. Application method did not influence yields of peanut, soybean, and maize. Rice did not respond differentially to the P that was applied to the previous crops by the four methods.

Band placement of 10-15 kg P/ha in the row with the seed on upland rice in southern Sumatra produced near maximum yields.

In Sarawak, Malaysia, where rice is dibbled on steep slopes, DAP was extensively tested as a seed dressing in planting holes at 0.36 kg/kg seed (Liong 1987). All 53 trials over several years showed a positive response, with an average yield increase of 28% and a cost-to-benefit ratio of 1:94.

Banded P in Yurimaguas, Peru, increased maize grain yields over broadcast P (McCollum et al 1987). With banding, plant population markedly increased under acid soil conditions, which consistently prevented establishment of an adequate crop stand. In Manaus, Brazil, band application of 22 kg P/ha per crop of maize or cowpea was as good as or better than a single broadcast application of 176 kg P/ha for 4 crops (Smyth et al 1987); most farmers preferred banding P since crops are planted by hand.

In the Brazilian Cerrado, Yost et al (1979) observed superior maize yields with broadcast P compared with banded P at rates as low as 70 kg P/ha. Root measurements were not taken but they surmised that the plants in broadcast P treatments had more uniformly distributed root systems, which enabled them to better withstand a drought stress period. Fox (1988) argued that fertilizer in band is inefficiently utilized because the P concentration in the soil solution may exceed the root capacity for uptake in the band, and a low proportion of total root surface area is accessible to the band.

Barber (1977) found that P banded densely was not as effective as that applied in more diffuse bands in a larger volume of soil. He speculated that banding may be more effective with crops having close row spacing (e.g., rice) than with those having wide rows, such as maize. In numerous closely spaced rows, a higher proportion of the soil volume is fertilized.

Soil management practices are needed to promote deeper rooting of all crops in strongly acid soils. Because drought stress is common in many areas, the implications of banding for root development need direct study. The diverse results and limited data on P placement on acid soils in the humid tropics defy generalization at present. A satisfactory predictive theory on the utility of banding awaits more comprehensive treatment of the numerous interactive environmental factors. But as Adiningsih et al
(1988) noted, banding P incurs a labor cost up to 10 times that for broadcasting P; therefore it is not practicable unless it consistently outperforms broadcasting. In the meantime, the degree of success it has shown in several studies indicates that it has definite value under some conditions.

**Management of phosphorus in relation to other nutrients**

Phosphorus interacts with a number of other elements in ways that have quite important implications. We review three of these interactions.

**Lime × phosphorus interactions**

Applying lime to strongly acid soils neutralizes the exchangeable Al and may increase soil P availability. To bolster P availability liming is often less expensive than increasing P fertilization. Liming is often highly advantageous for annual crops produced on Ultisols and Oxisols with an Al saturation exceeding 30%, but rice is relatively tolerant of high Al, and its response to lime is inconsistent and of less economic importance. Rice strongly responded to P application in two 2-yr studies in

2. Effects of P, lime (L), and previous crop residue (R) incorporation on grain yield in an upland rice - maize cropping sequence, Claveria, Mindanao, Philippines (Magbanua et al 1988).
Claveria, Mindanao, Philippines (IRRI 1986, Magbanua et al 1988a) but did not respond to lime in the presence or absence of P application (Fig. 2). However, the yield of maize following upland rice was increased by both lime and P. In a third study, deep incorporation of lime produced a positive yield response on rice (Magbanua et al 1987).

The interaction between lime and three sources of P—TSP, PR, and fused magnesium phosphate (FMP)—was evaluated on upland rice at three sites in the Philippines (C.P. Mamaril, D. Estrella, and R. Rosales, unpubl. data). The soil pH at the sites ranged from 4.3 to 5.4, and available P (Bray 11) ranged from 6.7 to 14 ppm. The PRs used were Christmas Island (15.2% P), Citaraphos (13.2% P), and Morocco (14.5% P). Lime was applied at 0.75 and 1.5 t/ha in the row near the drilled seeds. The average yield advantage over the control increased in successive years (Fig. 3). The response to TSP was improved when TSP was combined with 0.75 t lime/ha. There was no further advantage from 1.5 t lime/ha. FMP performed poorly compared with TSP. Lime did not interact positively with FMP. The PR sources gave slightly lower yields than TSP during the first and second years. With time, however, rice yields increased with increasing levels of PR. Yields gradually increased over three consecutive years of liming.

### Silicon × phosphorus interactions

Silicate applications also decrease P fixation and increase P uptake on some strongly acid soils. The application of rice hulls (20% silica) or hull ash (95% silica) increased the dry matter yield of upland rice on an Ultisol with very high P fixation capacity in Cavinti, Laguna, Philippines (D. P. Garrity and M. Tamisin, unpubl. data).

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**Figure 3.** Average yield increase over control for the various treatments in the International Network on Soil Fertility and Sustainable Rice Farming (INSURF) P × lime interaction trial at 3 sites in the Philippines.
amendments did not increase the Si concentration in the soil or in the rice plants. Thus, the positive growth effects may have been partially due to increased P availability. The possible benefit of silica in reducing rice blast is another factor indicating that more research on silica application is needed.

**Nitrogen × phosphorus interactions**

The balance between N and P application on highly P-deficient soils is a matter of considerable importance. Nitrogen is often deficient in acid upland soils, but when P is more limiting we observe that N application alone may actually reduce upland rice biomass and grain yield compared with no fertilization (Fig. 1). This observation was consistent over 4 yr of trials (Table 2).

Improved plant nutrition drastically increases rice blast epidemics. Perhaps blast infection can be reduced through manipulating the balance between applied N and P by elevating the P availability relative to N. There is much circumstantial evidence, and recently some controlled experimental observations, showing that blast infection is enhanced in plants growing on P-deficient soils. Due to the immense impact of blast, these issues require more research.

**Exploiting the mycorrhizal complex**

The symbiosis between mycorrhiza and the roots of many crop plants is known to be crucial to the uptake of adequate amounts of P from low-P soils. Upland rice is no exception, but there is scant knowledge of how the vesicular-arbuscular mycorrhiza (VAM) fungi that infect the roots can be manipulated to further enhance P uptake.

Luis and Brown (1986) found that seed inoculation with *Glomus mosseae* or *G. fasciculatum* VAM species on a highly P-deficient Ultisol in the Philippines consistently increased upland rice dry matter and grain yield by 50-100% in a 2-yr study with no P application. *G. fasciculatum* inoculation elicited a similar response with 15 kg P/ha in 2 yr of field trials. *G. mosseae* inoculation also increased maize yields 28% in experiments conducted in Mindanao, Philippines (Khadge 1988).

Mycorrhizal inoculation in high P-fixing soils offers the possibility of decreasing P fertilizer requirements. However, exploitation of this opportunity requires the development of new technology to efficiently multiply and maintain pure cultures of VAM species.

**Acid-tolerant crops and cultivars**

Selection of cultivars that can produce superior yields in soils with a low-P soil test can be one of the most important tools in cost-efficient P management. A fast-growing body of evidence shows that superior acid soil tolerance is a genetic character complex in many crops with considerable potential for enhancement. In rice, worldwide attention is focusing on upland japonica germplasm as a superior source of adaptation to acid soils (Arraudeau et al 1988). Improved cultivars of japonica/japonica crosses (e.g., IR47686-6-2-1) now available combine high levels of blast resistance and
Phosphorus in upland rice systems

343

superior yield with low or moderate P levels in strongly acid soils. Work at the Centro Internacional de Agricultura Tropical and International Institute of Tropical Agriculture (IITA) is also making strong progress in this direction.

But crop rotation is important on acid soils, and upland rice is virtually never grown sequentially as a monocrop system. When this was attempted (Sanchez 1983), a disastrous loss in productivity resulted, even when full fertilization practices were employed. Acid-tolerant cultivars of all the important crops grown in association with rice are needed, particularly the grain legume crops. Such cultivars are not available on a significant scale.

Developing successful cereal - legume rotations for acid upland areas is one of the major challenges of the coming decade. Cowpea cultivars originating from IITA with 60-d maturity (e.g., IT82D-889) have shown outstanding potential for acid soils in Southeast Asia (Torres et al 1989). The rhizobial nodulation and productivity of cowpea exceeded that of soybean and mungbean. Stable rice - cowpea rotations in the Amazonian tropics include IITA cowpea selections (Gicheru and Sanchez 1988).

Phosphorus management and system sustainability

The sustainability of food crop systems on acid upland soils remains a difficult issue. But little evidence is available by which to evaluate it.

Longer term rotation experiments

The management of nutrients on a system basis rather than on a crop basis will have to receive more in-depth investigation to maximize the efficiency of nutrient use and to explore how or even whether productivity can be sustained indefinitely. McIntosh et al (1981) found that with balanced crop nutrition, high productivity could be maintained on a strongly acid soil in southern Sumatra with a cropping pattern that included as many as five crops per year: upland rice intercropped with maize and cassava, followed by peanut followed by rice bean. The rice - maize - cassava combination is a common system in the uplands throughout Indonesia. The fertilizer P inputs, applied independently to each crop, totaled 109 kg P/ha per yr. The system maintained an average total production of 18.4 t rice yield equivalent/ha per yr (Fig. 4), an exceptional level of output for an upland environment.

The work of the Tropsoils group in the humid Peruvian Amazon indicates that soil testing will be critical to appropriate fertilizer formulation in many areas. Sanchez (1983) reported that it initially took 5 yr to develop a full fertilizer regimen to sustain production in an upland rice-based system after forest clearing; and the sustainability of the system remained a question, even when the nutrient and weed management problems were overcome with substantial cash and labor inputs. Long-term productivity may have been even more threatened by the degradation of the soil physical properties as a result of tillage and erosion. He concluded that it may be more difficult to correct these constraints. Therefore, the low-input approach being developed relies on zero tillage (Gicheru and Sanchez 1988).
Biological phosphorus cycling

Finally, there is the issue of whether the cropping system can be biologically reconstructed to restrict the loss or removal of P, and to concentrate labile P to the maximum extent in the surface soil layer where the annual crops can gain access to it. The importance of returning all crop residues to the soil has been emphasized by several research groups (e.g., McCollum et al 1987, McIntosh et al 1981). In the long run, the value of returning residues may be substantial (Fig. 4). The problems are that farmers often have an immediate profitable use for the residues as animal fodder: they may have difficulty soil-incorporating residues in animal-powered systems: and the effect of residue application is often not apparent on a crop-to-crop basis in the short run. Magbanua et al (1988) found that residue application depressed yields and reduced fertilizer P response in the second year of a rice - maize rotation, presumably through N or P immobilization, but interacted positively with P fertilizer in the third year (Fig. 2).

The effects of associating deeper rooted perennial legumes, either trees or forage crops, with food crops in hedgerow or alley cropping systems are receiving much attention. Research interest in these legumes is almost exclusively directed toward N cycling. However, in acid upland environments, the effects of deep-rooted legumes on the P cycle of the agroecosystem may be even more significant.

Likewise, interest has been widely stimulated in the integration of forage legumes in annual crop rotations as improved fallow vegetation for soil regeneration (Bandy and Sanchez 1981, Sanchez et al 1987), or as dry season cover crops for fodder and green manure (Aggarwal and Garrity 1987). The capacity of these crops to supply N to the succeeding cereal has proven to be substantial, but their role in P cycling also needs much more investigation.

4. Total annual crop yields of an intensive cropping system composed of upland rice intercropped with maize and cassava, followed by peanut followed by rice bean. Bandarjaya, Central Lampung (adapted from McIntosh et al 1981).
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Notes

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Acknowledgment: The authors wish to express their appreciation to Mr. Roger Magbanua and Ms. Glorylyn Acaylar for their assistance in literature compilation and manuscript compilation.

Citation information: International Rice Research Institute (1990) Phosphorus requirements for sustainable agriculture in Asia and Oceania. P.O. Box 933, Manila, Philippines.
Phosphorus requirements and management of maize, sorghum, and wheat

N.N. Goswami, M.B. Kamath, and Djoko Santosono

Maize, wheat, and sorghum are major upland cereal crops; the first two are normally grown with irrigation, while sorghum is essentially a rainfed crop and is extensively grown in dryland fields in India. Phosphorus uptake per ton of grain produced is around 4.4 kg, and the fertilizer P requirement to meet this level of nutrient may well be 26-66 kg P/ha or more, depending upon the native soil supply and the extent of P deficiency, the yield potential, and climatic conditions. Fertilizer P is a costly input, and its utilization by a single crop is often less than 20%, particularly in soils with high P-fixing capacity such as Vertisols, Oxisols, and Alfisols, and under conditions of low pH, high calcium carbonate, or high sesquioxide content. Phosphorus management is essentially a soil problem, and for maximum benefits from P application the concept of cropping system should be adopted instead of the single-crop approach. The critical level of P in the soils, below which a profitable response to applied P is most probable, varies with both soil and crop, and there are reports of varietal differences in P utilization. An ideal P management strategy should make fertilizer recommendations based on soil tests, nutrient balance, and interactions; correct deficiencies of other nutrients; ameliorate soil acidity; and adopt agronomic techniques such as band placement of fertilizer P.

Phosphorus contents of plants vary with species and the age and nature of plant tissues; they are generally between 0.1 and 1.2% in the dry matter.

The P requirements of cultivated crop plants are high right from the early growth stages, and by and large the P uptake by crop plants is complete toward the end of maximum growth. Cultivated field crops have an annual requirement of between 18 and 53 kg P/ha, depending on soil, climate, and yield potential.

It is important to know the quantity of P required by a crop to produce a unit yield. This provides an estimate of the net demand for P by the crop on the soil-fertilizer complex. For most grain crops, both straw and grain are removed from the field, and the uptake of nutrients is about equal to crop removal.

Maize Zea mays L., indigenous to North America, is now grown throughout the world. It is one of the most efficient crops in converting sunlight into food or animal feed, and it ranks in area and production next only to wheat and rice among the field crops of the world. Maize occupies some 33 million ha in the United States and about 118 million ha worldwide. In India, maize is an important cereal, and both its area and production have steadily increased during the past three decades, reaching 5.3 million ha with a production of 6.5 million t during 1987. In Indonesia, maize is
grown on more than 3 million ha, often unirrigated, in upland fields or off-season ricefields, with a production of about 4.5 million t.

Sorghum *Sorghum vulgare*, known as *jowar* in India, is an important food and fodder crop in dryland agriculture. It is grown on about 18 million ha, with an annual production of 8-10 million t. The ability of sorghum to tolerate drought makes it suitable for regions where the yield of other cereals such as maize is not assured.

In terms of production, wheat *Triticum aestivum* L. occupies first place among world food crops. In India, it is the second most important cereal crop after rice, and it contributes about 25% to the total foodgrain production of the country; in 1987, the area under wheat was 22.8 million ha, and total production was about 45 million t.

**Phosphorus requirements**

Tandon (1987) compiled data for average P uptake per unit of grain production for different crops (Table 1). Based on a large number of data from multilocation experiments in India, Velayutham and Reddy (1987) gave the average P uptake as 6.1, 3.8, and 5.8 kg P/t of produce (grain) for maize, wheat, and sorghum, respectively. The data given by Tandon (1987) and Velayutham and Reddy (1987) differ rather widely for sorghum. Such differences are expected because of variations in yield, variety, location, and other soil and environmental factors. Phosphorus requirements appear to be in the order maize > sorghum > wheat, with an overall average of 4.4 kg grain/ t (Tandon 1987). Assuming 4 t/ha as a moderately good yield, the P uptake would be around 18 kg P/ha.

A clear distinction should be made, however, between nutrient uptake and removal, and nutrient requirement. While nutrient removal refers to the amount of nutrient obtained in the harvested portion of the crop, nutrient uptake refers to the amount that has been absorbed by the plant, including that portion of the plant that is not harvested. Since the P concentration in the straw/stover/stalk is much lower than that in the grain, there might not be much difference between uptake and removal. However, the crop P requirement of added fertilizer also takes into account the soil P supply and its contribution, and the efficiency of P fertilizer in a given soil-climate environment. For example, Singh et al (1976) reported that for a similar yield response of wheat to P, 53 kg P/ ha would be required on a high P-fixing soil as against 26 kg P/ ha on a low P-fixing soil; and Sharma and De (1974) concluded that to obtain a yield response of 1 t/ha, 18 kg P/ha was required on a soil having 15 kg

<table>
<thead>
<tr>
<th>Crop</th>
<th>P uptake (kg/t grain)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Range</td>
</tr>
<tr>
<td>Maize</td>
<td>3.6-6.9</td>
</tr>
<tr>
<td>Wheat</td>
<td>2.8-4.9</td>
</tr>
<tr>
<td>Sorghum</td>
<td>2.2-6.2</td>
</tr>
</tbody>
</table>
available P (Olsen)/ha as against 35 kg P/ha on a soil with 7.5 kg available P (Olsen)/ha. Sudjadi (1988) reported that maximum yields of maize were not reached until well over 88 kg P/ha was applied in West Sumatra.

**Crop responses to phosphorus application**

Reviewing Indian work, Tandon (1987) concluded: “Yield increases brought about by P application in India are widespread, significant and economically attractive. There is a large mass of data on this subject covering all the important crops and various agroclimatic regions of the country.” Yield responses to P have been obtained both at experiment stations and in numerous trials on farmers’ fields (Table 2) (AICARP 1985a,b; Nambiar and Ghosh 1984; Pillai et al 1985; Randhawa and Tandon 1982). Some of these results have been obtained with improved varieties grown with irrigation or assured rainfall. Results from fertilizer experiments on farmers’ fields are now increasingly used to compute the magnitude of yield responses to P, measures of additional production expected per unit of P applied, and their economics.

At research stations, application of 26 kg P/ha to wheat gave 1.2-1.8 t/ha extra yields over N alone (Bhardwaj 1978). Data from coordinated wheat experiments show that even at 35 kg P/ha, response to P was on the order of 26 to 35 kg grain/ kg P. In an earlier analysis (Tandon 1986) based on 6,900 trials, P accounted for 35% of the total yield increase brought about by NPK application, which was 10% over the unfertilized control. The overall guideline used in India for planning cereal production is 9-10 kg grain/kg nutrient applied.

Singh et al (1981) observed a mean optimum level of 18 kg P/ha for rainfed sorghum in India. The overall magnitude of response was in the order Altisols > Entisols > Vertisols. The response to P was as high as 73.5 kg grain/kg P in an Alfisol. In contrast, Tandon and Kanwar (1984) observed that under good management at an available P level of 5.8-7.0 kg/ha, a yield of 3.540 t/ha could be obtained on an Entisol, but only 1 t/ha on an Alfisol; in both cases, additional yield could be obtained with P application in the presence of adequate N.

**Factors influencing phosphorus uptake and utilization**

Several soil and plant factors affect P utilization. These include the P fertility status of the soil, cultivar, and adequacy of other macro- and micronutrients.

**Table 2. Average yield responses to P in trials on farmers’ fields in India (Tandon 1987).**

<table>
<thead>
<tr>
<th>Crop</th>
<th>Season and irrigation status</th>
<th>Trials (no.)</th>
<th>Yield without fertilizer (t/ha)</th>
<th>Yield response (t/ha) to 26.4 kg P/ha</th>
<th>Yield response (kg grain/kg P)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maize</td>
<td>Kharif, irrigated</td>
<td>354</td>
<td>1.67</td>
<td>0.62</td>
<td>23.4</td>
</tr>
<tr>
<td>Maize</td>
<td>Rabi, irrigated</td>
<td>179</td>
<td>1.60</td>
<td>0.66</td>
<td>25.0</td>
</tr>
<tr>
<td>Wheat</td>
<td>Rabi, irrigated</td>
<td>10,133</td>
<td>1.55</td>
<td>0.57</td>
<td>21.6</td>
</tr>
<tr>
<td>Sorghum</td>
<td>Kharif, unirrigated</td>
<td>288</td>
<td>1.27</td>
<td>0.32</td>
<td>12.0</td>
</tr>
</tbody>
</table>
Maize

Oza et al (1977) tested several maize cultivars in both field and pot to study their relative efficiency in utilizing applied P and adapting to salinity and waterlogging. Maize hybrid Deccan could feed mainly on fertilizer P, while Ganga Safed-2 and Ganga 5 utilized soil P more efficiently. Genotype differences in P absorption or utilization might be exploited to improve fertilizer use efficiency or to obtain higher productivity of P-deficient soils (Table 3). Elliott and Lauchli (1985) determined the rates of P absorption, accumulation, and utilization by 15 inbred maize lines at 3 P supply levels using nutrient solution; they reported significant differences among genotypes in P utilization but not in rate of P absorption by roots. Phosphorus utilization was negatively correlated with the ratio of inorganic P accumulation rate to total P accumulation rate, indicating that P utilization is limited by partitioning of P between free orthophosphate and organically combined forms. Absorption of P by roots and utilization of P in shoots were positively correlated. Iron deficiency occurred with all genotypes. Phosphorus-induced Fe deficiency in maize evidently involves both inhibition of Fe absorption by roots and inhibition of Fe transport from roots to shoots.

Root activity and rooting systems of crops have been found to influence nutrient uptake by crops. Kamath et al (1974) reported that the root systems of maize cultivars that were tested in normal and adverse soils showed a shift in the root system toward shallowness and compactness in adverse soils. This finding suggests that a suitable method of fertilizer application, depending upon the variety and soil conditions, is required.

Dravid et al (1982) evaluated the P nutrition of maize in pot culture when NPK was supplemented with Fe and Zn in saline and nonsaline soils, using maize cultivars Kisan, Ganga-5, Deccan, and Vijay. Ganga-5 was best in salt tolerance. Yield of dry matter, total P uptake, percent P derived from fertilizer (Pdff) as well as percent P utilization increased significantly when the NPK dose was applied in combination with Zn and Fe, either singly or together (Table 4).

Raju et al (1982) studied the influence of split application and seed coating on P utilization by maize in the greenhouse in a P-deficient soil of the Indian Agricultural Research Institute farm, New Delhi. Maize absorbed P more from diammonium phosphate (DAP) than from single superphosphate (SSP), perhaps because of the presence of intimately associated $\text{NH}_4^+$ ions in DAP. When P was split-applied,

<table>
<thead>
<tr>
<th>Cultivar</th>
<th>$P$ content (%)</th>
<th>Pdff (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Deccan</td>
<td>0.33</td>
<td>56</td>
</tr>
<tr>
<td>Ganga Safed-2</td>
<td>0.31</td>
<td>17</td>
</tr>
<tr>
<td>Ganga-5</td>
<td>0.38</td>
<td>26</td>
</tr>
<tr>
<td>Vijay</td>
<td>0.32</td>
<td>30</td>
</tr>
<tr>
<td>Kisan</td>
<td>0.33</td>
<td>39</td>
</tr>
<tr>
<td>JM L-22</td>
<td>0.36</td>
<td>28</td>
</tr>
</tbody>
</table>

Table 3. $P$ content and P derived from fertilizer (Pdff) in maize cultivars planted in fields (Oza et al 1977).
maize utilized less P from the topdressed than from the basally applied fertilizer, which could have been due to the deep and more extensive root system of the crop. Though yield increases due to seed coating with DAP were observed, the uptake of P from DAP-coated seed was less than with soil application of the fertilizer at the same level, suggesting that the treatment induced the maize plant to absorb more soil P.

**Sorghum**

Singh et al (1980) presented evidence for a residual response of P applied to rabi pulse crops on the succeeding kharif (wet season) fodder sorghum crop. The study demonstrated that failure to include residual response could lead to significant underestimation of benefits from P fertilization, which ranged from 7 to 23%, and could be more if higher valued crops were grown in succession.

Based on experiments to assess the effect of legumes on succeeding fodder sorghum yields, Singh and Singh (1986) reported that chickpea increased sorghum fodder yields and P uptake more than did lentil and pea. Phosphorus application up to the highest level increased yields progressively. The residual effect of P up to the highest level given to legumes resulted in increased K, N, and P harvest in the subsequent fodder sorghum (Table 5).

Information is limited on the nutrient requirements of high energy sorghums (HESs), which are currently being developed for both grain and biomass production (Creelman et al 1981). In a study to compare a HES, an intermediate grain cultivar, and a conventional grain cultivar for grain and biomass yield and nutrient removal

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**Table 4. Influence of Fe and Zn on P utilization by maize in normal and saline soils (Dravid et al 1982).**

<table>
<thead>
<tr>
<th>Treatment</th>
<th>Dry matter (g/pot)</th>
<th>Total P uptake (mg/pot)</th>
<th>Pdff (%)</th>
<th>P utilization (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Normal</td>
<td>Saline</td>
<td>Normal</td>
<td>Saline</td>
</tr>
<tr>
<td>Control</td>
<td>8.0</td>
<td>4.7</td>
<td>5.5</td>
<td>4.2</td>
</tr>
<tr>
<td>NPK</td>
<td>33.9</td>
<td>19.4</td>
<td>30.6</td>
<td>22.5</td>
</tr>
<tr>
<td>NPK + Fe</td>
<td>38.1</td>
<td>19.7</td>
<td>33.1</td>
<td>24.6</td>
</tr>
<tr>
<td>NPK + Zn</td>
<td>37.4</td>
<td>25.5</td>
<td>33.1</td>
<td>25.9</td>
</tr>
<tr>
<td>NPK + Fe + Zn</td>
<td>40.6</td>
<td>26.8</td>
<td>33.7</td>
<td>30.9</td>
</tr>
</tbody>
</table>

---

**Table 5. Mean P uptake by fodder sorghum grown after variably irrigated and P-fertilized legumes (Singh and Singh 1986).**

<table>
<thead>
<tr>
<th>Cropping sequence</th>
<th>P uptake (kg/ha) with fertilizer rates (kg/ha) of 0</th>
<th>15</th>
<th>30</th>
<th>45</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chickpea - sorghum</td>
<td>27.8</td>
<td>37.942.0</td>
<td>45.5</td>
<td></td>
</tr>
<tr>
<td>Lentil - sorghum</td>
<td>27.4</td>
<td>30.234.6</td>
<td>40.5</td>
<td></td>
</tr>
<tr>
<td>Pea - sorghum</td>
<td>23.2</td>
<td>33.339.4</td>
<td>41.8</td>
<td></td>
</tr>
</tbody>
</table>
in response to applied N and P, Hons et al (1986) reported that cultivars differed in grain and biomass production and in removal of some nutrients, but not in N and P uptake. Applied N increased the crop removal of all nutrients, while added P had little or no effect. Based on this study they observed that HESs produced for both grain and biomass removed an additional 140 kg K, 45 kg N, 80 kg Ca, and 10 kg P/ha when compared with grain cultivars harvested only for grain.

**Wheat**

Wheat grains contain a high level of P (0.5%). Adequate P nutrition of the wheat crop has beneficial effects during the whole growing cycle. Phosphorus application is a key component of modern wheat production technologies. The fertilizer requirement is on the order of 22-26 kg P/ha for yields of 5 t ha.

Among the major grain crops grown, wheat is most responsive to P, particularly in northern India. Thus, while allocating fertilizer P among component crops in a sequenced cropping system, the needs of wheat often receive priority. In times of fertilizer shortage, wheat yields are most vulnerable to cuts in fertilizer dose.

From field studies involving rice - wheat rotations conducted during 1972-77, Saggar et al (1985) reported that wheat responded to P significantly up to 40 kg P/ha. The first season effect of P application was significantly better than its residual effect, suggesting that P should be applied directly to the wheat crop. The two water-soluble P sources—SSP and triple superphosphate—were equally effective for grain yield production in both crops and proved better than phosphate rock (PR).

The choice of form of P should consider the soil type. The splitting of P fertilizer application between sowing and tillering for wheat has also shown promise.

In a study to determine the uptake and utilization of P by wheat and its response to graded doses of P, Rao and Sinha (1980) observed that fertilizer P uptake increased with P application. Use efficiency of applied P tended to decline with increase in P application. The uptake of soil P as well as of fertilizer P continued until the crop matured. Soil P uptake slightly increased at lower levels of applied P, but decreased at higher levels. P remaining in an available form (A value) after the 1st season was nearly constant. The economic optimum dose of P was found to be 43-48 kg P/ha, and the response in grain yield continued up to 66 kg P/ha.

Sinha (1980) observed that P applied in contact with wheat seed proved slightly superior to either broadcast or band placement with respect to yield and uptake of fertilizer P.

The volume of soil treated with P fertilizer affects P uptake by the crop. In pot culture, P-stimulated root growth in wheat was similar to that of maize and soybean (Jiapeng and Barber 1986). The effect could be described by the equation

\[ Y = 0.7 \]

where \( Y \) is the fraction of the root system in the P-fertilized soil and \( x \) is the fraction of the soil mixed with P. The greatest P uptake and plant growth occurred when added P was mixed with 20% soil.
The effect of intercropping wheat and lupins on the growth and mineral composition of the two crop species was evaluated by Gardner and Boundy (1983); they observed significant interactions between wheat and lupins below ground. Wheat intercropped with lupins had access to a larger pool of available P, Mn, and N than did wheat grown in monoculture. This suggests that wheat is able to take up nutrients produced or made available by lupins grown in association with it.

The utilization of P and the causes for its differential response in a rice -wheat rotation were evaluated by Gill and Meelu (1983), who indicated that 26 kg P/ha applied to the wheat only was sufficient to meet the P requirements of both crops. They concluded that for efficient use and economic returns from fertilizer input, the fertilizer schedule should be worked out in the cropping system rather than on a single-crop basis.

In a study by Dahama and Sinha (1985), wheat grain yield tended to increase as a result of the residual effect of P applied to preceding kharif legumes. A soybean - wheat sequence gave the lowest grain yield of wheat. Application of 40 kg P/ha to grain legumes showed a more pronounced residual effect than other levels ranging from 0 to 26 kg P/ha.

Singh and Faroda (1985) investigated the carryover effect of P applied to pigeonpea in the cropping system on P uptake by wheat with two N levels and three P levels. A beneficial effect on the concentration and uptake of P by wheat was observed more with pigeonpea + mungbean - wheat than with pigeonpea - wheat. Kharif crops showed an encouraging response to residual P with higher levels of applied P.

In a tracer study reported by Dahama and Sinha (1983), P utilization by wheat grown after kharif grain legumes in the field was higher at lower doses of P applied to previous crops. Utilization of applied P by wheat was higher after cowpea than in other sequences.

**Phosphorus management**

Any rational P management system for optimum crop production must ensure economy and cost effectiveness on one hand and conservation of depletable natural resources on the other. Phosphorus management must take the following into account:

- The utilization efficiency of applied fertilizer P is often below 20%.
- Soils fix applied P to varying degrees, resulting in the unavailability of fertilizer P to the crop.
- The “fixed P” can be available to the succeeding crop to varying extents, resulting in a residual effect.
- Crops and their varieties have a differential ability to utilize both native and applied P and have variable P use efficiency.

Phosphorus management must also necessarily aim at economizing on the use of P fertilizer through discovery of the best means of using it in multiple cropping systems. Specifically, which crops in the sequence should receive P fertilizer and
which others should benefit largely from the residual effect? What application rates are mandated by soil test results? What application methods and fertilizer types should be used to reduce soil fixation? Relatively cheaper sources such as indigenous PR, P-solubilizing organisms and mycorrhiza, and economically viable agrotechniques such as organic matter application in conjunction with P, dung-coated or biogas slurry-coated superphosphate, etc. are promising.

Efficient P management should have the following components:

- Phosphorus addition as fertilizer must be based on soil tests. This could be done by using the “targeted yield” approach, which has made soil test-based fertilizer recommendations more quantitative, precise, and meaningful (Ramamoorthy et al 1967) or on the basis of the “critical level” of P in the soil (Goswami et al 1971). Some typical results based on these approaches are given in Table 6. In Thailand, Duangpatra (1987) reported good response of maize in coarse-textured (loamy sand) soils having < 10 ppm native available P.
- Lime must be applied in acid soils to get a profitable response to P. Goswami et al (1976) reported that liming in acid soils (pH 5.1 and 5.6) increased wheat yields, as did P application; but lime plus P increased the wheat yield much more (Table 7). Similarly, Prasad et al (1983) observed that liming increased P

<table>
<thead>
<tr>
<th>Crop and soil</th>
<th>Yield target (t/ha)</th>
<th>Recommended P (kg P/ha) at Olsen P rates (kg/ha)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>10</td>
<td>20</td>
</tr>
<tr>
<td>Wheat, alluvial soil</td>
<td>4</td>
<td>47</td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>64</td>
</tr>
<tr>
<td>Sorghum, kharif, irrigated, black soil</td>
<td>4</td>
<td>11</td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>23</td>
</tr>
<tr>
<td>Sorghum, kharif, not irrigated, black soil</td>
<td>4</td>
<td>8</td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>18</td>
</tr>
<tr>
<td>Sorghum, rabi, irrigated</td>
<td>4</td>
<td>16</td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>16</td>
</tr>
</tbody>
</table>

Table 6. P recommendations based on the “targeted yield” approach (Tandon 1987).

<table>
<thead>
<tr>
<th>Fertilizer</th>
<th>Wheat yield (t/ha)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Unlimed</td>
</tr>
<tr>
<td>Kharagpur soil (pH 5.1, laterite)</td>
<td></td>
</tr>
<tr>
<td>N</td>
<td>2.3</td>
</tr>
<tr>
<td>N + P</td>
<td>2.7</td>
</tr>
<tr>
<td>Pelampur soil (pH 5.6, hill soil)</td>
<td></td>
</tr>
<tr>
<td>N</td>
<td>2.2</td>
</tr>
<tr>
<td>N+P</td>
<td>4.2</td>
</tr>
</tbody>
</table>

Table 7. Effect of lime and P on wheat yield in acid soils (Goswami et al 1976).
uptake by maize by 118% and grain yield by 94% over unlimed plots. Didi Ardi et al (1986) who studied the effects on maize cultivar H6 of P, lime, and farmyard manure (FYM) on an Ultisol in Rangkasbitung, West Java, observed that higher yields could be obtained with P in conjunction with lime and FYM (Table 8).

- Indigenous and cheap sources such as PR should be used wherever agronomically effective and economically viable.
- Phosphorus fertilization must take cognizance of the residual effects of past application.
- Other limiting factors (nutrients or water) should be considered. Balanced fertilization based on crop needs should be adopted.
- Phosphorus availability is intimately linked with soil moisture. The lower the moisture content, the greater is the need for P application.
- Band placement of P shuld be practiced to ensure greater P availability to plants.

### Table 8. H6 maize yield as affected by P, lime, and farmyard manure (FYM) application on an Ultisol in Rangkasbitung, Indonesia (Didi Ardi et al 1986).

<table>
<thead>
<tr>
<th>Phosphorus (kg/ha)</th>
<th>Maize yield $^a$ (t/ha)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Unlimed</td>
</tr>
<tr>
<td></td>
<td>No FYM</td>
</tr>
<tr>
<td>20</td>
<td>1.5</td>
</tr>
<tr>
<td>40</td>
<td>2.1</td>
</tr>
<tr>
<td>60</td>
<td>2.9</td>
</tr>
</tbody>
</table>

$^a$ (-) = no data.

References cited


Notes

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Citation information: International Rice Research Institute (1990) Phosphorus requirements for sustainable agriculture in Asia and Oceania P.O. Box 933, Manila, Philippines.
Phosphorus requirements and management of grain legumes

R.K. Pandey and J.L. McIntosh

Phosphorus requirements and management for grain legume production are reviewed in light of a) application rates, b) fertilizer sources, c) utilization efficiency of various forms of P fertilizer, and d) interaction with other nutrient elements and water. Experimental results show positive responses of grain legumes to P on many soil types in different countries. The magnitudes of the responses are discussed in relation to liming, use of other nutrients, and sources and placement of P in the soil. In acid soils, liming may be necessary to secure the maximum effect from P fertilizer. Phosphorus fertilization of grain legume crops may reduce their fertilizer N requirement in some cropping systems. An adequate P supply is important for balanced fertility for grain legume production.

Phosphorus is frequently a primary factor limiting the total protein and dry matter production of grain legumes. Consequently, investigations of the P nutrition of grain legumes require detailed understanding of P sources, forms, and rates, as well as other factors that may affect P uptake and crop performance (Barber 1985). Considerable emphasis must be placed on the efficiency of P utilization by different crops, since higher energy costs may increase the costs of P fertilizers. Prasad and De (1980) reported that application of P fertilizer was the first step toward increasing legume production in India. Adequate P fertilization of the legume crop may eliminate or considerably reduce the amount needed for succeeding grain crops in a cropping system.

The P requirements of grain legumes in the field differ widely from site to site, depending on the availability of soil P and the management required to change it. An example of P uptake by nine grain legumes is shown in Table 1. The management required depends upon soil pH, organic matter content, mineralogy, and soil P level. Several experiments in Asia have shown that applying from 17.6 to 26.4 kg P/ha is sufficient in many P-deficient soils. In Tel Hadia, Syria, in 1977-78, applying 22 kg P/ha increased broad bean seed yield significantly (Saxena 1979).

In soils with slightly acid to neutral pH, the P requirement depends on the
• soil P level,
• crops to be grown,
• expected crop yield, and
• nature of the soil.
Table 1. Phosphorus uptake of 9 grain legumes in the field, India.

<table>
<thead>
<tr>
<th>Legume</th>
<th>Uptake (kg P/t produce)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Range</td>
</tr>
<tr>
<td>Cowpea</td>
<td>3.4 - 5.1</td>
</tr>
<tr>
<td>Pea</td>
<td>5.2 - 7.8</td>
</tr>
<tr>
<td>Chickpea</td>
<td>2.8 - 5.5</td>
</tr>
<tr>
<td>Green gram</td>
<td>9.2 - 10.9</td>
</tr>
<tr>
<td>Black gram</td>
<td>3.8 - 5.2</td>
</tr>
<tr>
<td>Lentil</td>
<td>3.2 - 6.9</td>
</tr>
<tr>
<td>Pigeonpea</td>
<td>5.7 - 9.7</td>
</tr>
<tr>
<td>Soybean</td>
<td>9.3 - 18.0</td>
</tr>
<tr>
<td>Groundnut (pods)</td>
<td>4.7 - 19.3</td>
</tr>
</tbody>
</table>

A sound and economic P management strategy for crops grown on acidic and infertile soils requires that other factors be considered. These include:

- determining rates and placement of P fertilizer to increase its efficiency, both initially and residually;
- use of cheaper, less soluble forms of P such as phosphate rock (PR), partially acidulated PR, and granulated mixtures of PR with more soluble forms of P; and
- use of farmyard and green manures to improve P availability.

**Phosphorus rates**

Several experiments with a number of crops have determined the P rates necessary to maximize production. Although some of the experiments included different P carriers, only triple superphosphate (TSP) will be discussed in this section.

Howeler and Leon (CIAT 1978) established an experiment with field beans on a P-deficient Popayan Typic Dystrandept in Colombia. Phosphorus was applied at 0-968 kg/ha before the first planting (Fig. 1) to determine the levels necessary from both an initial and residual standpoint. The first harvest showed good yield response up to 360 kg P/ha, and the second and third crops up to 180 kg P/ha. Since the yield of the third harvest was quite low, it appears that these soils with high allophane contents were fixing large amounts of the applied P. One management strategy would be to apply less-soluble forms of P initially, or to apply the soluble forms on an annual basis. Andepts in many places are valuable for vegetable crop production. The productivity of the Andepts of Indonesia depends on the generous use of a combination of farmyard and green manures in addition to P.

Pigeonpea responses to P in farmers’ fields in India were similar to those of chickpea—for most situations about 18-26 kg P/ha was sufficient (Kulkarni 1980, Singh and Marok 1983a). There are, however, situations where higher rates of 22-44 kg P/ha may be used—for example, in New Delhi (Saraf 1983) and in certain black soil areas (Kanwar 1986). A higher pigeonpea plant density may also be used to increase yields, but only if it is accompanied by P application. In a plant population
1. Field bean response to P in Popayan, Colombia (CIAT 1978).

If soil acidity is high, production can be increased many times if limestone is applied. An exception may be newly opened lands with soils high in undecomposed organic matter. The correction of soil acidity by liming may increase Mo availability, supply Ca, improve the response to P, and consequently increase legume crop production. When P fertilizer was broadcast and incorporated at various rates of lime
application in Rio Grande do Sul, Brazil, an interaction between liming rate and P was observed (Raij 1979). Higher yields were found at higher rates of P and lime application (Table 2).

**Placement effects of phosphorus levels**

When P fertilizer is mixed with soil, part of the P added is adsorbed by the soil, so that its availability to plants is reduced. The amount of P tied up in this way varies with soil properties. As the application rate is increased, the amount of P tied up from each increment decreases. So, at very high levels of soil P only small amounts of each additional increment may be tied up by the soil. Therefore, fertilizer is often banded to reduce fixation by the soil compared with that occurring when the fertilizer is mixed throughout the soil. The restriction of P to a small volume of the soil reduces fixation, at least in the short run, and leaves more of the nutrient in an available form for uptake by plant roots. However, this restriction also means that only a small fraction of the root system will be in contact with the fertilizer band, which will tend to reduce uptake. A balance between reduced availability as fertilizer is mixed with more soil, and increased availability due to contact with more roots, will determine the most effective placement if soil moisture is not limiting.

For Andept soils of Latin America, P fertilization of row crops like beans is generally by row application at planting. Numerous experiments have determined which application method is best for various crops.

Howeler and Leon conducted an experiment on a Typic Dystrandept soil near Popayan, Colombia, with varying P rates, sources, and application methods (CIAT 1978). Three P fertilizers—TSP, basic slag, and Huila PR from Colombia—were applied in a triangular configuration (Fig. 2). The triangle base simulated broadcast application; the tip, band application; and the intermediate section, strip application. Phosphorus was applied at 33, 66, and 132 kg P/ha. Yields were significantly higher when TSP was band-applied rather than when broadcast or strip-applied, especially at 132 kg P/ha. Band application of 33 kg P/ha as TSP was as effective as 132 kg/ha broadcast. The efficiency of TSP was increased when P fixation was reduced by minimizing soil-fertilizer contact. Application method did not affect the efficiency of basic slag. Phosphate rock, on the other hand, was slightly more efficient when broadcast and incorporated.

**Table 2. Effect of liming and P fertilization on soybean grain yield on an Oxisol, Rio Grande do Sul, Brazil (Raij 1979).**

<table>
<thead>
<tr>
<th>P applied (kg/ha)</th>
<th>Yield (t/ha)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>No lime</td>
</tr>
<tr>
<td>0</td>
<td>1.20</td>
</tr>
<tr>
<td>68</td>
<td>1.44</td>
</tr>
<tr>
<td>135</td>
<td>1.84</td>
</tr>
<tr>
<td>203</td>
<td>1.98</td>
</tr>
<tr>
<td>270</td>
<td>1.80</td>
</tr>
</tbody>
</table>
2. The effect of fertilizer distribution, applied at 3 levels, and P source on bean yield in Popayan, Colombia (CIAT 1977)

When a second crop was reseeded in the same rows as the first without disturbing the original P treatments, the beneficial effect of banding TSP was lost, and banded TSP was no more effective than other application methods (CIAT 1977).

Although more study is needed on the placement effects of various P sources, particularly in high P-fixing soils, these results do not support the conventional concept that major fertilizer savings can be achieved by localized placement of soluble P sources. For the widely distributed coarse Alfisols and Ultisols in West Africa, P placement method does not appear to be critical for P efficiency.

In India, drilling or placing P below the surface is recommended to improve P fertilizer efficiency in drylands; broadcasting of P is not advocated even if it is incorporated (Kanwar 1986, Singh and Venkateswarlu 1977). The average yield increase of dryland crops due to placement of 18 kg P/ha was 200 kg grain (Venkateswarlu 1986), which is equivalent to the cost of 18 kg P. In field trials at 5 locations, deep placement of 80 kg N + 18 kg P ha gave an extra 1.13 t sorghum grain over broadcast application (Venkateswarlu and Spratt 1977); this advantage was 2 times the monetary value of the NP applied and resulted in an extra 9 kg grain/ kg NP applied. Other results from Andhra Pradesh show that placement of P increased the yield of sorghum by 25% and of castor (Ricinus communis) by 16% over broadcast application (Raman and Subba Rao 1979).

For soybean and chickpea, drilling P below the seed increased seed yield significantly over broadcast P (Singh and Singh 1986). Sowing a mixture of seed and fertilizer was superior to broadcasting (Table 3).
Table 3. Relative comparison (%) of yield by P application method on chickpea and soybean (Singh and Singh 1986, Venkateswarlu 1986).

<table>
<thead>
<tr>
<th>P application method</th>
<th>Chickpea yield with 18 kg P/ha</th>
<th>Soybean yield 18 kg P/ha</th>
<th>Soybean yield 2.3 kg P/ha</th>
</tr>
</thead>
<tbody>
<tr>
<td>Broadcast</td>
<td>100</td>
<td>100</td>
<td>100</td>
</tr>
<tr>
<td>Drilled</td>
<td>137</td>
<td>123</td>
<td>169</td>
</tr>
<tr>
<td>Mixed with seed</td>
<td>118</td>
<td>123</td>
<td>135</td>
</tr>
</tbody>
</table>

**Effectiveness of fertilizer carriers**

Results from subhumid areas of West Africa (Kang and Juo 1979) showed greater efficiency of the more soluble forms of P (monocalcium, dicalcium, and ammonium phosphates) over PR and slags. The effectiveness of various P carriers was studied on two Alfisols and an Entisol, and pronounced differences were observed between single and compound (NP) carriers (Kang and Juo 1979). Ammonium orthophosphate (15-66-0), ammonium polyphosphate (15-27-0), and the less watersoluble nitric phosphate (20-9-0, 35% water solubility) carriers were superior to TSP and PR. Superiority of the NP fertilizers may be explained by the complementary effect of N. Fertilizer N, especially in the ammonium form, enhances fertilizer P uptake by plants if the P and N are chemically or physically associated (Grunnes 1959, Miller and Ohlrogge 1958). Long-term trials to compare the effectiveness of some PRs and TSP have been conducted at several locations on Ultisols and Oxisols in Sumatra. In terms of response and residual effects, ground Tunisia PR was more effective than TSP (Fig. 3) (Sri Adiningsih et al 1988). Low water solubility and a slow-release P source can reduce P fixation in acid upland soils; hence PR is more suited to acid upland soils than TSP. The effectiveness of PR depends on its reactivity, application time, and soil properties.

Data from studies in dryland fields are rather limited, but in general fertilizers containing substantial proportions of their P in water-soluble form are preferred for field crops, both in red and black soils (Kanwar 1986). In acidic P-deficient soils, powdered PR has been advocated for grain legumes.

**Use of partially acidulated and minigranulated phosphate rock**

Although many PRs perform well with time, they are initially inferior to the more soluble P sources. McLean and Wheeler (CIAT 1978) indicated that partially (10-20%) acidulated PRs could overcome this problem (Fig. 4).

In general, PR must be finely ground to be effective. This creates an application problem, as ground PR is dusty and hard to spread evenly on the field. A field experiment determined the effectiveness of both partial acidulation and granule size of both high- and low-reactivity PRs on peanut yield on a Carimagua Oxisol. The granules were made by taking finely ground PR, partially acidulating it with H$_2$SO$_4$,

and granulating with a 3.3% KC1 binder. Two particle sizes were used: powdered (<200 mesh) and minigranules (51 mesh). Ground 10% acidulated PR was superior to minigranulated 10% acidulated PR at 44 kg P/ha.

**Interaction of phosphorus with other nutrients**

Phosphorus can interact strongly with other plant nutrients. It can promote increased efficiency of symbiosis and \( \text{N}_2 \) fixation by grain legumes. The N concentration in the tops of P-deficient legumes is usually low, and good correlations between P and N concentrations in tropical grain legumes have been established. This effect may be attributed to at least four possible functions: root development, nodulation, nodule efficiency, and plant metabolism. Applying P to deficient soils has been shown to increase number and weight of nodules in several legumes.

In studying the P nutrition of plants, it is necessary to consider other nutritional and environmental factors. For example, strong interactions may occur with pH and nutrients such as Ca, Al, Zn, and Mo. Furthermore, the species or cultivar of plants may have definite characteristics relating to one or more of these factors. Greater attention should be given to studies that include quantitative and qualitative assessment of root systems. The role of mycorrhiza and other associated rhizosphere organisms, the utilization and reutilization of P in relation to dry matter, and N reduction in plant systems should be studied further.

### Table 4. Cumulative yields of a 5-yr rice - rice - maize cropping pattern, Bogor, 1974-1979 (Source: Suhartatik et al [1981] as reported by Juber and McIntosh [1983]).

<table>
<thead>
<tr>
<th>Treatment</th>
<th>Rice Lowland</th>
<th>Rice Upland</th>
<th>Soybean Lowland</th>
<th>Soybean Upland</th>
<th>Maize Lowland</th>
<th>Maize Upland</th>
</tr>
</thead>
<tbody>
<tr>
<td>No NPK + no crop residue</td>
<td>6.38</td>
<td>4.37</td>
<td>5.78</td>
<td>4.70</td>
<td>7.71</td>
<td>5.40</td>
</tr>
<tr>
<td>No NPK + crop residue as mulch</td>
<td>7.80</td>
<td>5.07</td>
<td>5.39</td>
<td>4.09</td>
<td>8.45</td>
<td>5.87</td>
</tr>
<tr>
<td>No NPK + crop residue incorporated</td>
<td>9.12</td>
<td>5.23</td>
<td>5.71</td>
<td>5.25</td>
<td>8.84</td>
<td>6.79</td>
</tr>
<tr>
<td>No NPK + animal manure</td>
<td>7.39</td>
<td>5.06</td>
<td>5.97</td>
<td>5.20</td>
<td>8.41</td>
<td>6.38</td>
</tr>
<tr>
<td>NPK + no crop residue</td>
<td>15.36</td>
<td>12.54</td>
<td>5.45</td>
<td>5.74</td>
<td>16.29</td>
<td>16.03</td>
</tr>
<tr>
<td>NPK + crop residue as mulch</td>
<td>18.46</td>
<td>13.10</td>
<td>5.91</td>
<td>5.92</td>
<td>15.98</td>
<td>17.12</td>
</tr>
<tr>
<td>NPK + crop residue incorporated</td>
<td>18.86</td>
<td>12.78</td>
<td>5.71</td>
<td>6.08</td>
<td>16.23</td>
<td>16.24</td>
</tr>
<tr>
<td>NPK + animal manure</td>
<td>15.99</td>
<td>13.31</td>
<td>5.94</td>
<td>5.82</td>
<td>16.16</td>
<td>17.13</td>
</tr>
</tbody>
</table>

*The rates of NPK were 120-20-42, 20-20-42, and 120-20-42 for rice, soybean, and maize, respectively.*
Phosphorus application in rice - grain legume systems

In cropping systems, applying P to one crop may eliminate or considerably reduce the requirement of the succeeding crop. Srivastava and Pathak (1970) noted that applying P fertilizer to the legume in a rice - legume cropping pattern was more beneficial than applying the same amount to the rice. On soils testing low in P, 13-22 kg P/ha should be applied. Band placement of P fertilizer is generally more efficient than broadcasting. Deep placement is generally beneficial, especially when the surface layers become dry.

On the basis of several years of cropping systems studies in India, P is applied for dry season crops such as grain legumes rather than for wetland rice. It is assumed that grain legumes cannot effectively use Fe-P, which is the major transformation product of P, after lowland rice. However, where soil P is very deficient, applying P to both crops is necessary (Mahapatra et al 1981).

In Indonesian studies, Juber and McIntosh (1983) reported that soybean grown after lowland rice that had received P application rarely responded to NPK fertilizer. After upland rice, however, P application increased soybean yields substantially. They also reported results of continuous cropping of a rice - soybean - maize sequence receiving different fertility treatments (Table 4) on a Typic Dystropept soil. Soybean grown after lowland rice was unresponsive to NPK treatments, crop residues, or manure but tended to grow and yield as well as soybean grown after upland rice when NPK was added. Soil conditions after lowland rice appeared to enhance P availability. On the other hand, soybean grown after upland rice responded positively to NPK and NPK plus crop residues and manure, and gave about the same yield as that grown after lowland rice.

References cited


Notes

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Citation information: International Rice Research Institute (1990) Phosphorus requirements for sustainable agriculture in Asia and Oceania. P.O. Box 933, Manila, Philippines.
Phosphorus requirements and management of oilseeds

K.L. Sahrawat and M.S. Islam

The recent literature on the P requirements and management of annual edible oilseeds groundnut *Arachis hypogaea*, sunflower *Helianthus annuus*, safflower *Carthamus tinctorius*, rapeseed *Brassica campestris*, mustard *B. juncea*, and sesame *Sesamum indicum* is reviewed. The internal P requirement to produce a given level of seed yield varies among the oilseeds, but in general they use the soil and fertilizer P efficiently. The external P requirement is also greatly modified by soil moisture, season, supply of nutrients other than P, and P status of soil. Effects of P management practices, especially those relating to source, method, and time of application, on the yield response and fertilizer P requirement of oilseeds are discussed. Recommendations are made for future research.

Oilseeds form an important component of the human diet in Asia and the Pacific. Oilseeds are grown on diverse soils, mostly under unirrigated and less than ideal conditions, and plant nutrients are one of the most important constraints on their growth and yield (Directorate of Oilseeds Research 1984, 1985; Reid 1981). The P requirement of oilseeds is higher than that of cereals because P is involved in the synthesis of energy-rich oils and proteins. However, such requirement varies not only from crop to crop but also among cultivars of the same crop.

This paper reviews the recent literature on the P requirements and management of selected annual edible oilseed crops in Asia and the Pacific region. Where available, preference is given to data from well-planned field studies and to reports with wider scope and broader perspective. The oilseeds covered in this review are groundnut *Arachis hypogaea*, sunflower *Helianthus annuus*, safflower *Carthamus tinctorius*, rapeseed *Brassica campestris*, mustard *B. juncea*, and sesame *Sesamum indicum*. Phosphorus requirements and management are discussed separately for each oilseed crop.

Several soil fertility and agroclimatic factors that affect growth and yield also affect the P requirements of oilseeds.

- **Soil fertility factors**
  - Available P status of soil
  - Supply of macro- and micronutrients other than P
  - Available soil moisture
  - Importance of vesicular-arbuscular mycorrhizal fungi
• **Agroclimatic factors**
  — Total rainfall and its distribution during the cropping season
  — Availability of irrigation
  — Temperature
  — Solar radiation

In addition, the source and time of fertilizer P application, as well as soil type greatly affect the P response of oilseeds.

*The term internal Requirement of an oilseed generally refers to the minimum P concentration in tissue or the P uptake by tops at maximum seed yield or at the yield corresponding to a critical limit, e.g., 90% of maximum yield. However, in this paper, internal P requirement has been used rather loosely to signify P concentrations and content, not necessarily at 90% of maximum yield.*

**Groundnut**

Groundnut is a legume oilseed, and most of its N requirement is met by biological N$_2$ fixation. Groundnut is monocropped or intercropped with various crops in different cropping sequences (Directorate of Oilseeds Research 1985).

**Internal phosphorus requirement**

Satyanarayana and Krishna Rao (1962) found that the leaves of healthy groundnut plants at the start of flowering contained 0.22% total P, which is similar to the values reported by Nelson (1980). Typical approximate P concentrations of groundnut at harvest have been reported as 0.07% in the haulms, 0.03% in the shells, and 0.36% in the kernels (Nelson 1980).

Tissue concentration in the uppermost fully expanded leaves during vegetative growth was 0.3% and declined linearly during reproductive growth from 0.27% at 60 d after emergence (DE) to 0.12% at 100 DE. Regression equations satisfactorily described the relationships between yield and tissue P concentration at all stages of plant growth except at day 42, which corresponded to the early reproductive development period when P accumulated in the developing pods. Variability could also have been caused by translocation of P from vegetative tissues to developing fruit parts (Bunting and Anderson 1960).

Tissue testing for the internal P requirement of groundnut during early reproductive development may not be valid.

**Fertilizer phosphorus requirements and management**

Aulakh et al (1985) determined the P content of several oilseed crops including groundnut by analyzing seed and stover samples. The oilseeds were grown at four sites on the Punjab Agricultural University farm in Ludhiana, India, and in farmers’ fields. Yield and P uptake data (Table 1) show that the total amount of P taken up to produce 1 t of seed varied from 8.3 to 20.0 kg among the oilseeds. Groundnut required about 10 kg to produce a 1-t kernel yield. The amounts of P taken up by different oilseeds to produce 1 t of seed were much higher than those for cereals such as rice and sorghum, as well as pulses such as chickpea and pigeonpea (Tandon 1987).
Table 1. Seed yield and P uptake of selected oilseeds (from Aulakh et al 1985).

<table>
<thead>
<tr>
<th>Crop</th>
<th>Cultivar</th>
<th>Seed yield (t/ha)</th>
<th>Total P uptake (kg/ha)</th>
<th>P taken up to produce 1 t of seed (kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Raya (B. juncea)</td>
<td>RL 18</td>
<td>2.0</td>
<td>18</td>
<td>9.0</td>
</tr>
<tr>
<td>Groundnut (A. hypogea)</td>
<td>M 145</td>
<td>1.9</td>
<td>19</td>
<td>10.0</td>
</tr>
<tr>
<td>Sarson (B. campestris)</td>
<td>BSH1</td>
<td>1.5</td>
<td>17</td>
<td>11.3</td>
</tr>
<tr>
<td>Taramira (E. sativa)</td>
<td>Selection 1</td>
<td>1.5</td>
<td>17</td>
<td>11.3</td>
</tr>
<tr>
<td>Sesame (S. indicum)</td>
<td>Pb. Till No. 1</td>
<td>1.2</td>
<td>24</td>
<td>20.0</td>
</tr>
<tr>
<td>Sunflower (H. annuus)</td>
<td>Ramson Record</td>
<td>0.6</td>
<td>5</td>
<td>8.3</td>
</tr>
</tbody>
</table>

*Sarson and taramira are also known as rapeseed, and raya as mustard.

In a recent study, Sahrawat et al (1988) found that 15.1 kg of total P/ha was taken up by a groundnut crop (cultivar Robut 33-1) producing 3.1 t pods. After correcting for shelling percentage, the total P uptake for a crop producing 1 t groundnut kernels would be around 7.2 kg P/ha. At harvest, the P concentrations were 0.41% in the kernels, 0.14% in the haulms, and 0.09% in the husks (shells).

Bell (1985) made detailed investigations of the P requirement of Virginia Bunch groundnut grown on virgin cockatoo sand (pH 5.7, 2.0 mg 0.5 M NaHCO₃-extractable P kg, CEC 2.0 meq/100 g) in a 3-yr study. A range of 0.5 M NaHCO₃-extractable P levels in soil was created by incorporating 0-80 kg P/ha as triple superphosphate (TSP) in band in the first year and as broadcast application in the second year. The soil P concentrations (0.5 M NaHCO₃-extractable) required for 90% of maximum pod and kernel yield were 7.3 and 7.9 mg/kg, respectively. These soil critical values for 0.5 M NaHCO₃-extractable P are similar to that of 8.3 mg/kg soil found by Singh and Rana (1979) for sandy soils in Punjab (India).

Bell (1985) further showed that the relation between pod or kernel yield and extractable soil P level before planting in the top 10 cm of soil followed a Mitscherlich-type equation and could be represented by the following equations:

\[
\text{Pod yield (t ha)} = 4.7 - 6.4 \times 0.395 \text{ extractable P} \\
R^2 = 0.85
\]

\[
\text{Kernel yield (t ha)} = 3.1 - 4.1 \times 0.395 \text{ extractable P} \\
R^2 = 0.83
\]

Fertilizer P responses vary with the soil's available P status, its phosphate adsorption-desorption characteristics, and the supply of other nutrients (Nelson 1980, Tandon 1987). Unfortunately, a large number of experiments gave only minimum data on the status of available soil nutrients, making their interpretation difficult.

Hall (1975) examined the effects of P, K, and Ca on Virginia Runner groundnut grown in Nuata clay loam (New Zealand); P and Ca together gave large yield increases, but P or Ca applied separately was relatively ineffective. Potassium depressed yield when applied together with P and Ca. This shows the interdependence of P response on Ca supply.
Nelson (1980) analyzed fertilization data from 722 location-years in the United States and reported that 1 kg of applied P increased groundnut yield by $20.0 \pm 4.3$ kg/ha. The experiments had P rates ranging from 10 to 41 kg/ha (average, 21.5 kg/ha).

Laurence (1982) made a detailed 2-yr evaluation of P response of groundnut under irrigated conditions on Cockatoo Sands in the Ord River Valley of Western Australia. The soils (2 sites) had pH 6.5 and 6.1, extractable P 3 and 10 mg/kg, and CEC 3.3 and 1.4 meq/100 g. Pod yield increased from 3.35 to 4.56 t/ha with 20 kg P/ha; the highest mean pod yield reported was 4.68 t/ha at 60 kg P/ha. Shelling percentage was improved from 66.8 to 68.9% at 20 kg P/ha.

Tandon (1987) summarized the data from numerous experiments conducted during 1969-84 in India under rainfed and irrigated conditions (Table 2). Although indicating a response of groundnut to P application, the data are hard to interpret because the experiments were conducted under diverse soil and climatic conditions; details about soil P status, other soil characteristics, source of P, and supply of other nutrients are not available.

A guide to fertilizer P recommendations for oilseeds in India prepared by the Directorate of Oilseeds Research is summarized in Table 3. As expected, the rates recommended for irrigated conditions are higher than those for rainfed farming. The rates of fertilizer P recommended for groundnut are similar to the typical recommendations for the United States and other parts of the world, which range from 15 to 50 kg P/ha, depending on available soil P (Nelson 1980). In the Punjab (India), single superphosphate (SSP) gave superior yield responses in groundnut compared with TSP and diammonium phosphate (DAP) (Pasricha et al 1987). The response to SSP could be due to S rather than to P in view of the high S requirement of groundnut. The N content of DAP may have depressed yields. Evidently, P content in groundnut kernels was increased by all sources, while S content increased only where SSP was added. The P content of groundnut kernels was poorly correlated with pod yield ($r = 0.23$), but S content was significantly correlated with pod yield ($r = 0.77**$). These results confirm the superiority of SSP to DAP and TSP because of S supply (Pasricha et al 1987). SSP is a good source of secondary nutrients such as Ca, Mg, and S and of some micronutrients that could markedly affect the yield, oil content, and shelling percentage of groundnut (Puri 1972). Early

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Rainfed</th>
<th>Irrigated</th>
</tr>
</thead>
<tbody>
<tr>
<td>Trials (no.)</td>
<td>1307</td>
<td>266</td>
</tr>
<tr>
<td>Season</td>
<td>Rainy (Jun-Sep)</td>
<td>Postrainy (Oct-Jan)</td>
</tr>
<tr>
<td>Average pod yield without applied P</td>
<td>0.86 t/ha</td>
<td>1.62 t/ha</td>
</tr>
<tr>
<td>P applied</td>
<td>26 kg/ha</td>
<td>26 kg/ha</td>
</tr>
<tr>
<td>Average yield response to P</td>
<td>290 kg/ha</td>
<td>450 kg/ha</td>
</tr>
<tr>
<td>Average yield response</td>
<td>11 kg/kg P</td>
<td>17 kg/kg P</td>
</tr>
</tbody>
</table>

Trials made during 1969-84 using different P fertilizers.
Table 3. Fertilizer P recommendations for oilseeds in India (adapted from Directorate of Oilseeds Research 1984, 1985).

<table>
<thead>
<tr>
<th>Oilseed</th>
<th>Recommended fertilizer P (kg/ha)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Rainfed</td>
</tr>
<tr>
<td>Groundnut</td>
<td>16-60</td>
</tr>
<tr>
<td>Sunflower</td>
<td>13-17</td>
</tr>
<tr>
<td>Safflower</td>
<td>9-13</td>
</tr>
<tr>
<td>Rapeseed and mustard</td>
<td>15-40</td>
</tr>
<tr>
<td>Sesame</td>
<td>10-40</td>
</tr>
</tbody>
</table>

\(^a\) P recommendations are general and depend on soil P status and yield goal. Other nutrients, especially N, K, and micronutrients, are essential; their requirements and rates vary widely. \(^b\) Data not available.

root growth in groundnut is primarily by the taproot. Lateral root growth contributes little to P absorption until the crop is 10-11 wk old. Therefore, fertilizer P placement below the seed row is most satisfactory for P management of groundnut (Directorate of Oilseeds Research 1984,1985; Nelson 1980; Pasricha et al 1987).

**Sunflower**

Sunflower is an important oilseed crop in Asia and the Pacific. Its oil is assuming importance as a high-quality product for human consumption. Sunflower can be cultivated year round, but being a nonlegume, it requires fertilizer N. Sunflower is grown both as a monocrop and as an intercrop in different combinations, especially in India (Directorate of Oilseeds Research 1985). It is better adapted to water stress and salinity than other oilseeds. After N, P is the most important nutrient limiting sunflower productivity (Blamey et al 1987, Robinson 1978).

**Internal phosphorus requirement**

In one greenhouse and three field experiments, Spencer and Chan (1981) found that the lamina of the youngest fully expanded leaf is a suitable plant part for diagnosis. Critical P concentrations for this tissue decreased from about 0.35% in the 4th week from sowing to 0.20% in the 10th week. The P content of the lamina of the youngest fully expanded leaf reflected shoot growth at 7 and 10 wk, and seed yield under both rainfed and irrigated conditions (Table 4).

Loubser and Human (1983) determined P concentrations in sunflower leaves in a 5-yr field study. Low-oil cultivar Kortrus and high-oil hybrid cultivar SO 320 were grown in a P-deficient soil with treatment combinations of 0, 60, 120, or 180 kg N/ha and 0, 20, 40, or 60 kg P/ha. The P content of the youngest fully expanded leaf tissue was highly correlated with seed yield. The critical P concentration required to achieve 90% of maximum yield varied among cultivars and years in the range 0.21-0.31% P. The critical P concentrations for the low- and high-oil cultivars were 0.27 and 0.24%, respectively. These results agree with those of Spencer and Chan (1981) and reinforce the utility of tissue testing for P requirements for sunflower.
Table 4. Effect of applied P on shoot growth, leaf P concentration, seed weight, and oil content of sunflower cultivar Hysun 10 (from Spencer and Chan 1981).

<table>
<thead>
<tr>
<th>P applied(^a) (kg/ha)</th>
<th>Top weight (g/plant)(^b) at 7wk</th>
<th>Top weight (g/plant)(^b) at 10wk</th>
<th>P content of youngest fully expanded leaf at 6 wk (%)</th>
<th>Seed weight (t/ha)</th>
<th>Seed oil content (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>2.5</td>
<td>2.3</td>
<td>11.5</td>
<td>0.31</td>
<td>38.9</td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>3.6</td>
<td>17.2</td>
<td>0.34</td>
<td>39.5</td>
</tr>
<tr>
<td></td>
<td>8</td>
<td>4.4</td>
<td>20.6</td>
<td>0.41</td>
<td>40.2</td>
</tr>
<tr>
<td></td>
<td>14</td>
<td>5.8</td>
<td>22.0</td>
<td>0.43</td>
<td>41.6</td>
</tr>
<tr>
<td></td>
<td>30</td>
<td>7.0</td>
<td>25.8</td>
<td>0.48</td>
<td>41.3</td>
</tr>
<tr>
<td></td>
<td>LSD</td>
<td></td>
<td></td>
<td></td>
<td>0.06</td>
</tr>
</tbody>
</table>

\(^b\)P applied as TSP was drilled below the seed. All other nutrients (N, K, S, B, and Mo) were added in adequate amounts.

|                         | Rainfed\(^b\)                     |                                  |                                               |                  |                     |
|                         | 0                                |                                  |                                               | 0.24             | 48.9                |
|                         | 20                               |                                  |                                               | 0.31             | 46.5                |
|                         | 40                               |                                  |                                               | 0.35             | 45.4                |
|                         | LSD                              |                                  |                                               | 1.21             |                     |

\(^c\)P applied as TSP was drilled below the seed. A basal application of 2 t limestone/ha and 160 kg N/ha as NH\(_4\)NO\(_3\) was given.

Aulakh et al (1985) reported that the P concentrations in the seed and stover of sunflower cultivar Ramson Record at harvest were 0.57 and 0.05%, respectively.

Ramam and Dhingra (1981) reported that maximum P uptake rates in cultivars EC68414 and Latur occurred between 60 and 120 d. Field studies on the pattern of P uptake and its distribution in sunflower showed that 41-70% of the P was taken up during the grain filling and ripening stages. Phosphorus accumulated in the leaves during vegetative growth, in the head during button formation and flowering, and in the grain during grain filling and ripening (Mitreva and Iliev 1984). Maximum P concentrations in the tissues of the 2 cultivars grown in an alluvial soil occurred at 40 or 60 d and were 0.12 and 0.08% in the stem, 0.16 and 0.12% in the leaves, 0.20 and 0.16% in the inflorescence, and 0.16 and 0.08% in the root, respectively.

Blamey et al (1987) found that 5.1 kg P (3.9 kg by the seed and 1.2 kg by the stover) was taken up by a sunflower crop producing 1 t seed/ha. Phosphorus concentration was 0.39% in the seed and 0.08% in stover. The 5.1 kg total P uptake is lower than the 8.3 kg P reported by Aulakh et al (1985) (Table 1), perhaps because of differences in the harvest index of the cultivars used. (Blamey et al [1987] assumed a harvest index of 40%).

Fertilizer phosphorus requirements and management

In an early study, sunflower was similar to wheat in uptake and utilization of soil and fertilizer P but was less efficient than barley (Warder and Vijayalakshmi 1974).

In a series of experiments, Spencer and Chan (1981) reported that the P response of sunflower depended greatly on the availability of irrigation and the yield levels
Phosphorus and oilseeds

obtained (Table 4). In general, the P fertilizer requirement of sunflower, as of other oilseeds, is higher under irrigated conditions (Table 3). Spencer and Chan (1981) (Table 4) found that under rainfed conditions, seed yield increased from 0.31 (no P applied) to 0.48 t/ha with 30 kg P/ha applied as TSP; under irrigated conditions, seed yield increased from 2.74 (no P applied) to 4.02 t/ha with 40 kg P/ha applied as TSP when other nutrients were added in adequate amounts. While P application under rainfed conditions increased the seed oil content, it decreased the oil content under irrigated conditions. Generally, P fertilization was reported to have increased the oil content of sunflower seeds (Directorate of Oilseeds Research 1985).

Available Australian literature indicates that the fertilizer P requirement for sunflower resulting in 90% of the maximum yield is on the order of 20 kg/ha (Spencer and Chan 1981). Studies in India indicate a requirement ranging up to 30 kg/ha, depending on the soil available P status and yield goal (Ankineedu et al 1983, Tandon 1987). Yield responses to applied P have commonly occurred up to 20 kg P/ha if the fertilizer was banded below and to the side of the seed; about 4 times this rate was required when the fertilizer was broadcast and incorporated by plowing, especially in phosphate-fixing soils (e.g., Spencer and Chan 1981). Generally, deep band placement of P has been found most effective under rainfed conditions (Ankineedu et al 1983, Tandon 1987).

Safflower

Like sunflower, safflower requires fertilizer N and other macro- and micronutrients, which affect its P requirements and seed yield.

Internal phosphorus requirement

Data on the internal P requirement of safflower are lacking. A recent study at the International Crops Research Institute for the Semi-Arid Tropics (ICRISAT) (T.J. Rego, ICRISAT, unpubl. data) showed that 4.1-6.0 kg P was taken up by safflower (cultivar Manjira) grown on a Vertisol with application of 21 kg P/ha (as SSP) and 120 kg N/ha (as urea) to produce 1 t of seed (Table 5).

<table>
<thead>
<tr>
<th>Year</th>
<th>P concentration (%)</th>
<th>Yield (t/ha)</th>
<th>Total P uptake (kg) to produce 1 t seed</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Seed</td>
<td>Stover</td>
<td>Seed</td>
</tr>
<tr>
<td>1984</td>
<td>0.30</td>
<td>0.05</td>
<td>0.93</td>
</tr>
<tr>
<td>1985</td>
<td>0.47</td>
<td>0.05</td>
<td>0.26</td>
</tr>
<tr>
<td>1987</td>
<td>0.35</td>
<td>0.08</td>
<td>0.97</td>
</tr>
<tr>
<td>Mean</td>
<td>0.37</td>
<td>0.06</td>
<td>0.72</td>
</tr>
</tbody>
</table>

Unpublished data from T. J. Rego, ICRISAT, Patancheru, Andhra Pradesh, 502 324, India. The crop was grown in the postrainy season (Oct-Jan) and received 120 kg N/ha as urea and 21 kg P/ha as SSP.
Fertilizer phosphorus requirements and management

Gaur and Tomar (1980) studied the response of safflower N.P. 30 grown on a sandy loam (pH 8.0) to application of N and P fertilizers; at 60 kg N/ha and 12 kg K/ha, P application at 9 kg/ha significantly increased seed yield from 0.78 to 0.87 t/ha. Further increase in the P rate to 17 or 26 kg/ha did not affect seed yield. In rainfed trials during 1974-76, safflower yield increased with up to 60 kg N/ha and 17 kg P/ha (Sharma and Verma 1982).

The limited data on P response of safflower indicate that up to 20 kg P/ha may be enough for meeting the fertilizer P requirement under rainfed conditions, and about 30 kg P/ha may be needed for irrigated safflower cultivation. In a recent study, application of 13 and 26 kg P/ha to safflower at 12- or 24-cm soil depth increased the growth and P uptake of fertilizer P compared with broadcast P (Sinha et al 1985).

Rapeseed and mustard

Several oilseeds belonging to the Cruciferae are included under rapeseed and mustard. These can be divided into four groups:

- Brown mustard (raya or laha): *Brassica juncea* (L.) Czern. & Coss
- Sarson = Yellow sarson: *B. campestris* L. var. *sarson* Prain; and Brown sarson: *B. campestris* L. var. *dichotoma* Watt
- Toria (lahi): *B. campestris* L. var. *toria* Duth
- Taramira: *Eruca sativa* Mill

Commercially, sarson, toria, and taramira are known as rapeseed, and raya as mustard.

Rapeseed and mustard are important oilseed crops in the Indian subcontinent (Directorate of Oilseeds Research 1984, Kaul and Das 1986). Their cultivation is confined mostly to the temperate and warm-temperate regions of China, Pakistan, Bangladesh, and India where both summer and winter varieties are common (Kaul and Das 1986). These crops are grown on a small scale in Australia (Reid 1981).

Internal phosphorus requirement

Aulakh et al (1985) found that P concentrations in mustard (*B. campestris*, cultivar BSH1) seed and stover at harvest were 0.77 and 0.08% P, respectively, while those for raya (*B. juncea*, cultivar RL 18) were 0.65 and 0.06% P, respectively. The amounts of P taken up by mustard and raya crops producing 1 t seed were 11.3 and 9.0 kg P, respectively (Table 1). Calculations made from the data of Singh et al (1988), who studied P utilization by *B. juncea* for 2 yr in a sandy loam soil (pH 8.2. 13.2-14.4 kg available P/ha) show that about 9 kg P was taken up by the crop producing 1 t of seed. For taramira cultivar Selection 1, 11.3 kg P was taken up to produce 1 t of seed (Aulakh et al 1985, Table 1).

Fertilizer phosphorus requirements and management

Osborne and Batten (1978) investigated the effects of soil and fertilizer N and P on the yield and on oil and protein contents of rape (cultivar Zephyr) grown at two sites in Wagga Wagga, New South Wales, Australia, having a range of available P
concentrations. At both sites, drilled TSP caused significant increases in dry matter production and in seed, oil, and protein yields. Phosphorus response was greatly affected by the soil N supply. Oil yields were 237-1,273 kg ha at the high-N site and 229-916 kg ha at the low-N site.

The results from 1,014 experiments in 1977-78 and 1981-82 on the P response of rapeseed-mustard in farmers’ fields throughout India showed a large response to P (Pillai et al. 1984). The average yield from unfertilized plots was 0.56 t/ha (range 0.24-1.20); average responses to P application of 9 and 17 kg P/ha were 191 (range 51-267) and 329 (range 116-453) kg ha, respectively. (Unfertilized plots did not receive any N, P, or K fertilizer, while fertilized plots received 60 kg N ha uniformly.) These results, conducted under diverse agroclimatic and soil conditions, indicate the role of P fertilization in increasing the yield of this group of oilseeds. The data from these national demonstrations further indicate that it is possible to obtain seed yields of 1.5-2.0 t/ha with balanced fertilization and good cultural practices (Pillai et al. 1984). A rate of 17.4 kg P/ha was found to be adequate when other nutrients such as N and K were supplied in optimum amounts.

Singh et al. (1988) showed from a 2-yr study of P response of mustard grown on a sandy loam (pH 8.2, 0.5 M NaHCO₃-extractable P 13.2-14.4 kg/ha) that seed yield was significantly increased by application of 13 kg P ha as SSP. Further increasing P rate to 26 and 39 kg/ha did not significantly increase seed yield. Single superphosphate blended with biogas plant slurry was a superior source of P in both years for increased yield and P uptake.

It thus seems that about 20 kg P/ha may be sufficient for moderate yields of the rapeseed-mustard cultivars, depending on the soil P level, availability of irrigation, and yield target. Higher P rates are recommended for irrigated crops (Table 3).

Sesame

Sesame is an important oilseed crop in India, Pakistan, Burma, Indochina, Japan, and China (Kaul and Das 1986). It is grown as a rainfed crop in the rainy season and also as an irrigated crop after the rainy season in the Indian subcontinent. Sesame is very responsive to N, and P response is greatly dependent on the N supply.

**Internal phosphorus requirement**

Aulakh et al. (1985) reported that sesame cultivar Pb. Till No. 1 at harvest had P concentrations of 0.80% in the seed and 0.30%; in the stover. By their data, about 20 kg P would be taken up by a sesame crop producing 1 t of seed (Table 1). This value is the highest for the oilseeds discussed in this paper. However, Ankineedu et al. (1983) reported that a sesame crop producing 2.2 t seed/ha removed about 32 kg P/ha, which works out to be 14.5 kg P uptake to produce 1 t of seed—a considerably lower P requirement than that reported by Aulakh et al. (1985).

**Fertilizer phosphorus requirements and management**

The fertilizer P requirement of sesame has been investigated much less than those of the other oilseeds discussed in this paper. The limited data available indicate that, depending on the available P status of the soil, about 15-20 kg P/ha would be
sufficient to meet a crop’s need for P for moderate seed yields (Kaul and Das 1986, Singh and Kaushal 1975). In a 2-yr study in Peshawar, Pakistan, Zaidi and Khan (1981) found that cultivar S 17 gave a higher seed yield than Calida, P 37-4, or the local black seed varieties. Application of nitrophos (20% N, 8.7% P) at 165 kg/ha to supply 33 kg N/ha and 14.3 kg P/ha gave a higher seed yield than those obtained with SSP applied at 14.3 kg P/ha or urea at 33 kg N/ha, clearly suggesting the need for applying N and P together for best results.

Placement of P at 2 or 4 cm below the seed in a soil low in available P (pH 4.5) increased the height and P uptake of sesame. Placement of P with or immediately below the seed increased dry matter production (Ramirez et al 1975). Phosphorus placement near the seed was found to promote initial development of the sesame plant.

Suggestions for research

The foregoing discussion on the P requirements and management of selected edible oilseeds brings out the role of P nutrition in increasing oilseed yields under both rainfed and irrigated conditions. The yields of oilseeds and their P requirements are clearly modified by the availability of other nutrients. Available P status and the behavior of fertilizer P, especially phosphate adsorption-desorption, are good indices of the amount of P likely to be available to plants. Unfortunately, a large body of data on the P response of oilseeds is difficult to interpret because of lack of minimum data sets on available P and other soil characteristics that control P availability. It is also not clear from the literature whether the experiments were irrigated or not, and for a number of studies the data on rainfall during the growing season are not available. There is little information available about the P requirements of oilseeds under rainfed conditions; future research should devote attention to that important area. Different sources of P have been used, but there is no mention of balancing the secondary nutrients supplied by some P sources, making comparison with other sources invalid. Also, there is little mention of the availability of the other nutrients (in soil or through added fertilizers) that greatly affect P response and yield.

For P response, very few rates have generally been employed, giving data that cannot be used for precise determination of a crop’s P requirement. Experiments with at least five or six P rates are needed to compute the P requirement from a range of yield levels. Data are lacking on the internal P requirements of oilseeds, except perhaps for groundnut. The data from experiments described by Laurence (1982) and Bell (1985) on groundnut and by Spencer and Chan (1981) on sunflower provide excellent examples of how plant analyses can be used to determine the internal and fertilizer P requirements of crops. Data on P uptake at maximum yield or at yields corresponding to a critical limit, e.g., 90% of maximum seed yield, would be true indicators of the internal P requirement of an oilseed. In most cases, however, the data on P uptake are available without reference to maximum yield, which could be at best treated as a gross requirement. Fewer but well-planned experiments would furnish highly desirable and useful information in developing suitable P management strategies for increasing the productivity of oilseeds.
References cited


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Notes

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Phosphorus requirements and management of tea, coffee, and cacao

A.H. Ling, P.E. Harding, and V. Ranganathan

Published reports on P requirements and management of tea, coffee, and cacao with special reference to Asia and Oceania are reviewed. Although P is required in relatively small amounts in all three crops, it is nevertheless an essential nutrient for growth and, in the case of coffee and cacao, for flowering, fruit development, and yield. The demand for P will continue to rise as high yields are being produced. Difficulties in establishing yield responses to P, particularly in mature tea and coffee, and the techniques adopted for P management in all three crops in various countries are discussed. The need to develop more cost-effective agronomic, or manuring approaches to ensure more efficient P utilization in tea, coffee, and cacao is stressed.

Tea, coffee, and cacao are three important crops grown extensively in Asia and Oceania. India, China, Sri Lanka, Japan, and Indonesia are major producers of tea. Most of the coffee in this part of the world is grown in Indonesia, India, Philippines, Papua New Guinea (PNG), and Thailand. Cacao is grown mainly in Malaysia, PNG, and Indonesia.

Improvements in planting material and agronomic practices have increased the productivity of these 3 crops tremendously over the last 25 yr. Tea yields exceeding 4.5 t marketable tea/ha per yr are not uncommon in southern India, Japan, and Kenya. Well-managed coffee plantations can yield above 3.0 t green beans/ha per year. In Malaysia, commercial cacao yields exceeding 2.0 t beans (dry basis)/ha per yr have been obtained, while a maximum yield of 6.1 t (dry basis)/ha per yr was reported in an experiment by Chan and Lim (1986). To produce and sustain high yields, adequate fertilizer inputs, including P, are essential.

Although tea, coffee, and, to a lesser extent, cacao are cultivated over a wide range of soils, many of the soils in Asia and Oceania where the crops are planted are acidic and P deficient (Bleeker and Freyne 1981, Briones 1982, Harding 1984, Ranganathan 1977, Widjaja-Adhi and Sudjadi 1987, Wyrley-Birch and Shao 1971). These soils generally have high Fe and Al oxides in their clay fractions, resulting in substantial P-fixation problems (Bachik and Baert 1982, Fox and Searle 1978, Radcliffe and Gillman 1984, Zahurul et al 1981). The low P status of these soils and their strong reaction to applied P necessitate careful P management. Research toward more efficient P usage in tea, coffee, and cacao, however, has not been totally neglected.
This paper reviews the research findings on the P requirements and management of tea, coffee, and cacao, with special reference to countries in Asia and Oceania.

**Tea (Camellia spp. L.)**

**Phosphorus uptake and role**

Studies in India and Kenya showed that tea plants require only a small amount of P compared with other major nutrients (Magambo 1979, Ranganathan 1979). In southern India, tea assimilates about 2.48 kg P for every 100 kg marketable tea produced (Table 1). Of this, 0.50 kg P is in the plucks (marketable tea) and 0.83 kg in the wood collected for fuel by laborers at the time of pruning, making a total of 1.33 kg P removed from the system. Phosphorus in maintenance foliage, fallen leaves, and roots—amounting to 1.15 kg—is retained in the field itself. These data formed the basis for calculating the P requirements of tea for targeted production (Ranganathan 1986).

Willson and Choudhury (1969) claimed that P helps improve the quality of tea. Phosphorus is reported to be essential for the flavor of tea (Sugianto 1985) and also to offset the adverse effects of N on flavor and quality. Recent studies by Ranganathan and Natesan (1987) have shown that manuring levels (N, P, and K) have little effect on fermentation time and quality of tea.

**Response to phosphorus**

In most tea-growing areas, it is difficult to establish the response to P by field experimentation. Numerous attempts have been made to reduce experimental error by standardizing block size and orientation of plots, raising marker clones between plots, lane cutting between plots, randomizing pluckers, and breaking time consciousness (tendency of pluckers to start and stop plucking at the same time without regard to crop on bushes due to treatments). Analysis of southern Indian experiments carried out over the years yields interesting observations warranting a new approach to the statistical interpretation of results. The probability level at which differences are significant showed progressive improvement over the years from P = 0.20 to P= 0.05 with advances in manuring and cultural practices, increase in productivity levels, and better control of experimental error (Table 2).

Despite the difficulties in carrying out field experiments, all tea-growing areas have carried out field trials on P. The responses to P obtained in southern India are summarized in Table 2. Long-term average response to P is in the range of 1 to 10%, with an overall average of 8%, which is used in all cost-benefit analyses.

Phosphorus also interacts with other nutrients. Sharma et al (1977) observed significant response to 22 or 44 kg P/ha only with a potash application greater than 62 kg K/ha in Assam and 25 kg K/ha in West Bengal. Significant P × K interaction was also reported by Ranganathan et al (1982) in southern India. The efficiency of P sources is increased by increasing the N-K ratio from 5:2 to 5:4, and the increase is more pronounced with less efficient sources such as diammophos and superphosphate.
Table 1. P contents of various parts of the tea plant to produce 100 kg marketable tea in southern India.

<table>
<thead>
<tr>
<th>Plant part</th>
<th>Dry matter (kg)</th>
<th>Proportion (%)</th>
<th>P content&lt;sup&gt;a&lt;/sup&gt;</th>
<th>Concentration (g/kg)</th>
<th>Amount (kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Plucks (marketable tea)</td>
<td>100</td>
<td>12.5</td>
<td></td>
<td>5.0</td>
<td>0.50</td>
</tr>
<tr>
<td>2. Maintenance foliage</td>
<td>120</td>
<td>15.0</td>
<td></td>
<td>3.6</td>
<td>0.43</td>
</tr>
<tr>
<td>3. Fallen leaves</td>
<td>80</td>
<td>10.0</td>
<td></td>
<td>3.6</td>
<td>0.29</td>
</tr>
<tr>
<td>4. Stems/branches</td>
<td>320</td>
<td>40.0</td>
<td></td>
<td>2.6</td>
<td>0.83</td>
</tr>
<tr>
<td>5. Roots</td>
<td>180</td>
<td>22.5</td>
<td></td>
<td>2.4</td>
<td>0.43</td>
</tr>
<tr>
<td></td>
<td>800</td>
<td>100.0</td>
<td></td>
<td>3.1</td>
<td>2.48</td>
</tr>
<tr>
<td>Amount removed&lt;sup&gt;b&lt;/sup&gt;</td>
<td>420</td>
<td>52.5</td>
<td></td>
<td>–</td>
<td>1.33</td>
</tr>
</tbody>
</table>

<sup>a</sup>Mean of number of clones and agroclimatic zones of southern India. <sup>b</sup>Removed as crop (1) and for fuel at pruning (4); 2, 3, and 5 are retained in the fields.

Table 2. Response of tea to P in southern India.

<table>
<thead>
<tr>
<th>Location, material</th>
<th>Period</th>
<th>Design&lt;sup&gt;c&lt;/sup&gt;</th>
<th>Mean (kg/ha)</th>
<th>Mean yield response</th>
<th>Level of significance</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>N P&lt;sup&gt;b&lt;/sup&gt; K</td>
<td>t/ha %</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Devarshola (seedling)</td>
<td>1940-53</td>
<td>33 45 34 34</td>
<td>0.8 10 (0-15)</td>
<td>2 yr at P = 0.20 and 7 yr at P = 0.10</td>
<td></td>
</tr>
<tr>
<td>High Range (seedling)</td>
<td>1948-60</td>
<td>RCBD 68 34 34</td>
<td>0.9 14 (0-30)</td>
<td>4 at P + 20, 3 at P = 0.1 and y at P = 0.05</td>
<td></td>
</tr>
<tr>
<td>Cinchona (SP/4/5)</td>
<td>1968-75</td>
<td>RCBD 160 15 91</td>
<td>1.7 8 (4-15)</td>
<td>2 yr at P = 0.10 and 6 yr at P + 0.05</td>
<td></td>
</tr>
<tr>
<td>Sirikundra (seedling)</td>
<td>1969-76</td>
<td>Split plot 212 20 112</td>
<td>2.6 5 (3-13)</td>
<td>6 yr at P = 0.05</td>
<td></td>
</tr>
<tr>
<td>Cinchona (seedling)</td>
<td>1972-76</td>
<td>RCBD 225 17 119</td>
<td>2.5 6 (5-8)</td>
<td>3 yr at P = 0.05</td>
<td></td>
</tr>
<tr>
<td></td>
<td>1976-80</td>
<td>RCBD 265 17 169</td>
<td>3.5 2 (0-4)</td>
<td>2 yr at P = 0.10</td>
<td></td>
</tr>
<tr>
<td></td>
<td>1980-84</td>
<td>RCBD 263 17 239</td>
<td>3.9 4 (1-17)</td>
<td>2 yr at P = 0.10 and 2 yr at P = 0.05</td>
<td></td>
</tr>
<tr>
<td>Cinchona (C/194)</td>
<td>1969-73</td>
<td>RCBD 150 26 94</td>
<td>2.1 12 (2-21)</td>
<td>2 yr at P = 0.05</td>
<td></td>
</tr>
<tr>
<td></td>
<td>1973-77</td>
<td>RCBD 229 25 124</td>
<td>3.1 9 (5-14)</td>
<td>All years at P = 0.05</td>
<td></td>
</tr>
<tr>
<td></td>
<td>1977-81</td>
<td>RCBD 343 24 212</td>
<td>4.3 12 (5-14)</td>
<td>All years at P = 0.05</td>
<td></td>
</tr>
</tbody>
</table>

<sup>a</sup>3 = NPK, RCBD = randomized complete block design. <sup>b</sup>P source was rock phosphate. <sup>c</sup>Based on 13 yr and 4 locations.
The striking improvement noticed in the response to P with increases in N and K suggests the need for more P in intensive cultivation systems.

**Phosphorus management in tea**

*Phosphorus sources.* Results of a long-term trial conducted in southern India showed that all P forms—whether water soluble, citrate soluble, or acid soluble—are equally efficient. This is because they are fixed by Fe and Al oxides and are made available through similar mechanisms involving solubility product principles and ageing effects of precipitated phosphates. Recently, rock phosphate was found to be a better source than superphosphate in Bangladesh even though the difference was not statistically significant (Golam Kibria 1983). The final choice of P source, therefore, depends on cost and availability. Rock phosphate is used in most of the tea-growing countries except Kenya and Indonesia, where superphosphate is used extensively because of availability.

*Application methods.* Studies by Ranganathan (1971) in southern India showed that subsoil P contributes more toward yield than surface soil P. Subsequent long-term trials substantiated the need for placement of P at 15-25 cm (Table 3). This finding led to the application of P as straight fertilizer by placement at 15-25 cm depth in “alavangoo” holes (cylindrical holes, 5-7 cm in diameter, 15-30 cm deep made with a sharp spike) once in 2 yr in fields yielding below 3 t/ha and once a year in fields yielding 3 t/ha or higher.

However, Willson et al (1975) reported significant response in East Africa to broadcast P as superphosphate in undisturbed soil with thick organic mulch. In Malawi, Kenya, and other countries, P is usually broadcast as NPK fertilizer once or twice a year.

*Application frequency.* Phosphate fertilizer is applied periodically once in 3 yr in northeast India, and annually in other countries. In southern India, P was applied once a year until 1976; then, based on field experiments, this was changed to once in 2 yr at double the rate, mainly to save on placement cost. In 1987, annual application was reinstated in fields yielding 3 t/ha or more, because application once in 2 yr could not meet the demand made by the plants (Ranganathan 1986).

*Soil and leaf analyses.* Because of low P requirements and other reasons discussed earlier, P rates vary within a narrow range when discriminated by soil test values. Neither do tissue analyses show any marked variation except in extreme situations, which normally do not happen in the field. Hence, a blanket recommendation for P is generally advocated even in countries where soil or foliar analysis is used for making recommendations. The efficacy of soil tests and of applied P are high in tea compared with that in other crops, suggesting the dominant effect of contact exchange and mycorrhizal associations (Ranganathan 1971).

Tissues used for diagnostic purposes vary; flush is used in Indonesia and the Soviet Union; young, maintenance, and mature foliage in Sri Lanka; and second leaf, third leaf, and green internodes in southern India (Ranganathan 1971). Phosphorus contents in these tissues in healthy bushes vary between 0.22 and 0.50% and decline with age.

No useful system of tissue analysis for diagnostic purpose has been developed for tea so far.
Table 3. Response of tea to P placement\(^a\) (after Ranganathan 1971, Ranganathan et al 1982, UPASI Tea Science Department 1984).

<table>
<thead>
<tr>
<th>Location and clone</th>
<th>Control (% of control)</th>
<th>Surface broadcast</th>
<th>Placement depth</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>5-10 cm (every year)</td>
</tr>
<tr>
<td>Cinchona (SP/4/5)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1968, K limiting</td>
<td>100</td>
<td>97</td>
<td>91</td>
</tr>
<tr>
<td>1969-70, adequate K</td>
<td>100</td>
<td>102</td>
<td>105</td>
</tr>
<tr>
<td>Sirikundra (seedling)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1969-76</td>
<td>–</td>
<td>100</td>
<td>–</td>
</tr>
<tr>
<td>Cinchona (seedling)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1972-76, &lt; 3 t/ha</td>
<td>100</td>
<td>98</td>
<td>–</td>
</tr>
<tr>
<td>1976-84, &gt; 3 t/ha</td>
<td>100</td>
<td>98</td>
<td>–</td>
</tr>
<tr>
<td>Cinchona (C/194)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1979-81, NK = 5:2</td>
<td>100</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>1979-81, NK = 5:4</td>
<td>100</td>
<td>–</td>
<td>–</td>
</tr>
</tbody>
</table>

\(^a\) (–) = no data.

*Rates of application of phosphate.* The rates of P recommended for tea vary between 4 and 26 kg/ha per yr in different countries depending on soil P level, growth stage, and productivity level. A general fertilizer program for tea is given by Ranganathan and Natesan (1984). The recommended P rates range from 26 to 44 kg P/ha per yr.

**Coffee (Coffea spp. L.)**

**Phosphorus uptake and role**

Several detailed studies have been made of the nutritional requirements of coffee. Catani and Moraes (1958) found that 5-yr-old trees took up 7 g P/tree per yr, and that after 4 yr the P requirements were fairly constant. By measuring the net monthly uptake of nutrients by 3- to 4-yr-old trees growing in a nutrient solution, Carvajal et al (1969) derived an annual uptake of 8 g P/tree per yr. Working in East Africa with 3 1/2- to 5-yr-old trees, Cannell and Kimeu (1971) recorded an annual uptake of 6.1 g P/tree, equivalent to about 10 kg P/ha at 1,600 trees/ha. They demonstrated that P was the only nutrient stored and remobilized within the tree in any quantity, the branches being the primary storage organ and the flower buds and fruits the major P sinks.

The amount of P removed from the soil by harvest has also been well studied (Table 4). For every ton of green beans produced, about 2-3 kg P is removed from the system. Carvajal (1972) pointed out that arabica requires slightly less P than other commercial species.

The amount of P required is relatively small compared with other major nutrients. However, P is an essential nutrient. In Kenya, the Coffee Research Foundation considers P in young coffee necessary for root growth, wood formation,
Table 4. P content of coffee (per 1 t green beans).

<table>
<thead>
<tr>
<th>Cultivar</th>
<th>Country</th>
<th>P^a (kg)</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Arabica</td>
<td>Brazil</td>
<td>2.3</td>
<td>Catani and Moraes 1958</td>
</tr>
<tr>
<td>Arabica</td>
<td>India</td>
<td>2.2</td>
<td>Mathew and Krishnamurthy R 1980</td>
</tr>
<tr>
<td>Robusta</td>
<td>Indonesia</td>
<td>2.6</td>
<td>Roelofsen and Coolhaas 1940</td>
</tr>
<tr>
<td>Robusta</td>
<td>Ivory Coast</td>
<td>3.0</td>
<td>Malavolta et al 1962</td>
</tr>
<tr>
<td>Robusta</td>
<td>Ivory Coast</td>
<td>2.7</td>
<td>Snoeck and Dueau 1978</td>
</tr>
<tr>
<td>Liberica</td>
<td>Equatorial Africa</td>
<td>2.8</td>
<td>Malavolta et al 1962</td>
</tr>
<tr>
<td>Excelsa</td>
<td>Equatorial Africa</td>
<td>2.7</td>
<td>Malavolta et al 1962</td>
</tr>
</tbody>
</table>

^aAssuming coffee pulp is not returned to the field.

sound fruit formation, and early maturity of the berries. Schnitzler (1974) found P particularly necessary following heavy pruning of mature coffee, and also for reliable fruit formation. The P nutritional status of mature coffee at the time of flowering may be related to the final yield (Cannell and Kimeu 1971).

Phosphorus has also been reported to affect the quality of the coffee beverage. Amorin et al (1967) report a decrease in beverage quality when the soil P level was inadequate.

Response to phosphorus

Nursery. M’Itungo and Van der Vossen (1981) recorded a significant positive effect on the growth of coffee seedlings when 0.09 g P/seedling was incorporated in the potting mixture as single superphosphate (SSP). Even when farmyard manure was included in the potting mixture, consistent, positive effects of P were noted.

A recent nursery trial in PNG showed a significant response to applications of organic and inorganic P (Table 5). Incorporation of coffee skins in the potting mixture was found to improve dry matter production by 27% after 12 mo of growth. Significant responses to inorganic P were also noted, with soluble phosphates (SSP and triple superphosphate [TSP]) more effective than Christmas Island rock phosphate (CIRP). Table 6 summarizes the relative benefits of incorporating coffee skins and/or SSP in the potting mixtures. These studies confirm the importance of an adequate supply of P for rapid growth of young coffee seedlings.

Young coffee. Van Dierendonck (1959) reported positive responses to P application in young coffee in India, Cameroons, Ivory Coast, and Java. Aduayi (1972) applied 6 levels of P (0- 800 ppm) in a complete nutrient solution to 2 1/2-yr-old coffee in sand culture; significant responses were recorded up to 100 ppm P, but above 400 ppm P, detrimental effects were apparent.

In an ongoing trial in PNG, six levels of P were applied as TSP to the planting holes just prior to field planting of arabica coffee seedlings. Interim results indicate a response to P and suggest a maximum benefit with 60 g TSP/planting hole (P.E. Harding, unpubl. data).

Mature coffee. Reports of significant, consistent responses by mature coffee to P applications are few. In a wide-ranging review, Carvajal (1984) reported no response to P from coffee in Angola, Brazil, Colombia, Costa Rica. Kenya, Puerto Rico, or Tanzania. No P response by mature coffee was reported in Zimbabwe (St. J. Clowes
Table 5. Effects of P fertilizers and coffee skins\(^a\) on P uptake and dry matter production in 12-mo-old arabica coffee seedlings, Papua New Guinea (Harding, unpubl. data).

<table>
<thead>
<tr>
<th>Treatment</th>
<th>Dry matter (g/plant)</th>
<th>P uptake (g/plant)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Shoot</td>
<td>Roots</td>
</tr>
<tr>
<td>With coffee skins</td>
<td></td>
<td></td>
</tr>
<tr>
<td>No fertilizer</td>
<td>8.27</td>
<td>4.86</td>
</tr>
<tr>
<td>LSD (0.05)</td>
<td>6.23</td>
<td>4.09</td>
</tr>
<tr>
<td>No coffee skins</td>
<td>5.52</td>
<td>3.94</td>
</tr>
<tr>
<td>LSD (0.05)</td>
<td>7.06</td>
<td>4.13</td>
</tr>
<tr>
<td>ClRP (0.3 g P)</td>
<td>7.69</td>
<td>4.93</td>
</tr>
<tr>
<td>TSP (0.3 g P)</td>
<td>8.53</td>
<td>4.90</td>
</tr>
<tr>
<td>SSP (0.3 g P)</td>
<td>0.69</td>
<td>0.57</td>
</tr>
</tbody>
</table>

\(^a\)Coffee skins provide 0.18 g P + 3.2 g N/seedling.

Table 6. Effects of coffee skins and/or SSP on dry matter production and P uptake in 12-mo-old arabica coffee seedlings (Harding, unpubl. data).

<table>
<thead>
<tr>
<th>Treatment</th>
<th>Dry matter (g/plant)</th>
<th>P (%)</th>
<th>P uptake (g/plant)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Soil</td>
<td>8.7</td>
<td>0.25</td>
<td>0.023</td>
</tr>
<tr>
<td>Soil + coffee skins</td>
<td>10.22</td>
<td>0.27</td>
<td>0.029</td>
</tr>
<tr>
<td>Soil + SSP</td>
<td>11.84</td>
<td>0.24</td>
<td>0.030</td>
</tr>
<tr>
<td>Soil + SSP + coffee skins</td>
<td>15.02</td>
<td>0.24</td>
<td>0.038</td>
</tr>
</tbody>
</table>

and Hill 1981) and PNG (Carne and Charles 1966, Southern 1969). However, Oruko (1977) reported a significant positive response to P in the absence of K, but a negative response in the presence of K. He concluded that the commonly reported lack of response to P may often be due to a negative interaction between the low P and the high levels of N and K used.

Reviewing 30 yr of coffee research in India, Mathew and Krishnamurthy Rao (1980) concluded that few trials showed a significant response to P, although one 25-yr trial indicated an average yield increase of 170 kg green beans/ha per yr with an application rate of 22 kg P/ha. Another trial from the Central Coffee Research Institute revealed linear yield increases from 0 to 79 kg P/ha. Muller (1966) cites an experiment in Brazil in which P application produced a 385% yield increase.

The lack of consistent yield responses to P may be due to various soil and climatic conditions. The P-fixing capacity and limitations or excesses of other nutrients, and annual variations in climate are important factors that can influence the outcome of experiments. More investigation in this area is needed to improve P fertilization of coffee in tropical soils.

Phosphorus management in coffee

Phosphorus sources. The coffee tree itself provides several sources of organic P. Fallen leaves and prunings are usually left in the field. Cannell and Kimeu (1971)
estimated that 57% of the annual P uptake of a mature single-stem coffee tree in Kenya can be returned to the soil in that way. Garcia (1980) reported that if coffee skins and pulp are returned to the soil after pulping, 37% of the P removed in the cherries is recycled. Other sources of organic P include leaf fall from shade trees and mulches.

Superphosphate, rock phosphate, diammonium phosphate, basic slag, and others have been used as inorganic P sources for coffee. Since the quantities of P required are often relatively small, much of the P applied to coffee is one component of a bulk blend or compound fertilizer.

Application methods. In the nursery, organic P and inorganic P are best mixed in the beds or potting mixtures, where the P is most easily available for uptake by the roots. Supplementary fertilizer may be applied later to the soil surface but is most efficiently applied by foliar application.

Similarly, just prior to field planting, organic and inorganic P should be mixed with the soil in the planting holes to make it readily available for uptake by the roots.

Although foliar application results in a greater efficiency of absorption (Malavolta et al 1962), the quantities of P and other nutrients required would necessitate a great many applications, since concentrations must be kept low to avoid leaf damage. In practice, therefore, most of the nutritional needs of mature coffee are provided through ground application supplemented by foliar application when necessary.

Muller (1966) referred to radio-tracer studies in Brazil demonstrating that absorption was higher when P fertilizer was broadcast evenly on the ground under the branches than when applied in furrows. He also cited similar results from Puerto Rico and contrary findings from Costa Rica, where applications in furrows or holes were more efficient than broadcasting. Mathew and Krishnamurthy Rao (1980) cited later radio-tracer studies from Brazil indicating that the most active roots were 30-45 cm from the stem. They therefore recommended that fertilizer be applied in the drip circle. For soils with high P-retention capacities, Parfitt and Mavo (1975) suggested banding and burying of P fertilizers to minimize fixation.

Thus, for mature coffee on soils with medium or low P-retention capacities, broadcasting P fertilizer evenly on the ground under the branches to within about 30 cm of the stem is the most practical application technique. But on soils with a high P-retention capacity, P fertilizers are best concentrated in narrow bands 30-45 cm from the stem.

Soil and leaf analyses. Several authors, for example Fahmy (1977), Robinson (1985), and Harding (1986), suggest critical soil available P levels that are appropriate to coffee production. Using the Olsen bicarbonate extraction, suitable critical levels are 0-5 ppm (very low), 6-10 ppm (low), 11-15 ppm (medium), and above 15 ppm (high). However, as many soil-, plant-, and fertilizer-related factors can affect P uptake, leaf analysis is more commonly used in assessing the P status of the tree.

Many authors have reported on critical leaf nutrient levels for coffee, and useful reviews have been presented by Muller (1966), Carvajal (1984), and Wilson (1985). A generally accepted critical level, below which P deficiency is indicated, is 0.10% P in the 3d or 4th pair of leaves from the tips of primary branches. More than 0.20% P is
generally considered excessive, but exactly where “subnormal” levels are separated from “normal” ones is not so clear. Most authors consider as normal the range between 0.12 and 0.15% to 0.20%. Since P tends to accumulate in older leaves under conditions of high P supply, and to be retranslocated to the young leaves under conditions of P deficiency (Ozanne 1980), comparing the P contents of both old and young leaves can provide early indications of P deficiency (Muller 1966).

Seasonal variations in P uptake and leaf P level have been reported (Malavolta et al 1962, Muller 1966, Carvajal et al 1969, Southern 1969, Cannell and Kimeu 1971). Leaf P levels reach a minimum when the fruits are ripe and/ or at the end of the dry season, which are therefore the most useful times for leaf sampling.

Rates of application of phosphate. Despite the low P requirement and a paucity of convincing experimental evidence, particularly from mature coffee, P applications are almost always recommended. However, recommended rates vary considerably from place to place because of the effects of soil-related factors such as available P level and P-retention capacity, climatic factors such as those influencing the soil moisture status, and other interactions. The following application rates are therefore intended as a general guide only.

Coffee seedlings grow well in potting mixture containing 15-20% organic material such as farmyard manure or coffee skins and inorganic P fertilizer at a rate equivalent to 0.1-0.3 g P/seedling (Coffee Research Foundation 1983, Robinson 1985).

Just before planting in the field, planting holes should be filled with a 4:1 mix of topsoil and organic material, plus P fertilizer at a rate of 10-15 g P/hole (Coffee Research Foundation 1983; P.E. Harding, unpubl. data).

During the first 2 yr in the field, immature coffee should receive P through ground-applied fertilizers and foliar feeds. A suitable rate is 2.5 g P/tree in the first year, increasing to 5.0 g P/tree during the 2d yr (Robinson 1985).

From year three onwards, the nutritional requirements of coffee are estimated from anticipated yield. Recommended N:P:K ratios vary considerably from 40:13:33 in India (Mathew and Krishna murthy Rao 1980) to 30:4:25 in Colombia (Federacion Nacional de Cafeteros de Colombia 1979), 30:4:33 in Zimbabwe (St. J. Clowes and Hill 1981), and 40:4:33 in PNG (Harding 1987). The recommended rates are mostly in the range of 20-45 kg P/ha per yr.

Cacao (Theobroma cacao L.)

Phosphorus uptake and role
Nutrient uptake by cacao plants has been studied in detail in Malaysia by Thong and Ng (1980), Ling and Mainstone (1982), and Ling (1986). Their studies indicate that the amount of P required by cacao for growth is small in relation to its requirement for other major nutrients. The average uptake is about 5 kg P/ha per yr. The amount of P removed by the crop from a plantation yielding 1.5 t dry beans/ha per yr is similarly small: 5.4 kg P/ha per yr with and 7.4 kg P/ha per yr without recycling of pod husks. With yield increasing to more than 2.0 t dry beans/ha per yr as a result of advances in breeding and agronomic practices, the amount of P removed will increase proportionately.
Ling and Mainstone (1982) reported that the beans, cherelles, and flowers are strong P sinks. The P concentrations in beans, cherelles, and flowers are twice those in leaves, three times those in roots, and four times those in branches and trunks (Table 7). Jadin (1976), working in the Ivory Coast, showed that correction for P and addition of N improve cacao flowering and pod yield. Flowers and cherelles require a rich supply of P, demonstrating the importance of this nutrient for pod production.

Response to phosphorus
Smith and Acquaye (1963) demonstrated the value of P application on a peasant cacao farm in Ghana. Since then, many studies throughout the cacao-growing areas of the world have demonstrated the advantages of P application: in Ghana (Ahenkorah and Akrofi 1971), in Nigeria (Wessel 1971), in the Ivory Coast, in Brazil (Cabala et al 1975a, Morais et al 1978), in Malaysia (Mainstone et al 1977, Ling 1988), and in Indonesia (Sugiyono et al 1983). Positive growth and yield responses have been obtained with differing cultivars (Amelonado, Cotango and Amazon/Trinitario hybrids) in contrasting environments.

Long-term fertilizer experiments on different soil types have been conducted in Malaysia (Table 8). On basaltic soil (Ferralsol) in Sabah, a significant yield response to superphosphate (up to 52.8 kg P/ha per yr) was reported by Wyrley-Birch and Ng (1970).

In a 3x4 NPKMg factorial trial on an Ultisol with cacao under medium shade, Ling (1984) found that rock phosphate applications at 33-66 kg P/ha per yr increased yield by 9-26% and also increased leaf P. The response to P was related to soil available P (Bray and Kurtz No. 2) of 9-17 ppm. Similar results were reported by Teoh et al (1986) on an Oxisol. Recent studies by Ling (1985) showed no indication of the need for P fertilizer reducing with time due to the residual effect of earlier applications.

Table 7. P content of various plant components in 9- to 10-yr-old cacao in Malaysia (Ling and Mainstone 1982).

<table>
<thead>
<tr>
<th>Plant part</th>
<th>Pa (kg/ha)</th>
<th>P concentration (% dry matter)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Foliage</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Green</td>
<td>11.4</td>
<td>0.158</td>
</tr>
<tr>
<td>Litter</td>
<td>3.4</td>
<td>0.084</td>
</tr>
<tr>
<td>Trunk</td>
<td>6.4</td>
<td>0.075</td>
</tr>
<tr>
<td>Branches</td>
<td>19.4</td>
<td>0.067</td>
</tr>
<tr>
<td>Roots</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Tap</td>
<td>4.1</td>
<td>0.110</td>
</tr>
<tr>
<td>Lateral</td>
<td>4.5</td>
<td>0.066</td>
</tr>
<tr>
<td>Fruits 1.5 t/ha</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Beans</td>
<td>5.4</td>
<td>0.358</td>
</tr>
<tr>
<td>Husks</td>
<td>2.0</td>
<td>0.145</td>
</tr>
<tr>
<td>Cherelles</td>
<td>0.4</td>
<td>0.329</td>
</tr>
<tr>
<td>Flowers</td>
<td>Negligible</td>
<td>0.289</td>
</tr>
<tr>
<td>Total</td>
<td>57.0</td>
<td>–</td>
</tr>
</tbody>
</table>

* Based on a stand 1.074 trees/ha.
Table 8. Response of cacao to P application in Malaysia.

<table>
<thead>
<tr>
<th>Soil type</th>
<th>pH</th>
<th>Available P (ppm)</th>
<th>aP (kg/ha per yr)</th>
<th>bResponse (%)</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Table (Ferralsol)</td>
<td>4.6</td>
<td>&lt;5</td>
<td>29.5-59.4</td>
<td>11</td>
<td>Wyrley-Birch and Ng 1970</td>
</tr>
<tr>
<td>Bungor (Ultisol)</td>
<td>4.5</td>
<td>9-17</td>
<td>33.0-66.0</td>
<td>9</td>
<td>Ling 1984</td>
</tr>
<tr>
<td>Jerangau (Oxisol)</td>
<td>5.1</td>
<td>&lt;6</td>
<td>39.6-79.2</td>
<td>17</td>
<td>Teoh et al 1984</td>
</tr>
<tr>
<td>Munchong (Oxisol)</td>
<td>4.3</td>
<td>12-18</td>
<td>35.2-70.4</td>
<td>11</td>
<td>Ling 1988</td>
</tr>
<tr>
<td>Bernam (Inceptisol)</td>
<td>4.1</td>
<td>&gt;40</td>
<td>53.7-107.4</td>
<td>ns</td>
<td>Teoh et al 1984</td>
</tr>
</tbody>
</table>

a Based on Bray and Kurtz No. 2 extraction method. b Phosphate rock use except in the trial by Wyrley-Birch and Ng (1970). c Superphosphate.

On the other hand, trials carried out on coastal clay soils (Inceptisols) showed no response to P (Ng and Chan 1977, Teoh et al 1986) perhaps because of the inherently high available P status (greater than 40 ppm) in such soils.

On red-yellow Podzolic soil (Ultisol) in North Sumatra, P applications of 66-132 kg P/ha per yr increased leaf P and yield (Sugiyono et al 1983). The soil available P (Bray and Kurtz No. 1) ranged from 6 to 11 ppm.

Phosphorus also interacts with other nutrients. In cacao, P had a positive interaction with K (Teoh et al 1986). K application enhanced the effect of P, suggesting the need to consider the P/K balance in P fertilization programs.

On acid tropical soils, e.g., Ultisols and Oxisols, an adequate P supply is thus necessary to sustain high cacao production.

**Phosphorus management in cacao**

**Phosphate sources.** Most of the P used in Malaysia is ground phosphate rock (PR). Its effectiveness as a P source for cacao on acid tropical soils has been well documented (Ling 1988). It is also much cheaper than other sources. In the other cacao-growing countries, soluble phosphates are generally used.

As P is important for flowering and cherelle formation in cacao, the presence of readily available P at those critical stages may be beneficial, especially on soils that are highly P-deficient and have not had the benefits of preplanting P treatment. In such cases, more readily available phosphates, e.g., superphosphate and reactive PR, may be useful. We need to evaluate the relative efficiency of the various P sources for cacao.

**Application methods.** Application methods vary with the stage of plant development.

- **Nursery.** Experiments in Malaysia have shown that PR enhances the growth of cacao seedlings. Mainstone et al (1977) demonstrated that mixing CIRP with soil used for filling polybags increased P uptake and growth.
• **Preplanting.** Mainstone et al (1977) reported that overall soil preplanting treatment with PR and ground Mg limestone improved cacao establishment and growth. However, the P rate (39.6 kg P/ha) was low. Recent studies by Ling (1988) demonstrated that preplanting incorporation of a high rate of PR (88 kg P/ha) by plowing into the top 15 cm of the soil improved not only the growth but also the initial yield of cacao. Preplanting incorporation of PR can help to reduce P fixation problems and provide residual P to enhance cacao yield.

• **Planting hole.** Trials by Mainstone et al (1977) on a sandy colluvial soil showed that application of rock phosphate in planting holes (170 g CIRP/hole) enhanced the establishment and growth of young cacao. Since P fertilizer is relatively immobile in the soil, the placement of a high concentration of P near or in direct contact with the core of roots at planting facilitates early P uptake and root development, resulting in better growth.

• **Field.** In mature cacao, P fertilizers are usually broadcast on the soil surface. Studies in West Africa on the effects of placement of radioactive P at different depths and distances from the trunk indicated that the zone of maximum P uptake is in the top layer (0-7.5 cm) of the soil and at a distance of 80-160 cm from the trunk (Ahenkorah 1975, Oyejola 1974). These data support the general practice of broadcasting P fertilizers on the soil surface for mature cacao.

**Soil and leaf analyses.** Several authors have suggested critical soil-available P levels for cacao production (Cabala et al 1975b, Hardy 1960, Wessel 1971). Although soil available P levels have proved useful to indicate potential response to P application, different extraction methods have been used. The extraction method must be standardized to allow more accurate transfer of results to other areas.

Leaf analysis as a diagnostic tool for fertilizer assessment in cacao and its problems were well reviewed by Eernstman (1968). Despite many limitations, leaf analysis has been used with success for detecting nutrient deficiencies and imbalances (Ling and Mainstone 1982, Mainstone et al 1977, Wessel 1971). Recent studies in Malaysia indicate that careful sampling techniques—taking into account the leaf position, age, and the flushing pattern—can improve the precision of detecting low or deficient P levels in cacao (Ling 1984). Generally accepted critical levels for leaf P (based on the 4th leaf of a recently hardened flush) are <0.13% = deficient, 0.14-0.20% = low, and >0.20% = normal.

**Rates of application of phosphate.** Nutritional studies throughout the world have confirmed that on acid tropical soils, adequate P supply is essential for rapid growth and high yield of cacao.

Phosphorus fertilizer recommendations for mature cacao were given by Wessel (1971) for Nigeria and by Cabala et al (1975b) for Bahia, Brazil. Recently, Ling (1988) used results from short- and long-term trials to outline a comprehensive P fertilization program, starting from the nursery through to preplanting, planting hole, and postplanting, for cacao plantations in Malaysia. The P rates recommended for mature cacao in some of the major cacao-producing countries are summarized in Table 9.
Table 9. P fertilizer recommendations for mature cacao.

<table>
<thead>
<tr>
<th>Location</th>
<th>P status</th>
<th>P recommendation (kg/ha)</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Soil</td>
<td>Leaf</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Brazil</td>
<td>&lt;5</td>
<td>39.6</td>
<td>Cabala et al 1975b</td>
</tr>
<tr>
<td>(Bahia)</td>
<td>6-15</td>
<td>19.8-39.6</td>
<td>Wessel 1971</td>
</tr>
<tr>
<td></td>
<td>&gt;15</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>Nigeria</td>
<td>&lt;10</td>
<td>22-28.6</td>
<td>Ling 1988</td>
</tr>
<tr>
<td></td>
<td>&gt;12</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>Malaysia</td>
<td>&lt;15</td>
<td>39.6-66</td>
<td></td>
</tr>
<tr>
<td>(Peninsular)</td>
<td>&gt;15</td>
<td>39.6-66</td>
<td></td>
</tr>
<tr>
<td></td>
<td>&gt;0.20</td>
<td>13.2-26.4</td>
<td></td>
</tr>
<tr>
<td></td>
<td>&gt;0.20</td>
<td>0</td>
<td></td>
</tr>
</tbody>
</table>

aSoil available P, based on Bray and Kurtz extraction method. b5- to 10-wk-old leaves sampled in Apr-May for Nigeria, and 4th leaf of recently hardened flushes in Apr-May for Malaysia.

Conclusions

Tea, coffee, and cacao require only a small amount of P for growth and production compared with their requirements for other major nutrients. Phosphorus is nevertheless an essential nutrient for growth and, in the case of coffee and cacao, for flowering, fruit development, and yield. The demand for P will increase when high yields are being produced.

Difficulties in establishing the yield response to P have been encountered, particularly in mature tea and coffee. Despite limited experimental evidence, P applications continue to be recommended and form an integral part of fertilization programs for all three crops.

Since most of the tea, coffee, and cacao in Asia and Oceania are cultivated on soils with low P and high P retention capacity, more efficient P usage is needed. Correct choice of P source, proper placement, and application of optimum rate at the appropriate time will continue to feature prominently in the management of these crops. Efforts to develop more cost-effective agronomic approaches to ensure more efficient P utilization must continue.

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Phosphorus and tea, coffee, and cacao


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Notes

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Acknowledgment: The authors are grateful to their respective organizations—Dunlop Estates Bhd, PNG Coffee Research Institute, and UPASI Tea Research Institute—for permission to present this paper.

Citation information: International Rice Research Institute (1990) Phosphorus requirements for sustainable agriculture in Asia and Oceania. P.O. Box 933, Manila, Philippines.
The paper reviews published work on P requirements and P management in oil palm, coconut, and rubber. Phosphorus responses by new plantings of oil palm and rubber and during the early growth phase in replanting are well established, but this is not so with coconut. Soluble phosphate may have an advantage as a P source in the initial growth phase, but on subsequent growth and production, high-grade phosphate rock is equally effective and often becomes the preferred source. Residual P can be appreciable, and available residual P is often considered in calculating P fertilizer requirements. Nutrient budgets for oil palm and rubber indicate that the current practice of P fertilization for these two crops is realistic.

Plantation crops such as oil palm, coconut, and rubber play a major role in the economies of many tropical Asian countries. These crops, though grown mainly by smallholders, account for a major portion of export revenue from agriculture. Agricultural inputs, including fertilizers, are added to these crops, but to varying degrees.

Phosphorus, though crucial to the productivity of perennial tree crops, is required in smaller amounts than are other nutrients such as N and K. With the advent of higher yielding varieties, however, improved management practices, and increased use of N and K fertilizers, P management becomes more important. This is further accentuated by newer areas with marginal soils being brought into cultivation.

Fertilizer phosphorus management

The P requirements of oil palm, coconut, and rubber are assessed, together with their differential response to different forms of P.

Response to phosphorus fertilizer

Chan (1982) and Pushparajah (1977) showed that the magnitude of response of oil palm and rubber to P fertilizer depends on the history of land use. In both crops, large responses were obtained when new plantings were established in jungle clearings. Large responses were reported for oil palm on cleared land by Taniputra and Panjaitan (1982) in Indonesia and by Ng (1986) in Malaysia (Table 1). On such new areas, the low level of inherent P in the soil would not be able to sustain yields for long, and hence the response to P fertilizers becomes larger with time. In the
Table 1. Oil palm yield response\textsuperscript{a} to phosphate rock.

<table>
<thead>
<tr>
<th>Soil</th>
<th>P rate (kg/palm)</th>
<th>Fresh fruit bunch (FFB) yield (t/ha) by given year after planting</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>45</td>
<td>6</td>
</tr>
<tr>
<td>Podzolic (Ultisol?\textsuperscript{b})</td>
<td>0</td>
<td>12.1</td>
</tr>
<tr>
<td></td>
<td>0.3</td>
<td>–</td>
</tr>
<tr>
<td></td>
<td>0.6</td>
<td>–</td>
</tr>
<tr>
<td>Red yellow podzolic (Paleudult, Ultisol)\textsuperscript{c}</td>
<td>0</td>
<td>15.5</td>
</tr>
<tr>
<td></td>
<td>0.29</td>
<td>16.5*</td>
</tr>
<tr>
<td></td>
<td>0.58</td>
<td>16.1</td>
</tr>
</tbody>
</table>

\textsuperscript{a} = significant at P < 0.05, \textsuperscript{**} = P > 0.001. \textsuperscript{b} After Taniputra and Panjaitan (1982). \textsuperscript{c} After Ng (1986).

absence of N, P alone at 0.4 kg/palm increased yield by 31 kg fresh fruit bunch (FFB)/palm per yr; but with N at 0.84 kg/palm, P fertilizer gave a yield increase of 41 kg FFB/palm (Table 2).

Good responses were obtained on replants during the early growth phase of 5 yr or more; responses in subsequent years were variable and often low. The initial response to P in the immature phase, and the limited response of mature rubber or oil palm were ascribed to the new stands being planted in the interrow spaces of older stands and hence away from the zone of former P application where there was residual P.

A review of P fertilization trials in coconut in many Asian and African countries (Wahid et al 1977) showed that P application had no effect. Where responses were observed, they occurred after many years of continuous P application (Muliyar and Nelliat 1971, Ouvrier and Ochs 1978). Nevertheless, Fremond (1966) and Muliyar and Nelliat (1971) found P response in the presence of K.

Chew (1978) indicated that response to P fertilizers in coconut was evident in most trials he considered; this could have been due to the generally low levels of fertilizers used in coconut plantings and thus the lack of P buildup in the soil, or to K not being a limiting factor. With continued use of P fertilizer and consequent buildup in soil, the need for it could be lower. Furthermore, in soils high in P (e.g., Tropudulfs) there would be no P response (Von Uexkull 1972); the leaves of coconut palms on these soils reflected sufficient P levels (0.15%).

Sources of phosphorus fertilizers

Generally, oil palm, coconut, and rubber are cultivated on acid soils (pH <5). With tree crops like rubber, phosphate rock (PR) (with at least 25% of the P being in the citric acid soluble P) was generally equally as effective as soluble phosphates (Pushparajah 1977). However, in the initial growth stages of rubber (up to 1 yr), soluble P gave an advantage. This was true with oil palm in Malaysia and elsewhere.

Despite these findings, both soluble phosphate and PR are used in all three crops, the choice being dictated by availability. Where other nutrients are also
Table 2. N-P interaction on FFB yield of oil palm\textsuperscript{d} (after Akbar et al 1976).

<table>
<thead>
<tr>
<th>Level of $p^b$ (kg/palm per yr)</th>
<th>FFB yield (kg/palm) at N$^c$ level of</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0</td>
</tr>
<tr>
<td>0</td>
<td>92</td>
</tr>
<tr>
<td>0.7</td>
<td>102</td>
</tr>
<tr>
<td>1.4</td>
<td>123</td>
</tr>
</tbody>
</table>

\textsuperscript{a}Averaged for 1972-73 and 1974-75. \textsuperscript{b}As triple superphosphate. \textsuperscript{c}$(\text{NH}_4)_2\text{SO}_4$.

required, compound fertilizers with soluble P are often used. Usually, the P in PR at source is cheaper than P from soluble phosphate. But when internal transportation and application costs are considered, the higher P content in soluble P sources could result in their being cheaper, hence the preference for this source.

Application methods
Fertilizer is initially applied to all three crops by broadcasting in a circle, the circle widening as the tree grows and the root system spreads. By the fifth or sixth year, the roots of adjoining trees overlap, and fertilizer could be broadcast over the whole area. However, application is still confined to weeded circles or strips to minimize competition from weeds. When the trees are planted on platforms or terraces, the tendency is to broadcast the fertilizer on the restricted zones. Thus, the area on which the fertilizer is applied is often only about a third to a quarter of the crop area. This results in the effective P fertilizer application rate per surface area being about three to four times the rate per crop area.

Frequency and rates of phosphorus application
The rate of fertilizer application varies with the age of the trees and the yield level in addition to soil conditions. In well-managed plantations, frond or leaf analysis is used to assess the sufficiency or deficiency of the nutrient in mature trees, and hence the rate of fertilizer application. In other areas, generalized schedules are used either on a regular or an ad hoc basis.

During immaturity, fertilizer is generally applied a number of times each year. When the plants are mature (yielding), fertilizer is applied once a year. For oil palm, Chan (1981) confirmed that P fertilizers, when needed, should be applied once a year or at least once in 18 mo (Table 3).

For coconut, Felizardo (1982) suggested rates based on soil P levels (Table 4). Rates applied in other countries vary, possibly because of differences in soil P and yield level.

Indices for phosphorus
Attempts have been made to determine a suitable index to relate crop requirement to level of P in the soil or in leaf tissues. The degree of such relationships observed seems to vary with the crop and the intensity of the investigation.
Table 3. Effects of P application frequency on oil palm yield (after Chan 1981).

<table>
<thead>
<tr>
<th>Application frequency</th>
<th>FFB yield (t/ha per yr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>2.07</td>
</tr>
<tr>
<td>Once in 24 mo</td>
<td>2.66</td>
</tr>
<tr>
<td>Once in 18 mo</td>
<td>2.96</td>
</tr>
<tr>
<td>Once in 12 mo</td>
<td>2.07</td>
</tr>
<tr>
<td>SE</td>
<td>± 0.08</td>
</tr>
</tbody>
</table>

Table 4. Suggested P application rate for coconut based on soil P level (Felizardo 1982).

<table>
<thead>
<tr>
<th>Olsen P (ppm)</th>
<th>P application (g/tree per yr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0-6</td>
<td>180</td>
</tr>
<tr>
<td>7-10</td>
<td>130</td>
</tr>
<tr>
<td>11-15</td>
<td>90</td>
</tr>
<tr>
<td>16-20</td>
<td>40</td>
</tr>
<tr>
<td>&gt;20</td>
<td>0</td>
</tr>
</tbody>
</table>

Soil phosphorus indices
Soil analysis as a predictive indicator of P need has been used relatively successfully in two of the three crops. Generally, samplings for analysis have been confined to the surface soil (0-30 cm depth). The relationships are discussed below.

Oil palm. For oil palm, soil analysis is used mainly to monitor P buildup.

Coconut. For coconut, Cordova (1965) considered 10 ppm available P in soil as the critical level. However, Limbaga (1986) considered 15-20 ppm as the critical level, and 30-35 ppm Olsen P as the optimal P level in surface soil. Yield tended to decrease at higher P levels.

Rubber. Of the three crops, only in rubber has a relationship between levels of P in soil and in leaf tissue been shown. Lau et al (1977) showed that P extracted by perchloric-sulfuric acid digestion and P extracted by ammonium fluoride-HCl (Bray and Kurts II) showed good correlation with leaf P in Oxisols and Ultisols. But for rubber on Entisols (e.g., Tropaquepts derived from marine deposits) with high organic matter (>2.5% C), extraction with hot 0.1 N NaOH showed better correlation with leaf P, thus suggesting the need for different indices depending on soil C content.

Owen (1953), working mainly with Ultisols and Oxisols, indicated that 11 ppm P (NH4F-HCl extraction) was the threshold value beyond which responses were unlikely. However, Pushparajah (1977) showed that this was applicable only in soils where C was <1.50%. In areas with higher organic matter, responses were unlikely even when NH4F-HCl- extractable P was lower.

Leaf index
In all three crops, relationships have been demonstrated between leaf P and plant growth. But, except for rubber, it is still not possible to predict P requirements based on such diagnoses.
Oilpalm. Foster and Chang (1977) suggested that the critical rates of leaf P (in frond 17 on oil palm) are 0.165-0.175% on Entisols on the coastal plains and 0.175-0.185% on Oxisols and Ultisols. However, Ng (1977) indicated that the optimal leaf P content decreases with age, becoming as low as 0.150-0.155% for palms older than 10 yr. It is still not possible to decide on the rate of P to be applied on the basis of frond analysis alone.

Coconut. Magat et al. (1981) showed a relationship between leaf P and coconut yield. A critical level of 0.12% in leaf 14 as suggested by Fremond (1966) and Magat (1978) was considered satisfactory for a long time. However, Limbaga (1986) showed that yield increases were obtained by increasing frond P up to 0.15%, indicating this to be the optimal level.

Rubber. The Rubber Research Institute of Malaya (1963) showed that, for mature rubber, responses were likely if the P content of leaves in the shade was <0.21%; at levels >0.27%, responses were unlikely. Subsequently, Pushparajah (1977) showed a relationship between leaf P and soil P (NH₄F-HCl and H₂SO₄-HClO₄ extraction) and the quantity of fertilizer needed by rubber.

Soil-phosphorus interaction

As the three crops are export crops, it is pertinent to consider the buildup and availability of any residual P.

Buildup of phosphorus

Oil palm, coconut, and rubber all have an economic life of >20 yr. Thus, the continued use of fertilizers, particularly P, results in nutrient buildup in the soil. This is further accentuated by the fact that the fertilizers are generally applied in circles around the tree bases or along the tree rows. Thus, though the rate per unit area may appear small, the effective rate per unit of soil area is large.

Using rubber as an example, Pushparajah (1966) and Pushparajah et al. (1976, 1977) showed that the continued use of P fertilizers resulted in a P buildup. The forms in which the residual P occurred in the soil differed with source of P applied (Table 5). When soluble phosphate was used, a relatively large portion was in the form of Al-P. However, when PR was used, Ca-P and Fe-P were dominant. The dominance of Ca-P was further reflected by the high Ca content in the soil receiving PR. Additionally, PR also increased soil pH.

Movement of phosphorus to lower depths

Though tropical soils have a high P-fixation capacity, movement of P down the profile was evident in both Oxisols and Ultisols. Such movement could be through movement of P in solution in the case of soluble P, or dissolution of PR or physical movement through root channels. Pushparajah et al. (1976) showed that higher amounts of residual P were found in the clay and silt fraction (about 90%), although most of the PR applied was in the sand fraction (63%). The concurrent use of (NH₄)₂SO₄ resulted in higher P accumulation in the clay fraction. Thus, PR generally undergoes dissolution on “weathering” in acid soils (pH 4.5), and (NH₄)₂SO₄ has an acidifying effect.
Table 5. Phosphate fraction in soil and availability of residual P on an Ultisol (after Pushparajah et al. 1977).

<table>
<thead>
<tr>
<th>Treatment</th>
<th>Depth (cm)</th>
<th>Soil pH (H₂O)</th>
<th>Phosphate fraction (mg/1800 g soil)</th>
<th>Total Ca (mg/1800 g soil)</th>
<th>P uptake by <em>Pueraria</em> (mg/1800 g soil)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Control</td>
<td>0-2.5</td>
<td>4.0</td>
<td>20 39 5 20</td>
<td>173</td>
<td>4.6</td>
</tr>
<tr>
<td></td>
<td>2.6-7.5</td>
<td>4.2</td>
<td>14 39 5 20</td>
<td>47</td>
<td>3.0</td>
</tr>
<tr>
<td></td>
<td>7.6-15.0</td>
<td>4.4</td>
<td>6 22 3 11</td>
<td>65</td>
<td>3.6</td>
</tr>
<tr>
<td></td>
<td>15.1-30.0</td>
<td>4.5</td>
<td>5 17 2 9</td>
<td>25</td>
<td>3.1</td>
</tr>
<tr>
<td></td>
<td>30.1-45.0</td>
<td>4.6</td>
<td>4 14 2 7</td>
<td>47</td>
<td>2.2</td>
</tr>
<tr>
<td>Soluble P*</td>
<td>0-2.5</td>
<td>4.5</td>
<td>447 190 119 553</td>
<td>220</td>
<td>109.4</td>
</tr>
<tr>
<td>Double super-</td>
<td>2.6-7.5</td>
<td>4.6</td>
<td>441 207 113 553</td>
<td>108</td>
<td>76.5</td>
</tr>
<tr>
<td>phosphate</td>
<td>7.6-15.0</td>
<td>4.4</td>
<td>194 135 57 268</td>
<td>61</td>
<td>55.1</td>
</tr>
<tr>
<td></td>
<td>15.1-30.0</td>
<td>4.4</td>
<td>331 60 65 29</td>
<td>32</td>
<td>25.4</td>
</tr>
<tr>
<td></td>
<td>30.1-45.0</td>
<td>4.6</td>
<td>6 23 5 11</td>
<td>28</td>
<td>5.0</td>
</tr>
<tr>
<td>Phosphate rock</td>
<td>0-2.5</td>
<td>4.3</td>
<td>186 409 644 284</td>
<td>2550</td>
<td>120.3</td>
</tr>
<tr>
<td></td>
<td>2.6-7.5</td>
<td>4.6</td>
<td>95 272 179 238</td>
<td>727</td>
<td>33.3</td>
</tr>
<tr>
<td></td>
<td>7.6-15.0</td>
<td>4.6</td>
<td>29 103 26 59</td>
<td>241</td>
<td>54.8</td>
</tr>
<tr>
<td></td>
<td>15.1-30.0</td>
<td>4.6</td>
<td>10 37 6 18</td>
<td>191</td>
<td>25.0</td>
</tr>
<tr>
<td></td>
<td>30.1-45.0</td>
<td>4.6</td>
<td>10 29 5 14</td>
<td>103</td>
<td>5.7</td>
</tr>
</tbody>
</table>

*1830 kg P per effective ha or about 350 kg P per crop ha from 1959 to 1976.

On the other hand, on a sandy loam soil in the dry zone in Sri Lanka, no movement of P down the profile was noticeable in the eighth year after application to coconut, particularly when PR was the P source (Loganathan and Nalliah 1973). This implies that rainfall is a factor influencing downward movement of P.

**Availability of residual phosphorus**

Pushparajah et al. (1977) showed through cropping that a substantial portion of residual P is available (Table 5). In a field trial, they also showed that such residual P was available to rubber, which required no additional P fertilizer for the first 10 yr of growth. Such buildup must be considered in formulating fertilizer use policy.

**Nutrient immobilization and removal in harvest**

The adequacy or inadequacy of a fertilizer regime is determined by the fertilizer budget, which is the balance between additions and removal.

**Fertilizer phosphorus applied**

The three crops are perennials, so not only annual additions but the cumulative amount applied throughout the life of the crop needs to be considered. Additions through leaf fall (or fronds or pruning) also merit consideration.

*Oil palm.* For oil palm, application rates are based on Ng (1972, 1986) and Chan (1982). Average application rates on inland soils, mainly Ultisols and some Oxisols,
have varied with the age of the trees. The totals applied over different time periods are shown in Figure 1. The application rates on replanting were somewhat lower.

In addition to applied inorganic P, organic P in plant residues (pruned fronds, male inflorescences, and often empty bunches) is returned to the soil. This accounts for an average of 11-13 kg ha per yr, a substantial contribution.

Coconut. For coconut, generalized recommendations are unavailable, except those of De Geus (1973) and Felizardo (1982) (Table 4).

Rubber. Application rates in rubber vary with the age of the trees and, during the later phase, with soil, exploitation system, clones, and yield level. Fertilizer rates for immature rubber were reported by Pushparajah and Mahmud (1977), those for mature rubber according to oil by Chan et al (1972), and those for clones and yield level by Pushparajah (1977). A survey (Pushparajah 1983) showed that the major rubber-producing countries were using P rates similar to that recommended in
Malaysia, particularly during the first few years of plant growth. The amounts applied are shown in Figure 1.

In addition, annual leaf fall in rubber accounts for 1.8-3.9 kg P/yr, varying with the age of the trees (Pushparajah and Tajuddin 1982, Shorrocks 1965). The total contribution of leaf litter is also shown in Figure 1.

**Nutrients immobilized and drained**

As the trees grow older, the total amounts of P and other nutrients immobilized increase.

*Oil palm.* Ng (1972,1986) showed that the amount immobilized in oil palm is as low as 0.8 kg P/ha in the first year, increasing to 17.4 kg/ha per yr during the peak growth phase. Removal in the harvest varies from a low of 2.3 kg P/ha in the first full year of harvest to a peak of about 11.6 kg P/ha per yr for a few years, declining somewhat with declining yield. The total immobilized in the tree amounts to about 330 kg/ha, while that removed in the harvest is about 220 kg/ha, accounting for a total immobilization and removal of 550 kg P/ha (Fig. 1).

*Coconut.* Well-defined figures are not readily available for coconut. However, Chew (1978), Omoti et al (1986), and Ouvrier and Ochs (1980) reported that over a 25-yr life cycle, about 9-10 kg P/ha is immobilized in the trunks each year. The removal of P in nuts (husks, shells, albumen, and water) varies with yield. With hybrid coconut (Mawa), such removal can be large: up to 15 kg P/ha per yr with a peak yield of 6 t. An average yield of 2 t of copra would remove about 4.4 kg/ha annually.

*Rubber.* About 200 kg P/ha is immobilized in rubber trees over a 25-yr period, while the amount removed in the harvest is just over 90 kg P/ha. The amount removed in the harvest varies from a low of 1.2 to 7.8 kg P/ha per yr with peak yields.

**Nutrient budget**

Based on the data presented, it is possible to attempt a P nutrient budget for oil palm and rubber but not for coconut. Preliminary estimates of such nutrient budgets are discussed below.

*Oil palm.* Over a 25-yr period, P removed by oil palm from the soil (both by immobilization and harvest) is less than that added, and the harvest removed only about 35% of that added. That which is taken up in the aerial portion (trunk, fronds, etc.) is often returned to the soil during replanting. In fact, the current trend of poisoning the old stands of palms and interplanting the new stands would be an ideal way of nutrient cycling. By this system, P application in future replantings may be reduced considerably.

*Coconut.* Available data in coconut are insufficient for an evaluation of the budget.

*Rubber.* In a replanted stand of rubber, the total amount of P immobilized in the trees and removed in the harvest is equal to or slightly less than the total fertilizer P added (Fig. 1). The total crop removed only about 33% of the P fertilizer added.

The apparent discrepancy in good performance of rubber and the apparent shortfall in P added in fertilizer may be due to residual P in the soil. Such residual P is
not only from the soil buildup but also from the crop residue left behind from previous stands. Even when the old stand of rubber is exploited for timber, only about one-third of the dry mass is removed. Thus, the debris left in the field would supply about 130–150 kg P/ha.

Conclusion

Relatively well-established systems of P management exist for both oil palm and rubber. The practices take into account the P budget, and thus fertilizer P use, in these two crops—the balance between soil P buildup and removal in the harvest. For coconut, however, the practice does not appear to be available, varying responses having been observed.

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Notes

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Citation information: International Rice Research Institute (1990) Phosphorus requirements for sustainable agriculture in Asia and Oceania. P.O. Box 933, Manila, Philippines.
Phosphorus requirements and management of sugarcane, pineapple, and banana

R.L. Fox, R.P. Bosshart, D. Sompongse, and Lin Mu-lien

Phosphorus in solution is the immediate source of P for plants growing in soils. In soil solutions, the P concentration associated with near maximum attainable growth is approximately 0.05 mg/liter for mycorrhizal bananas and 0.005-0.01 mg/liter for sugarcane. It is apparently less for pineapple. The soils on which these crops grow range from fertile alluvium to highly weathered and infertile materials of varied origin. Phosphate sorption varies accordingly, but it generally increases with weathering. Fertilizer requirements, which are products of plant requirements and soil quantity and capacity factors, range tremendously. Evidence indicates that pineapple is strongly mycorrhizae-dependent, banana perhaps less so, and sugarcane least of all. The P response curves are such that a minimum-inputs philosophy does not seem wise. The ideal P placement would have the entire soil volume supplied with P to a point of maximum yield. Restricting P fertilizer to an unmixed fertilizer band will seldom be the most efficient method of applying substantial quantities of P. Residual effects of P are much greater than is generally believed. Despite its bad reputation, P fixation is often a blessing in disguise. Yields of Hawaii sugarcane have been sustained at a high level by applying P equal to, or even less than, P removed by crops. Numerous methods have been devised for evaluating the P nutrition of crops and making recommendations about management practices. In some cases, zeal has exceeded scientific merit. All of the generally used methods have serious limitations; most of them have merit. A wise approach is to use all appropriate tools.

For the purposes of this paper, P for sustainable agriculture implies P nutrition that does not become limiting in crop production in the foreseeable future. We do not consider sustainable agriculture to be just one small increment above minimum inputs.

Sugarcane, pineapple, and banana are strikingly different in many respects. To deal with their P requirements and management in a single paper requires that the discussion proceed from a consideration of basic principles. Such is especially appropriate for P nutrition of banana because almost nothing on this subject has been published recently (see, for example, reviews by Lahav and Turner [1983] and Lin and Fox [1988]). Likewise, very little modern information is available for pineapple, although a book dealing with P nutrition with emphasis on past work by the Pineapple Research Institute, Honolulu, is in preparation (Sanford 1989).
Phosphorus in solution and the external phosphorus requirements of plants

Numerous solution-culture and soil-culture experiments have demonstrated that the concentration of P in solution (an intensity factor) is well correlated with P uptake by plants. The soil solution is the immediate source of P for plants growing in soils. The concentration of P in soil solution that is associated with near maximum (95%) attainable yield, we will call the external P requirement. For a particular plant species, the external P requirement is reasonably constant across a range of edaphic conditions, but not across climatic and management factors. The external P requirements of sugarcane and banana have not been investigated in detail, and those for pineapple not at all. Phosphorus concentrations in soil solutions can be estimated by analyzing saturation extracts of soils or from adsorption desorption curves. A backward extrapolation of P sorption curves from sugarcane soils of Hawaii indicates that acceptable sugar yields can be produced at approximately 0.01 mg P/liter (Fox 1983). One field experiment on furrow-irrigated sugarcane growing on an Oxisol in Hawaii showed approximately 95% of maximum attainable yield at a P concentration of 0.005 mg/liter (Fox 1983). Drip-irrigated sugarcane on the same soil type required 0.012 mg P/liter (Baclig 1987). Banana apparently requires more P in the soil solution than does sugarcane; Lin (1987) determined that the external requirement of mycorrhizal plants was 0.05 mg P/liter. In comparison, cassava requires 0.005 mg P/liter or less, maize approximately 0.02 mg P/liter, and tomato 0.2 mg P/liter (Fox 1986).

Pineapple that follows sugarcane usually does not require P fertilization and has lower critical soil P values. Thus we may assume that its external P requirement is less than for sugarcane. A re-evaluation of highly productive banana in Hawaii (Warner et al 1974) demonstrated that banana yields of 100 t/ha and plants well supplied with P (leaf P >0.2%) can be produced on soil with 0.05 mg P/liter in solution.

Although 0.2 mg P/liter has been used as a convenient and realistic solution concentration for comparing P sorption by different soils (Juo and Fox 1977), such a concentration was never intended to be a universally applicable value for all crops. Banana, sugarcane, and pineapple requirements affirm this.

Phosphate buffering in soils—a capacity factor in plant nutrition

Phosphate buffering in soils depends largely on the reactivity of mineral surfaces with phosphate and the extensiveness of those surfaces (Juo and Fox 1977). Important factors determining reactivity are the degree to which soil mineral surfaces have been desilicated by weathering, the reactions of organic compounds with mineral surfaces, and the status of exchangeable and soluble cations in soil systems. Soil maps can provide a qualitative evaluation of P buffering and quantities of P required.

A direct approach is more informative. One method (Fox and Kamprath 1970) involves constructing P adsorption curves by equilibrating soils with P-containing solutions and determining the P remaining in solution. Such curves have been
Table 1. Categories of P sorption in relation to soil mineralogy.

<table>
<thead>
<tr>
<th>Standard P requirement (mg P/kg soil)</th>
<th>Scale</th>
<th>Usual mineralogy</th>
</tr>
</thead>
<tbody>
<tr>
<td>&lt;10</td>
<td>Very low</td>
<td>Quartz and/or organic materials</td>
</tr>
<tr>
<td>10 - 100</td>
<td>Low</td>
<td>2:1 clays and/or 1:1 clays + quartz</td>
</tr>
<tr>
<td>100 - 500</td>
<td>Medium</td>
<td>1:1 clay with oxides</td>
</tr>
<tr>
<td>500 - 1000</td>
<td>High</td>
<td>Oxides, moderately weathered ash</td>
</tr>
<tr>
<td>&gt; 1000</td>
<td>Very high</td>
<td>Desilicated amorphous materials</td>
</tr>
</tbody>
</table>

constructed for many soils of the tropics, particularly for sugarcane lands (Fox 1983).

The range in P sorption by soils is from almost zero for quartz sands and some peats to a few thousand mg P/kg soil for weathered volcanic ash. Juo and Fox (1977) grouped standard P requirements (P sorbed to attain 0.2 ppm P in solution) as determined from P sorption curves as shown in Table 1.

Slopes of adsorption curves indicate the capacity of soils to adsorb P—and thus the quantity of P required to modify the P environment of roots. Slopes of P sorption curves in the interval of 0.15-0.25 ppm P for 11 highly weathered soils of Puerto Rico ranged from 60 to 290 mg P/kg clay (Fox 1982).

If there is no hysteresis in a P adsorption-desorption curve, the slope indicates the capacity of soils to supply P within a given concentration range. But there is usually hysteresis. Figure 1 presents composite P adsorption curves for sugarcane

![Composite P sorption curves for sugarcane soils in Hawaii. The curves represent a weathering sequence. Soil analyses and field experimentation suggest that groups I and II are marginally P-deficient for sugarcane.](image)

1. Composite P sorption curves for sugarcane soils in Hawaii. The curves represent a weathering sequence. Soil analyses and field experimentation suggest that groups I and II are marginally P-deficient for sugarcane.
soils representing a weathering sequence in Hawaii. Soils in groups I, II, and III—all of them Oxisols—are also typical of soils that are currently producing pineapple. Figure 2 is typical of productive banana fields in Hawaii with 2:1 silicate clays. The Mollisol (Fig. 2) is not as highly buffered as the Oxisols (Fig. 1), which accounts for the pronounced shift in the adsorption curve as a result of adding 220 kg P/ha a year earlier, and partially explains why banana leaf P began to decline after several years of high banana yields (Fox 1989, Lin 1987).

The P fertilizer requirement is the quantity of P required to adjust the solution P concentration of a specific soil to the external P requirement of a crop. The fertilizer requirement is crop specific and site specific. It should be obvious that generalized P fertilizer requirements should be made only after appropriate disclaimers.

If the external P requirement is known, and within constraints of weather, management, etc., fertilizer requirements can be estimated with reasonable confidence from P sorption curves. Fertilizer requirements are strongly influenced by edaphic and management factors: apparent specific gravity, soil mineralogy, soil texture, soil organic matter, and depletion or enhancement of the P supply by cropping, fertilizing, and manuring.

Single point estimates of P adsorption are used to adjust general fertilizer recommendations based on soil tests and for recommending fertilizer for highly retentive sugarcane soils in South Africa (Meyer 1979, 1980).

**Plant phosphorus uptake and crop yield response curves resulting from a range in phosphorus supply**

There is a threshold concentration of P in soil solution below which net P absorption by plants is zero; and there is a concentration (saturation value) beyond which increasing concentration produces no further uptake. Between these extremes the P-uptake response curve is sigmoid in shape.

Thus, for very infertile soils the first small increment of fertilizer applied, especially if it is mixed with a large volume of soil, may be ineffective. The threshold concentration for some field-grown (mycorrhizal) crops is in the range 0.001-0.003 mg P/liter (1 to 3 parts per billion). Nonmycorrhizal threshold concentrations may be an order of magnitude greater. Saturation values of 5-10 mg P/liter have been reported for a grass and a legume growing in soil (Fox et al 1986). Values based on flowing nutrient culture experiments are a little lower, as should be expected. Thus a yield response curve of the Mitscherlich type does not apply for those situations where the P supply ranges from near zero to excess; this was confirmed for banana (Lin 1987). Thus a concept of minimum inputs is not appropriate for extremely P-deficient situations such as occurs in the humid tropics.

Thomas (1988) reported on productivity changes of some very infertile (low P, low pH) Kentucky soils during a period of about 80 yr. In the early years (5-13), maize and wheat yields were near zero, with little improvement from low fertilizer rates. Later, responses were relatively much greater, but still low. Fertility continued to build up. The lesson for the tropics is that long-term fertility experiments are necessary to determine potential soil productivity.
Optimum fertilizer rates based on yield response curves of the Mitscherlich type are difficult to predict as yields approach maximum attainable. Frequently, yield response describes a linear response-plateau model. An example of this for maize growing on two soils was presented by Fox et al. (1982). A curvilinear model predicted an external P requirement of approximately 0.06 mg P/liter, whereas a linear response-plateau model predicted approximately 0.03 mg P/liter.

This brings into question the use of 95% of maximum attainable yield for determining critical P levels in soil solution, because if the P sorption curve (semilog plots) are linear and if the yield response curve semilog plots are linear, then there is no agronomic reason why the external P requirement should not be that concentration of P that corresponds to maximum yield using a linear response-plateau model. If 95% of maximum is underutilization of yield potential, how much more suspect is 85% or 90%, especially for high value crops?

Another problem arises when regression analysis is used to determine critical nutrient levels. When a fertilizer rate experiment is installed on a site, an attempt is made to make uniform all factors that influence yield other than the factor(s) under control and to tis those other factors at some desired standard or optimum level. Such is never the case. The result is yields at various unknown levels of adequacy of other growth factors. Regression analysis of such data will likely yield a low $R^2$; and, worse still, such curves will be shifted to the right, indicating greater than justified nutrient requirements. Compositing replicates leads to better-looking regression but does not preserve variability, which is the “stuff” out of which correlations are made. Problems with this approach have been discussed by Sumner (1987).

When several factors in plant growth vary simultaneously, well-defined yield response curves cannot be expected. Instead, a boundary line or ceiling on yield
develops (Webb 1972), which indicates that plant performance is being restrained within a response envelope. Below that ceiling, yields bear little relationship to nutrient levels. An example of data of this type is the work of Ho (1969), who plotted banana yield against fertilizer K. Regression analysis indicated that maximum yield should be attained at 5% leaf K. A response envelope of the same data shifted the critical level to 4% (Fox 1989), a more reasonable number. Examples of some response envelopes and their interpretation are presented by Kang and Fox (1980). Sumner (1987) used the boundary line approach for examining the relationship between extractable soil P and yield. Data for such plots need not be generated by replicated field plots of complex design. They can, in fact, be generated by individual plants using designs of the continuous-function type (Warner and Fox 1977), especially for crops like banana and sugarcane, which, because of their size and growth habit, are difficult to manage otherwise.

Crop response to phosphorus as a function of time

Phosphorus requirements, both internal and external, of most crops are greater during early growth stages than near maturity. In sugarcane, it is not unusual to obtain a large response to P fertilizer only until the canopy closes in, after which the response may disappear. Yaptenco (1963) demonstrated that the internal P requirement of maize decreased from 0.9 to 0.7 to 0.4% as age advanced from 1 to 3 wk. Baclig (1987) also noted that P contents of sugarcane leaf punches taken at 3-d intervals from the 30th day after planting decreased with time. Thus, young crops probably have a high external requirement. In the three crops considered here, appreciable amounts of nutrients are carried in the vegetative planting material. In sugarcane, P is extremely mobile; as much as 85% of the P in seed pieces may be taken into new plants.

Plant roots occupy a much larger volume of soil than is generally recognized. Banana roots may extend laterally for several meters. As the root system develops, band placement of P becomes less effective, and so the yield response from band-placed fertilizer declines.

Development of mycorrhizal associations, so essential for P uptake from many highly weathered soils, proceeds relatively slowly. This point has not been studied adequately for sugarcane and banana, and not at all for pineapple; but for several plant species, 2 wk elapse before evidence of enhanced P uptake appears. Until such time as the mycorrhizal association develops, a ready P source is important. This problem may be overcome by high P in the planting material.

The external P requirement of nonmycorrhizal banana is 0.1 mg P/liter (Lin and Fox 1987) and for sugarcane at age 5 mo it is apparently 0.025 mg P/liter, based on our evaluation of data presented by Baclig (1987). Many soils, even fertile ones, do not provide those concentrations of P in solution unless P is added. Therefore, growth response should be expected if these crops are fertilized with P. And if the fertilizer application is modest, the yield response will be greatest if the volume of soil fertilized is restricted and if that volume is accessible to young roots.

Because P is so important for early growth, it is important to establish P levels at the start of the crop. It is possible to reinforce P nutrition after planting, but it is
Phosphorus and sugarcane, pineapple, and banana are generally recognized for sugarcane, pineapple, and banana that if fertilizer P is delayed until after P deficiency has been diagnosed, much of the benefit from fertilizer will be lost.

**Influence of soil temperature on phosphorus uptake by crops**

Temperatures that are suitable for most temperate-zone plants are unfavorable for many tropical plants. Pineapple absorbs nutrients, including P, and water very slowly as root temperatures decrease from 20 to 15 °C (Ravoof et al 1973). Sugarcane is just as sensitive; Hart and Kortschak (1965) determined that in 5 min, sugarcane roots at 22.2 °C adsorbed 7.6 times as much 32P as roots at 16.7 °C. Banana may be even more sensitive to temperature; banana growers in Egypt insist that P fertilizer should be applied before the onset of winter, believing that the fertilizer “warms up the soil.”

Mean soil temperatures at low elevations near the equator are about 25 °C throughout the year, but cool-season temperatures <20 °C occur in many tropical areas. It should not be surprising, therefore, if results of P-placement experiments with tropical crops in the tropics are inconsistent with results obtained in the temperate zone, or, for the matter, that results obtained within the tropics at different elevations appear to be inconsistent.

Temperature affects P nutrition in other ways. Increased temperature increases biological activity and, depending upon the C-P ratio of the biomass and the soil organic matter, may lead to either mobilization or immobilization of P. Temperature also influences P adsorption-desorption. Whether or not elevated temperatures are beneficial depends on whether P is being sorbed or desorbed. High temperatures favor both sorption and desorption, which implies that for efficient P utilization, fertilizer should be applied to cold soil and utilized from warm soil—a concept that agrees with the practice of Egyptian banana farmers.

**Rational phosphorus placement**

A physical theory of fertilizer placement predicts mutual compensation between the volume of soil fertilized and the concentration of fertilizer within the volume of soil fertilized (Fox 1986). Thus, increased fertilizer concentration in the fertilizer band can compensate for a decrease in band volume; with increasing volume of the band, optimum concentration may decline. The theory predicts that fertilizing the entire soil volume may not be the most efficient use of fertilizer when the quantity of fertilizer used is less than that required for maximum uptake. It also predicts that restricting what would otherwise be adequate P fertilizer to very narrow bands is inefficient.

The theory has been confirmed for a very reactive volcanic ash soil (Fox 1986). Plant uptake did not equal requirements because P concentrations in the band exceeded the saturation value of roots. Field and pot experiments in the tropics generally agree that unmixed fertilizer bands offer little or no advantage if substantial P levels are applied to soils (Fox and Kang 1976). Placing the P in correct relation to the plant is obviously important. Phosphorus will not be taken up if it is
out of reach of roots; and it will be taken up earlier if it is placed adjacent to the planting material. On the other hand, it is not safe to assume that the closer P is placed to planting material the more effectively it will be utilized. In fact, Hilton and Nomura (1984) determined that 45% of P placed under the sugarcane seed piece was taken up, whereas 10-15% of P applied through drip tubing between rows was absorbed. With an adequate fertilization rate, the best results are usually obtained by incorporating P in the entire soil volume (Fox 1986). The increased P uptake observed when increasing quantities of P are applied in unmixed fertilizer bands results because P moves, either by diffusion or by bulk movement, into a larger volume of soil, not in response to increased P concentration within the band. Such considerations do not support the idea that major fertilizer economies can be achieved by localized placement of P fertilizer.

These relationships have a direct bearing on P levels required in rocky soils. It is necessary to adjust critical levels for rocky and shallow soils. Humbert (1968) gives an example of a soil, containing 50% rock, that required approximately 2 times as much extractable P as usual. This general relationship has been termed the “barrier effect” by Fox and Kamprath (1970), because roots that pile up against an obstruction are, to a considerable extent, removed from a soil environment. The barrier effect is one reason why pot studies, even in big pots, correlate so poorly with field results.

**Banding phosphorus fertilizer to decrease phosphorus fixation by the soil**

One of the most frequently invoked rules-of-thumb concerning P fertilization is that soluble fertilizer should be band-applied to decrease fixation by retentive soils. This generalization may not be as valid as assumed. In an Oxisol of Brazil, residual P (second crop of maize) was generally equally effective whether it had been originally applied broadcast, or banded, or by a combination of the two methods (Fox 1986, based on data of Yost et al. 1981). We have calculated the residual effects of broadcast P as indicated by leaf P percentage, corrected for P removed by the first crop, roots excluded. The values were approximately 40% for P fertilizer rates ranging from 70 to 560 kg P/ha. This is lower than residual efficiencies determined for highly weathered soils in Hawaii—80% (Fox et al. 1968)—but similar to values for kaolinitic soils in North Carolina (Fox and Kamprath 1970). Those determinations were based on shifts in P sorption curves, however, and are not directly comparable.

Appropriate data are not available for sugarcane, pineapple, and banana, but residual effects should be at least as good as those quoted. Such is indicated by the observation that ratoon crops of cane and pineapple seldom require P fertilizer if the plant crop has been sufficiently supplied. Also, leaf P of banana did not respond to a 200-kg P treatment until approximately 10 yr later (Lin 1987).

**Mixing vs banding insoluble phosphorus**

Experimental evidence is almost unanimous that insoluble P such as phosphate rock, properly used, are good sources for pineapple, sugarcane, and banana (Ayres and Hagihara 1955, Lin 1987, Smith 1960). Such sources should be mixed with the soil rather than band applied, for several reasons:
• acid soils decompose apatite minerals;
• phosphorus and Ca from the fertilizer material are adsorbed onto soil materials, thus increasing the dissolution rate of the P material;
• adequate plant uptake of P from dilute soil solutions such as those equilibrated with sparingly soluble P minerals dictates that a large percentage of the root system should be involved in uptake; and
• plant roots themselves, especially if mycorrhizal, interact with the fertilizer materials, enhancing their dissolution and uptake.

These factors should apply to the utilization of P derived from soluble sources that have reacted with soil to form sparingly soluble compounds.

**Mycorrhizae enhance phosphorus uptake**

Most agriculturally interesting plants except members of three families—Chenopodiaceae, Cyperaceae, and Cruciferae—form symbiotic associations with fungi, which enable the plants to more thoroughly extract P from soils. An understanding of crop response to P will benefit if mycorrhizae are considered.

Yost and Fox (1979) examined the contribution of mycorrhizae to the P nutrition of 7 species growing on an Oxisol providing 10 levels of P ranging from 0.003 to 1.6 ppm P in solution, nonmycorrhizal and mycorrhizal. Only *Brassica chinensis* did not respond dramatically to mycorrhizal infection. Later, the response of sugarcane was tested on the same plots (Baclig 1987), and banana was grown in 100-kg lots of soil in pots (Lin 1987) using the same P and mycorrhiza treatments. Both crops responded to mycorrhizae, but neither crop was as dramatically dependent as the six species investigated by Yost and Fox. In banana this may have been caused by the relatively sparse (about 10%) infection of the roots by mychorrhizae, and in sugarcane by low infection coupled with a low threshold for P uptake.

We are not aware of definitive investigations of mycorrhizal dependency in pineapple. However, circumstantial evidence suggests mycorrhizal dependence. Mosse (1981) determined that pineapple is heavily infected. The response of pineapple to a range of P treatments suggests that the crop is highly dependent on mycorrhizae (Fig. 3). Pineapple yield increased with increasing P fertilizer until a plateau was reached. As P levels were further increased, yield abruptly decreased and then increased. An almost identical pattern was observed in two experiments in Honduras. Lin and Fox (1987) observed this pattern for P uptake by mycorrhizal but not by nonmycorrhizal banana. Earlier, Yost and Fox (1979) observed this as a general pattern for several species of mycorrhizae-dependent plants, but not if the plants were normally nonmycorrhizal or if they had been made nonmycorrhizal by fumigation.

Thus, we assume that the pattern illustrated in Figure 3 is evidence of mycorrhizal dependence, and the fact that it is expressed better by pineapple than by banana or sugarcane indicates strong mycorrhizal dependence by pineapple and at least moderate dependence by banana.

These considerations offer a plausible explanation of the well-attested fact that, although fumigation of pineapple lands with material such as methyl bromide may
3. Yield of pineapple (Philippines plant crop) in relation to P fertilizer applied. Values in parentheses are modified Truog-extractable P. Depressed production at the intermediate P rate suggests mycorrhizal dependence.

increase extractable soil P slightly, P uptake by pineapple is depressed for 6-9 mo after planting (Smith 1960).

Soil pH, phosphorus availability, and phosphorus uptake

The relationships between soil pH, P availability, and fertilizer practice are controversial. Many first-time visitors to the tropics would solve the P problems there by liming to approximately pH 6.5. That such a practice may be more detrimental than beneficial is not difficult to document. There are good reasons for this:

- Phosphorus concentrations are depressed by polyvalent cations. When variable-charge soils are limed above approximately pH 5.6, Ca concentration increases appreciably. The unfavorable Ca environment is aggravated if Ca moves to roots in excess of uptake, which is likely to be the case in low-Ca plants such as sugarcane, pineapple, and banana.
- Phosphorus solubility is increased by increasing H⁺ concentration per se.
- The proportion of H₂PO₄⁻, the species most readily taken up by plants, decreases with increasing pH before pH 6.5 is reached.
- Within the range of pH encountered in productive soils, soil Al and Mn are so sparingly soluble that they do not influence P solubility very much.
- Anion exchange mechanisms of the electrostatic type are relatively unimportant for long-term P retention.

Although P solubility is not much influenced by pH in the pH range 5.6-6.5, P uptake by plants may be influenced by liming. This is apparently related more to
interactions of P with Al, Mn, and Fe at root surfaces or in roots, to decreased Al or Mn toxicity to roots, and to greater root development and activity associated with limed soils, than to increased P availability. Tomato plants that accumulated Mn tended to have higher internal P requirements than plants with low Mn contents (Jones and Fox 1978).

Pineapple is a Mn accumulator; Mn contents >1,000 ppm are not unusual. Banana growing on a soil with pH 6.5 in Hawaii contained more than 600 ppm leaf Mn. Sugarcane usually contains <200 ppm in leaves 3–6. Based on these differences, P responses of these crops to liming should be expected to vary, and responses by the same crop should differ according to soil properties. As far as we know, these relationships have not been investigated for the crops of special interest here. All three crops are frequently grown at soil pH values where Al toxicity problems can be expected. None of the crops are noted for being Al sensitive. It is generally believed that the value of lime for these crops is related to Ca as a nutrient rather than to amendment effects; but some evidence indicates that the lime response also results from increased P availability.

Residual efficiency of fertilizer phosphorus

Frequently, the efficiency of P fertilizers is given as about 10%. Such values are usually based on P recovery by one or two crops. They do not indicate the long-term residual effects of P. To our knowledge, good evaluations of residual fertilizer effects are not available for sugarcane, pineapple, or banana; however, responses of ratoon sugarcane to P fertilizer applied in the furrow for the plant crop are said to decrease on the average by a third for each subsequent 2-yr crop (Wood and Meyer 1988). Some statements on expected residual effects based on first principles seem to be justified:

- Phosphorus in excess of that removed by the current crop enters the labile pool and may be utilized by future crops.
- Fertilizer P reacts with soil materials, preventing them from reacting with P that may be supplied in the future.
- Fertilizer P may stimulate root activity and organic matter deposition so that P is more efficiently cycled in the system than would be the case if no P had been used. Thus, P accumulates at the soil surface but is depleted from the subsoil.
- Fertilizer P may enhance P uptake by the crop in excess of P input, which brings about a net P loss from the soil.

Residual effects of the first two types make for sustainable agriculture; the third type may appear to be sustainable, but unless P additions are greater than removal, the long-term effect will be depletion. The fourth type always leads to depletion; it has been observed in pastures of New Zealand (R.L. Fox, unpubl. data) and is doubtless a feature of much minimum-inputs agriculture.

Residual effects of P in highly weathered soils are greater than has generally been assumed (Fox 1980, 1986; Fox and Li 1986; Fox et al 1968). For example, the residual efficiency of P in an Oxisol of Hawaii was about 60%, while that for a Eutrandept was about half as great (Fox and Li 1986). Such results lead to the
conclusion that, after a few rounds of fertilization designed to give near maximum yields, the quantity of P required is not greatly in excess of P that is removed by the crop. For a 2-yr sugarcane crop, this is approximately 90 kg/ha, and for plant crops of banana and pineapple it is approximately 36 and 26 kg, respectively; much of this is returned to the land with the residue.

One of the best indications of substantial residual effects is that P deficiency, considered a major problem in sugarcane in Hawaii until substantial P applications were made, is not considered so today (Fox 1983). A review of the use of P for Hawaiian pineapples in the 1960s (Smith 1960, 1961a) reported the development and recognition of P deficiency in increasingly widespread pineapple-growing areas. Phosphorus deficiency is not considered a major problem today.

Predicting whether phosphorus is required by crops

Sugarcane and pineapple industry workers have tried to predict the need for P fertilizers for approximately 70 yr. An argument developed concerning the merits of soil analyses. Unfortunately, some work displayed more emotional than scientific content; it seems quite impossible to reach any general conclusion from reviewing it. Rather, we wish to emphasize that many factors—intensity, quantity, capacity, and rate—influence the availability of soil P to plants. The crop itself introduces its own complications; and superimposed over all are weather and management factors, which no simple test can hope to predict. If the question is whether or not P will be required in the future, then analysis of an appropriate soil extract will provide values that, if properly calibrated and combined with other soil and crop information, will predict correctly with reasonable success. If the question is whether or not P should have been applied, suitable plant analysis data (Humbert 1968, Lin and Fox 1987, Sanford 1961), properly calibrated and interpreted against a background of soil and weather information, should be superior, because plant P is at least one step closer to the final product than soil P is.

Questions dealing with the magnitude of the response that can be expected from a given quantity of fertilizer are not effectively dealt with by soil testing of the usual kind unless soil properties other than extractable P are relatively uniform—which they may be in certain areas where much of the surface is blanketed by losses, glacial till, or volcanic ash from a single event; but this is certainly not the case for most of the tropics.

If the question deals (as it should) with 1) whether or not deficiency exists; 2) how much fertilizer or other amendment should be applied to attain a desired P status of the crop; and 3) what the residual effects, including side effects, will be, then it is obvious that we will need something more than a “quick fix” soil and plant analysis service to supply the necessary data.

Factors that influence fertilizer phosphorus efficiency

Of the many practices that enhance fertilizer P efficiency, the following stand out as being especially important:
• Fertilizer P should be introduced into soil material in which roots will proliferate and into soil material that does not sorb P strongly. Almost invariably, this translates into adding P to the surface soil horizon, and to minimum contamination with subsurface materials.

• Phosphorus concentration in the soil should not exceed root saturation values. An appropriate concentration is probably in the range 5 to 10 mg P/liter in solution. Some mixing of fertilizer bands is almost always beneficial.

• Utilize crops that can take up P from sparingly soluble P compounds.

• Keep soil in the adsorption mode, not in the desorption mode, to avoid depressed P solubility associated with hysteresis effects. Do this by avoiding mixing P-fertilized soil with nonfertilized soil when the crops are ratooned.

• Manage organic residues and manures with a view to enhanced efficiency of P fertilizers. Adding P on top of residues is effective for ratooned sugarcane (Wood and Meyer 1988).

• Use soil amendments to immobilize Al and excess Mn, but avoid excess Ca in the soil solution. In pineapple, a pH in the range 5.0-5.6 is more favorable for root development than the more acid condition usually encountered and tolerated by the crop. In different situations, either favorable or unfavorable effects may predominate, and yields may be increased or decreased accordingly (Smith 1961b). In highly weathered soils, sugarcane may respond to silicate applications (Fox et al. 1967, Medina et al. 1988); such soils usually immobilize much P (Fox 1982). Silicate amendment benefits sugarcane, quite apart from its effect on P solubility (Roy et al. 1971). Some other crops may benefit from silicate applications more or less in proportion to their response to P. Efficiency of P in sugarcane seems to be positively influenced by silicate application (Roy et al. 1971). Applications of P as soil amendments can perhaps be performed better by CaSiO$_3$ or CaCO$_3$, and at lower cost.

• Use mulches, artificial and natural, to modify soil temperature and moisture in the immediate soil surface and thus encourage root activity there. Perhaps one of the greatest advantages of plastic mulches for pineapple is increased soil temperature before the crop has closed in (Ravoof et al. 1973).

• Avoid P losses by soil erosion. Banded fertilizer in planting furrows is especially susceptible to erosion loss. Also, eroded soils are invariably disproportionately high in soil materials that adsorb P and are low in organic materials that retard adsorption.

• Place P where it can be effectively utilized by the plant. With deep placement, P may be utilized readily (Golden 1965); however, the practice is expensive.

**Negative effects of phosphorus fertilization**

Interactions between P and Zn have been well documented for many crops, including sugarcane, and probably exist for pineapple and banana. Although sugarcane and banana are not very susceptible to Zn deficiency, pineapple is.

Of greater concern is Fe deficiency, a serious problem in pineapple growing on high-Mn soil, especially if limed. Likewise, ratoon sugarcane tends to be chlorotic in
Managing phosphorus inputs for sustainable agriculture

An outline for sustaining banana production, proposed by Twyford and Walmsley (1973-74), should be useful for sugarcane and pineapple as well. The method involves adding nutrients until contents of the crop are sufficient for the production desired, and then supplying nutrients as required to maintain that content.

The Hawaiian sugarcane industry provides a useful example of how P has been managed (mostly on the same lands) for more than 100 yr. A parallel plot of P applied and P removed in the millable cane illustrates some of the problems encountered, and some trends for consideration (Fig. 4). Until 1924, less P was applied to the fields than was being removed (exported) in the millable cane. Phosphorus exploitation was slow because yields were low. In 1925, a period of increased P fertilization began. In 4 yr, P inputs equaled export; in 8 yr inputs were twice exports, which in the meantime had also increased by more than 50% as a result of increased yields. Abruptly in 1933, P application rates began to decline because of the economic depression and, later, war. Sugar yields and P exports were approximately constant during that time, made possible by, but not totally the result of, residual fertilizer P. Then (in 1945) began a 12-yr period of increasing P fertilizer use until inputs equaled P export. There followed a period during which agronomic considerations usually dictated practice; soil and plant analyses were used to predict the need for P fertilizer, and experience dictated the quantity required. Inputs

### Figure 4

![Graph of P fertilizer application and P removed in millable cane](image)

4. Estimated P fertilizer application and P removed in millable cane by the Hawaii sugar industry as a function of time (based on unpublished data of the Experiment Station of the Hawaii Sugar Planters Association and Hawaiian Sugar Manual 1988).
generally corresponded closely to P export. More recently, short-term economic considerations have dictated practice, and, as is so frequently the case, sustainable agriculture finds little place.

So we can conclude by examining these long-term practices that Liebig was not altogether wrong when he proposed a patent fertilizer based on plant composition. The problem was, he could not wait a century to observe that he was correct. Neither can we. This is a pressing problem for our time, when low-input soil fertility programs have such appeal.

Here also, Hawaiian sugarcane can teach a valuable lesson; the yields of today, which made Hawaiian sugar and pineapple famous, would not be possible if it were not for the solid base of soil fertility built up beginning over 60 yr ago.

Fertilizer P additions that are only equal to P removed by crops are not sufficient for crops growing in P-deficient soils. During the early stages of plant development, it is important that additional P be added to compensate for soil immobilization until a point of adequacy is reached. During these early years, soil and plant analyses can provide valuable information for moving quickly to a state of P adequacy.

It may seem strange that the soil P status can be sustained, and even improved, by inputs of P that equal P export. This is because P fertilizer has remarkable residual value, especially in highly weathered soils. This idea seems to repudiate much of what we think we know about P chemistry. The exciting thing is that it substantiates what we do know. Phosphorus fertilization, even if insufficient for acceptable yields, does decrease the average age of P in the soil; and P availability depends on age.

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Notes

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Citation information: International Rice Research Institute (1990) Phosphorus requirements for sustainable agriculture in Asia and Oceania. P.O. Box 933, Manila, Philippines.
Phosphorus requirements and management of tropical root and tuber crops

R.H. Howeler

Root and tuber crops (mainly cassava, sweet potato, Irish potato, yam, and taro) are important calorie sources for millions of people in the tropics. Because of their high production potential, these crops may extract large amounts of soil nutrients, especially K, but considering per ton of dry matter produced, they generally are not more exhaustive of soil nutrients than cereals or grain legumes. P removal in the harvested product is very low compared with that of N or K. Phosphorus deficiency can be diagnosed by observing deficiency symptoms or by analyzing soil or plant tissue. When available, symptoms are described and critical P concentrations are given for soils as well as for specific indicator plant tissue. External P requirements, determined in soil solution, were very low for cassava and yam, intermediate for taro and sweet potato, and high for Irish potato. This indicates that cassava can be grown on very low-P soils, whereas potato requires high soil P levels or high applications of P fertilizer. However, when P requirements were determined in flowing nutrient solutions, cassava had an external requirement 1-2 times higher than the other crops tested, indicating the intrinsic low efficiency for P absorption by the root system. Cassava was found to be highly dependent on a vesicular-arbuscular mycorrhizal (VAM) association, and when grown in natural soils, the crop's root system becomes infected with mycorrhizal fungi, which greatly enhances soil-P absorption. In soils with an adequate native VAM population, cassava can grow well even at very low levels of available P; however, without efficient VAM species, the crop is highly responsive to P application and/or mycorrhizal inoculation. Most other root crops are also mycorrhizae-dependent and may grow well with only modest P application, whereas Irish potato requires a high rate of fertilizer P for maximum production.

Tropical root and tuber crops are important staple foods for about one-third of the world’s population, constituting a major source of carbohydrates in the diet; Chandra (1988) estimates that up to 450 million people in 26 countries get about 300 kcal/d from cassava alone. Since 75% of the population of the developing tropical countries suffer from calorie deficiency (Anonymous 1976), root and tuber crops can make a substantial contribution to eliminate this deficit and improve the health and welfare of these people.

The main tropical root and tuber crops are cassava Manihot esculenta Crantz, sweet potato Ipomoea batatas (L.) Lam., potato Solanum tuberosum, yam Dioscorea spp., and taro Colocasia esculenta (L.) Schott. Other less important tuber...
crops are tannia or new cocoyam *Xanthosoma sagittifolium*, giant taro *Alocasia macrorrhiza*, giant swamp taro *Cyrtosperma chamissonis*, elephant foot yam *Amorphophallus campanulatus*, and coleus *Coleus parviflorus*.

Table 1 shows the production statistics of the principal root and tuber crops in the world. Potato is by far the most important tuber crop, but only 18% is produced in the tropics, where it plays a major role in the diet only for people living in the highlands. Of the tropical root and tuber crops, cassava is the most important, followed by sweet potato, yam, and taro.

Since cassava is by far the most important tropical root crop and may have the greatest potential for expansion, most of this paper will describe the P requirements and management of cassava. Relatively little data are available on the requirements of other tropical root and tuber crops, and these will therefore be mentioned only in comparison with cassava.

### Production zones and nutritional constraints

Figure 1 shows the principal cassava-growing countries and the limiting nutrients at various locations, as reported in the literature. In Latin America, especially in Brazil and Colombia, P deficiency is by far the most limiting nutritional factor for cassava production. In Africa, a P response has been reported in Ghana (Stephens 1960, Takyi 1972), and P fertilization was recommended in Madagascar (Anonymous 1952). In Asia, small and often inconsistent P responses have been reported only on the gravelly lateritic soils of Kerala (classified as Eutrortox) (CTCRI 1985), on some sandy Ultisols in Thailand (Sittibusaya et al 1988), and on Ultisols in southern Sumatra, Indonesia (Wargiono 1988).

### Nutrient removal

Root and tuber crops are among the most efficient carbohydrate producers (De Vries et al 1967), the energy output per unit area being two to three times higher than

<table>
<thead>
<tr>
<th>Region</th>
<th>Production (X 1000 t)</th>
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<tbody>
<tr>
<td></td>
<td>Cassava</td>
</tr>
<tr>
<td>Africa</td>
<td>56,527</td>
</tr>
<tr>
<td>North and Central America</td>
<td>889</td>
</tr>
<tr>
<td>South America</td>
<td>28,409</td>
</tr>
<tr>
<td>Asia (except Soviet Union)</td>
<td>50,465</td>
</tr>
<tr>
<td>Oceania</td>
<td>243</td>
</tr>
<tr>
<td>Europe and Soviet Union</td>
<td>–</td>
</tr>
<tr>
<td>World</td>
<td>136,533</td>
</tr>
</tbody>
</table>

Table 1. Root and tuber crop production in various regions of the world (FAO 1986).
1. World cassava production in 1987 and the main limiting nutrients for cassava as reported in the literature.
that of grain crops (Chandra 1988). With their potential for high yields, these crops can also exhaust soil nutrients. Since K is required for root or tuber formation, and much absorbed K is removed with the harvest, these crops are heavy extractors of soil K. The amount of K removed is often 5-10 times as large as that of P, and usually 1-2 times as large as that of N (Table 2). Thus, P absorption and removal in the harvested product are minimal compared with those of K and N. Also, when nutrient removal is expressed in terms of kilograms per ton of dry matter (DM) in the harvest, nutrient removal is much lower than in most cereal grains or grain legumes. Thus, K exhaustion due to continuous cropping has often been reported (Howeler 1985b), but there are no reports of P exhaustion. In a long-term fertility trial in Colombia, yields >30 t/ha could be maintained during 8 consecutive cassava

Table 2. Average nutrient uptake and removal by root and tuber crops as compared with that by cereal grains and grain legumes, as reported in the footnoted references.

<table>
<thead>
<tr>
<th>Crop</th>
<th>Plant part</th>
<th>Yield (t/ha)</th>
<th>Nutrient (kg/ha)</th>
<th>Dry matter produceda (kg/t)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Fresh</td>
<td>Dry</td>
<td>N</td>
</tr>
<tr>
<td>Cassavaa</td>
<td>Roots</td>
<td>35.7</td>
<td>13.53</td>
<td>55</td>
</tr>
<tr>
<td></td>
<td>Total</td>
<td></td>
<td></td>
<td>149</td>
</tr>
<tr>
<td>Sweet potato</td>
<td>Roots</td>
<td>25.2</td>
<td>5.05</td>
<td>61</td>
</tr>
<tr>
<td></td>
<td>Total</td>
<td></td>
<td></td>
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</tr>
<tr>
<td>Potato</td>
<td>Tubers</td>
<td>23.3</td>
<td>4.67</td>
<td>106</td>
</tr>
<tr>
<td></td>
<td>Total</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Dioscorea esculenta</td>
<td>Tubers</td>
<td>17.87</td>
<td>7.21</td>
<td>73</td>
</tr>
<tr>
<td></td>
<td>Total</td>
<td></td>
<td></td>
<td>112</td>
</tr>
<tr>
<td>D. alata</td>
<td>Tubers</td>
<td>18.60</td>
<td>4.70</td>
<td>74</td>
</tr>
<tr>
<td></td>
<td>Total</td>
<td></td>
<td></td>
<td>114</td>
</tr>
<tr>
<td>D. rotundata</td>
<td>Tubers</td>
<td>28.99</td>
<td>9.63</td>
<td>91</td>
</tr>
<tr>
<td></td>
<td>Total</td>
<td></td>
<td></td>
<td>116</td>
</tr>
<tr>
<td>Amorphophallus campanulatus</td>
<td>Tubers</td>
<td>33.00</td>
<td>6.85</td>
<td>110</td>
</tr>
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<td>Total</td>
<td></td>
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</tr>
<tr>
<td>Colocasia esculenta</td>
<td>Tubers</td>
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</tr>
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<td></td>
</tr>
<tr>
<td>Coleus parviflorus</td>
<td>Tubers</td>
<td>25.74</td>
<td>5.75</td>
<td>55</td>
</tr>
<tr>
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<td>Total</td>
<td></td>
<td></td>
<td>107</td>
</tr>
<tr>
<td>Maize</td>
<td>Grain</td>
<td>6.47</td>
<td>5.56</td>
<td>96</td>
</tr>
<tr>
<td></td>
<td>Total</td>
<td></td>
<td></td>
<td>161</td>
</tr>
<tr>
<td>Rice</td>
<td>Grain</td>
<td>4.62</td>
<td>3.97</td>
<td>60</td>
</tr>
<tr>
<td></td>
<td>Total</td>
<td></td>
<td></td>
<td>87</td>
</tr>
<tr>
<td>Beans</td>
<td>Grain</td>
<td>1.09</td>
<td>0.94</td>
<td>37</td>
</tr>
<tr>
<td></td>
<td>Total</td>
<td></td>
<td></td>
<td>102</td>
</tr>
</tbody>
</table>

croppings without P application, while the soil P level (Bray II) remained around 4-6 ppm (CIAT 1988).

**Phosphorus absorption during growth cycle**

The accumulation and distribution of DM and nutrients in cassava during its growth cycle have been studied by several investigators (Howeler and Cadavid 1983, Lorenzi 1978, Nijholt 1935, Oelsligle 1975, Orioli et al 1967). Similar data have been reported for yams, aroids, and coleus by Kabeerathumma et al (1987). Figures 2 and 3 show the accumulation of DM as well as P in the whole plant and in the roots of cassava and the tubers of yam *Dioscorea esculenta*. Both crops showed initially very slow DM and P accumulation. In cassava, after the third month, DM and P accumulated at an almost constant rate until harvest at 12 mo. In yam, DM

2. Accumulation of dry matter and P in the whole plant and in the roots of cassava cultivar M Col 22 during a 12-mo growth cycle in Quilichao, Colombia.
3. Accumulation of dry matter and P in the whole plant and in the tubers of *Dioscorea esculenta* during a 9-mo growth cycle in Trivandrum, India (adapted from Kabeerathumma et al 1987).

Accumulation increased between 3 and 7 mo, after which it slowed down; total P accumulation also slowed down after the 5th month but continued in the tubers, indicating a marked retranslocation of P from the tops to the roots during the last 4 mo before harvest. Other yam species (*D. alata* and *D. rotundata*) showed an almost constant P absorption by the plant between 3 mo and harvest time (Kabeerathumma et al 1987). At harvest, about 60% of the absorbed P was found in the cassava roots and 76% in the yam tubers. Thus, in both cases most of the absorbed P is removed in the harvest, but the quantities of P removed are still small compared with those of N and K.

**Phosphorus concentration in plant tissue**

Nutrient concentrations in plant tissue vary with plant part as well as with the age of the tissue and the age of the plant. Nijholt (1935) analyzed cassava tissues at bimonthly intervals in Indonesia and found that the P concentration decreased from 0.29% at 2 mo to 0.23% at 14 mo in the leaves, from 0.27 to 0.12% in the stem, and
from 0.19 to 0.11% in the roots. Howeler and Cadavid (1983) reported a similar but more marked decrease in P concentration between 2 and 4 mo, after which the concentration decreased only slowly until harvest. Phosphorus, N, and K concentrations were highest in the leaf blades, followed by those in the stems, petioles, and roots; they were substantially higher in the upper than in the middle or lower part of the plant (Table 3). Kabeerathumma et al (1987) reported a similar decrease in P concentration in the tops of various yam species as well as in those of elephant foot yam, taro, and coleus. The concentration was always higher in the leaves than in the stems, roots, or tubers.

Diagnosis of phosphorus deficiency

Nutrient deficiencies can be diagnosed by observation of symptoms, or by plant tissue or soil analysis.

Deficiency symptoms

Like those of N and K deficiencies, symptoms of P deficiency in cassava are often not very clear. P deficiency is characterized mainly by slow growth, resulting in short and spindly plants with dark green leaves. Only in the case of severe deficiency at an early growth stage do plants show more specific symptoms: one or two lower leaves turn uniformly yellow or orange, lose their turgidity, and eventually drop off. Photographs of these symptoms have been published by Asher et al (1980) and Howeler (1981). In taro, P deficiency is characterized by slow growth, resulting in small, shiny leaves and short petioles (Ghosh 1988).

Table 3. Nutrient Concentrations in plant parts of fertilized and unfertilized cassava M Ven 1977 at 3-4 mo after planting in Carimagua, Colombia (Howeler 1985a).

<table>
<thead>
<tr>
<th>Plant part</th>
<th>Unfertilized</th>
<th>Fertilized</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>N (%)</td>
<td>P (%)</td>
</tr>
<tr>
<td>Leaf blades</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Upper</td>
<td>4.57</td>
<td>0.34</td>
</tr>
<tr>
<td>Middle</td>
<td>3.66</td>
<td>0.25</td>
</tr>
<tr>
<td>Lower</td>
<td>3.31</td>
<td>0.21</td>
</tr>
<tr>
<td>Fallen</td>
<td>2.31</td>
<td>0.13</td>
</tr>
<tr>
<td>Petioles</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Upper</td>
<td>1.50</td>
<td>0.17</td>
</tr>
<tr>
<td>Middle</td>
<td>0.70</td>
<td>0.10</td>
</tr>
<tr>
<td>Lower</td>
<td>0.63</td>
<td>0.09</td>
</tr>
<tr>
<td>Fallen</td>
<td>0.54</td>
<td>0.05</td>
</tr>
<tr>
<td>Stems</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Upper</td>
<td>1.64</td>
<td>0.20</td>
</tr>
<tr>
<td>Middle</td>
<td>1.03</td>
<td>0.18</td>
</tr>
<tr>
<td>Lower</td>
<td>0.78</td>
<td>0.21</td>
</tr>
<tr>
<td>Rootlets</td>
<td>1.52</td>
<td>0.15</td>
</tr>
<tr>
<td>Thickened roots</td>
<td>0.42</td>
<td>0.10</td>
</tr>
</tbody>
</table>
Plant tissue analysis

Nutrient concentrations in plants vary continuously during the growth cycle and differ in different plant parts. To use tissue analysis for diagnostic purposes, it is important to standardize the indicator tissue to be sampled and the physiological age of the plant. In cassava, the best indicator tissue is the youngest fully expanded leaf (YFEL) blade, sampled at about 4 mo after planting, when the nutrient levels have more or less stabilized (Howeler 1985a). For sweet potato, Leonard et al (1949) suggested the use of the 3 fully expanded leaves at the tip of the vine, while Rendle and Kang (1977) recommended sampling of index leaves at 9 wk after planting and analyzing either the blades or the petioles. For taro, the best indicator tissue is the YFEL blade at 3 mo after planting (De la Peña et al 1982). Table 4 shows the critical P concentration of indicator tissue of various tropical root and tuber crops reported in the literature. Cassava and taro have similarly high critical P concentrations of about 0.40% in YFEL blades, while those for sweet potato are only about 0.22%.

Soil analysis

Table 5 shows the critical level of available soil P for various root and tuber crops compared with those of other crops. Values range from about 10-15 ppm for maize, beans, or soybean to as low as 4-6 ppm for cassava. Thus, cassava is more productive in low-P soils than most crops; in addition it has an exceptional tolerance for high levels of Al and low soil pH, which makes it an ideal crop for very acid, low fertility soils.

External phosphorus requirements

While the “available” soil P is determined by extraction with various chemicals and is merely an index of the labile soil-P pool, plants absorb P only from the soil solution. Thus, plant growth is directly related to the P concentration in the soil solution, and an “external P requirement” is often defined as the P concentration in soil or nutrient solution at which plants reach 95% of maximum growth or production. Table 5 also shows the external P requirements for various crops, both

<table>
<thead>
<tr>
<th>Tissuea</th>
<th>P concentration (%)</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Shoots</td>
<td></td>
<td></td>
</tr>
<tr>
<td>YFEL blades</td>
<td>0.47-0.66</td>
<td>Jintakanon et al 1982</td>
</tr>
<tr>
<td></td>
<td>&gt;0.44</td>
<td>CIAT 1978</td>
</tr>
<tr>
<td>Sweet potato</td>
<td></td>
<td></td>
</tr>
<tr>
<td>YFEL blades</td>
<td>0.20-0.23</td>
<td>Leonard et al 1949</td>
</tr>
<tr>
<td></td>
<td>0.22</td>
<td>Rendle and Kang 1977</td>
</tr>
<tr>
<td></td>
<td>0.08</td>
<td>Rendle and Kang 1977</td>
</tr>
<tr>
<td>Taro</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Petioles</td>
<td>0.23</td>
<td>Kagbo et al 1973</td>
</tr>
<tr>
<td>YFEL blades</td>
<td>0.40</td>
<td>De la Peña et al 1982</td>
</tr>
</tbody>
</table>

aYFEL = youngest fully expanded leaf.
in soil and in nutrient solution. Among the tropical root and tuber crops, cassava and yam can grow well in soils that are extremely low in P; taro and sweet potato require intermediate levels; and potato can produce well only at very high external P concentrations. The cereal grains and grain legumes have intermediate P requirements, but tomato, Chinese cabbage, and lettuce have P requirements as high as that of potato. However, when cassava and several other crops were grown in flowing nutrient solution culture, the P requirements of cassava were one to two magnitudes higher than those of other crops tested (Table 5). This anomalously high P requirement of cassava in nutrient solution is due to its very coarse and inefficient root system (Howeler et al 1982a). In normal soils, cassava roots are always infected with vesicular-arbuscular mycorrhizal (VAM) fungi, which help the plant absorb soil P more efficiently than most other crops. That explains cassava’s low P requirement in soil solution and low critical soil P level. When VAM fungi were eliminated from natural soil by sterilization with methyl bromide, Vander Zaag et al (1979) found that cassava growth was seriously reduced and the P concentration of leaves went from 0.30 to 0.11%, indicating the important role of mycorrhiza in P uptake from low-P soils. Similar effects of soil sterilization on growth and P uptake by cassava were later reported by Howeler and Sieverding (1983) and by Howeler et al (1982b,c, 1987). Further evidence of the role of mycorrhiza in P uptake was provided by the fact that when 8 cassava cultivars were inoculated with VAM fungi

<table>
<thead>
<tr>
<th>Crop</th>
<th>Available P (ppm) (extractant)</th>
<th>Soil solution P (ppm)</th>
<th>Nutrient solution P (ppm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cassava</td>
<td>8 (Bray I)\textsuperscript{a}</td>
<td>0.01-0.04 \textsuperscript{a,b}</td>
<td>0.9-2.4 \textsuperscript{c,d,e}</td>
</tr>
<tr>
<td></td>
<td>4-6 (Bray II)\textsuperscript{f}</td>
<td>0.005-0.00 \textsuperscript{b,g}</td>
<td></td>
</tr>
<tr>
<td></td>
<td>3 (Olsen)\textsuperscript{b}</td>
<td>0.027-0.030 \textsuperscript{h}</td>
<td></td>
</tr>
<tr>
<td>Yam</td>
<td>0.01-0.02 \textsuperscript{g}</td>
<td>0.02\textsuperscript{g}</td>
<td></td>
</tr>
<tr>
<td>Taro</td>
<td>0.05-0.15 \textsuperscript{h,g,i,j}</td>
<td>0.18-0.20 \textsuperscript{b,i,k}</td>
<td></td>
</tr>
<tr>
<td>Sweet potato</td>
<td>0.028\textsuperscript{k}</td>
<td>0.028\textsuperscript{k}</td>
<td></td>
</tr>
<tr>
<td>Irish potato</td>
<td>0.005-0.04 \textsuperscript{a}</td>
<td>0.005-0.00 \textsuperscript{b,g}</td>
<td></td>
</tr>
<tr>
<td>Wheat</td>
<td>0.027-0.030 \textsuperscript{h}</td>
<td>0.027-0.030 \textsuperscript{h}</td>
<td></td>
</tr>
<tr>
<td>Maize</td>
<td>0.025-0.06 \textsuperscript{i,k}</td>
<td>0.05 \textsuperscript{f}</td>
<td>0.03 \textsuperscript{d,e}</td>
</tr>
<tr>
<td>Sorghum</td>
<td>0.030.12 \textsuperscript{j}</td>
<td>0.03 \textsuperscript{j}</td>
<td></td>
</tr>
<tr>
<td>Rice</td>
<td>0.06 \textsuperscript{n}</td>
<td>0.06 \textsuperscript{n}</td>
<td>0.03 \textsuperscript{d}</td>
</tr>
<tr>
<td>Common beans</td>
<td>15 (Bray I)\textsuperscript{a}</td>
<td>0.01 \textsuperscript{k}</td>
<td>0.03 \textsuperscript{d}</td>
</tr>
<tr>
<td>Peanut</td>
<td>0.016-0.1 \textsuperscript{p}</td>
<td>0.018-0.2 \textsuperscript{p}</td>
<td>0.03 \textsuperscript{d}</td>
</tr>
<tr>
<td>Cowpea</td>
<td>0.20 \textsuperscript{l}</td>
<td>0.20 \textsuperscript{l}</td>
<td>0.02 \textsuperscript{e}</td>
</tr>
<tr>
<td>Soybean</td>
<td>0.30-0.40 \textsuperscript{i,k}</td>
<td>0.20 \textsuperscript{k}</td>
<td>0.03 \textsuperscript{d}</td>
</tr>
<tr>
<td>Chinese cabbage</td>
<td>0.18-0.20 \textsuperscript{p}</td>
<td>0.20 \textsuperscript{k}</td>
<td>0.03 \textsuperscript{d}</td>
</tr>
<tr>
<td>Lettuce</td>
<td>0.005-0.04 \textsuperscript{a}</td>
<td>0.005-0.04 \textsuperscript{a}</td>
<td>0.03 \textsuperscript{d}</td>
</tr>
<tr>
<td>Tomato</td>
<td>0.030.12 \textsuperscript{j}</td>
<td>0.03 \textsuperscript{j}</td>
<td></td>
</tr>
<tr>
<td>Cotton</td>
<td>0.06 \textsuperscript{n}</td>
<td>0.06 \textsuperscript{n}</td>
<td>0.03 \textsuperscript{d}</td>
</tr>
</tbody>
</table>

\textsuperscript{a} Kang et al 1980. \textsuperscript{b} Vander Zaag et al 1979. \textsuperscript{c} Asher and Edwards 1978. \textsuperscript{d} Howeler et al 1982a. \textsuperscript{e} Jintakanon et al 1982. \textsuperscript{f} CIAT 1985, Howeler 1985a. \textsuperscript{g} Vander Zaag 1979. \textsuperscript{h} CIAT 1982. \textsuperscript{i} Fox et al 1974. \textsuperscript{j} Rendle and Kang 1972. \textsuperscript{k} Fox 1981. \textsuperscript{l} IITA 1982. \textsuperscript{m} Goepfert 1972. \textsuperscript{n} CIAT 1978. \textsuperscript{o} Howeler and Medina 1978. \textsuperscript{p} IITA 1981.
R.H. Howeler

in flowing nutrient solutions with an intermediate P concentration of 0.1 μM, both plant growth and the P concentration of tops and roots markedly improved (Howeler et al 1982a).

Role of vesicular-arbuscular mycorrhiza

Vesicular-arbuscular mycorrhizal fungi are present in nearly all natural soils; they infect the roots of the great majority of plants, including the major food crops. In this symbiotic association, the fungus utilizes carbohydrates produced by the plant, while the plant benefits from the increased uptake of P and some other nutrients through the external hyphae extending from the root surface into the soil (Mosse 1981). The beneficial effect of mycorrhiza is of special importance for plants with a coarse and poorly branched root system, since the external hyphae can extend several centimeters away from the roots, thus allowing the absorption of nutrients from a much larger soil volume than the absorption zone surrounding non-mycorrhizal plants. This is of particular importance for the absorption of low-mobility nutrients in the soil solution, such as P, Zn, and Cu.

Because of their thick roots and poorly branched root systems, tropical root and tuber crops are highly dependent on VAM fungi for P absorption from low-P soils. Yost and Fox (1979) found that cassava and Stylosanthes sp. were more mycorrhizae-dependent than cowpea, onion, soybean, and Leucaena sp. Similarly, Howeler et al (1987) found that cassava had a higher VAM dependency than Stylosanthes guianensis, cowpea, beans, Andropogon gayanus, maize, or rice. During a survey in Kerala State, India, CTCRI (1983) found that all root and tuber crops were highly infected with VAM fungi in all soils, but cassava had a generally higher level of infection and a higher spore density in the soil than other root or tuber crops.

Cassava is so mycorrhizae-dependent that it will not grow without mycorrhizal infection except in soils with extremely high available P. When grown in sterilized soil in pots, nonmycorrhizal cassava required the application of 1.6 t P/ha to obtain the same DM production as mycorrhiza-inoculated plants without P application (Fig. 4). Also, in this greenhouse trial the critical available soil-P level was found to be 15 ppm for mycorrhizal and about 190 ppm for nonmycorrhizal cassava (Howeler et al 1982b). Under field conditions, inoculation with VAM fungi increased cassava root yields 3-fold in a sterilized soil, and about 21 and 37% in a nonsterilized soil when 0 or 100 kg P/ha had been applied, respectively (Howeler and Sieverding 1983). In the sterilized soils, however, even noninoculated plants became mycorrhizal after 3-4 mo due to infection from the unsterilized subsoil, and plants subsequently recovered from their initial P deficiency. Completely non-mycorrhizal plants probably would not have produced anything at harvest.

Management of phosphorus nutrition

In low-P soils, P absorption can be maximized by manipulating the genetic absorption and utilization characteristics of the plant, by enhancing the symbiosis
4. Effect of various levels of applied P on dry weight of tops of inoculated and noninoculated cassava grown in sterilized soil from CIAT, Quilichao, Colombia.

with VAM fungi that may increase the soil volume from which P can be absorbed, and by increasing the P supply of the soil through application of P-containing fertilizers or adjustment in soil pH.

**Genetic selection for efficient phosphorus absorption and utilization**

Cassava varieties vary in their inherent ability to absorb P from soil solution. Jintakanon et al (1982) reported that for 12 cassava cultivars grown in flowing nutrient solution, the P concentration required for 95% of maximum DM yield varied from 28 to 78 µM (0.87-2.42 ppm), the rate of P absorption at near maximum growth varied from 6.3 to 11 µM P g fresh weight of roots per d, and maximum DM production varied from 3.6 to 10.0 g/plant. Thus, cassava cultivars that have a high P absorption rate at low P concentration in nutrient solution could be selected. In natural soils, however, cassava never develops without a mycorrhizal association, and the rate of P absorption is increased severalfold by this symbiosis. Thus, Howeler et al (1982a) reported that the P absorption rate for 8 nonmycorrhizal cassava cultivars grown at 1 µM P in flowing nutrient solution varied from 6.1 to 16.8 µM/g root DW per d, while for the same cultivars with mycorrhizae it varied from 22.2 to 35.4 µM/g root DW per d. Thus, screening of cultivars in nonmycorrhizal nutrient solutions may be completely irrelevant, as P absorption by cassava (and most other crops) is highly affected by the degree of mycorrhizal infection, which in turn depends on the pH and P level of the soil as well as the composition of the native VAM population. Thus, cultivars should be screened for low-P tolerance in natural soils and preferably under field conditions. After screening several thousand cassava
cultivars under field conditions in Quilichao, Colombia, CIAT (1988) identified some that produced root yields of about 50 t/ha without P application in soils with only 34 ppm Bray II-extractable P. These cultivars will be used as parents in the cassava breeding program.

**Mycorrhizal manipulation**

Since nearly all natural soils contain VAM spores, cassava roots will inevitably become infected, thus aiding the plant in absorbing P from the soil. Whether or not this natural symbiosis can be further improved by artificial inoculation or by agronomic practices that stimulate the most effective species of the mycorrhizal population depends on many factors, such as the density and composition of the native VAM fungal population; the P concentration, pH, temperature, and humidity of the soil; and the cassava variety (Howeler et al 1987).

The effect of artificial VAM inoculation of cassava grown under natural field conditions depends mainly on the efficiency of the native VAM population and on the P level of the soil. Table 6 shows the effect of inoculation in both sterilized and unsterilized soil in locations with high and low native VAM populations. With high VAM populations inoculation had no significant effect, inoculation was effective in increasing root yields only in those locations having low natural populations or where the population had decreased because of surface-soil erosion. In the 3 soils with low VAM populations, inoculation increased yields between 37 and 154%. The effect of P is indicated in Figure 5, which shows the yield response to inoculation at different levels of applied P in Carimagua, Colombia. Without applied P, inoculation had no effect because of the extremely low levels of available P in the soil. With increased P application, the positive effect of inoculation increased up to about 100 kg P/ha, but decreased at higher levels of applied P. Thus, inoculation is generally effective only at low and intermediate levels of soil P, as VAM root infection tends to decrease at high soil-P levels (Daft and Nicolson 1969, Howeler et al 1987).

**Table 6. Effect of soil sterilization and mycorrhizal inoculation on root yield of cassava grown in locations with high and low native VAM populations.**

<table>
<thead>
<tr>
<th>Site</th>
<th>Sterilized soil</th>
<th>Unsterilized soil</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Noninoculated</td>
<td>Inoculated(^a)</td>
</tr>
<tr>
<td>With high VAM population</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Quilichao</td>
<td>19.6</td>
<td>–</td>
</tr>
<tr>
<td>Mondomo, noneroded</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>With low VAM population</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mondomo, eroded</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>Carimagua-Yopare</td>
<td>7.7</td>
<td>20.2</td>
</tr>
<tr>
<td>Carimagua-Alegria</td>
<td>–</td>
<td>–</td>
</tr>
</tbody>
</table>

\(^a\)Species used: *Glomus manihotis* in Quilichao and Carimagua-Yopare, *Glomus caledonicum* in Mondomo and Carimagua-Alegria.
Besides inoculation, the efficiency of the native VAM fungi can be improved by certain agronomic practices such as application of fertilizers and organic manure, crop rotation, intercropping, application of certain fungicides and herbicides, and soil conservation practices. Much research is needed to elucidate the complicated interactions among soil, host plants, and VAM species before the effect of these practices on symbiosis can be predicted with any degree of certainty.

**Application of phosphorus**

When the P concentration of the soil solution is inadequate to support optimum plant growth, it can be increased by application of manure or P fertilizers. Since the availability of soil P is generally greatest between pH 5.5 and 7.0, P absorption by plants can also be increased by adjusting the soil pH to within this range.

The amount of P to be applied for maximum productivity varies with the crop, the native fertility of the soil, and the P source. As mentioned earlier, Irish potato has a very high P requirement, followed by those of sweet potato, yam, taro, and cassava. In general, potato responds markedly to relatively high P applications. Thus, Muñoz (1986) reported responses up to 132-198 kg P/ha in a volcanic-ash soil of Colombia.

Sweet potato may also require relatively high P application. Ravindran and Bala Nambisan (1987) reported yield increases due to application of 10 t farmyard manure and 75-33-62 kg NPK/ha ranging from 8.3 to 19.6 t/ha under lowland and from 8.0 to 18.9 t/ha under upland conditions in India. However, Rendle and Kang (1977) found sweet potato to be relatively unresponsive to P, with the most responsive variety still producing 73% of maximum without P application. Ghosh et al (1988) also reported a rather low response to P in sweet potato grown in India, with the recommended dosage ranging from 11 to 22 kg P/ha.

---

**Figure 5.** Effect of mycorrhizal inoculation and various levels of P application (mean of 5 P sources) on root yield of cassava cultivar MVen 77 in Carimagua, Colombia.
Although taro was found to have a relatively low external P requirement (De la Peña et al. 1982, Vander Zaag 1979), the optimum P application rate in Hawaii was 240 kg/ha for upland taro and 490 kg/ha for lowland taro (Plucknett and De la Peña 1971). In India, the recommended rate is only about 22 kg P/ha for rainfed taro and 26 kg P/ha for irrigated taro (Ghosh et al. 1988). Yam tends to be more responsive to N and K than to P. At the International Institute of Tropical Agriculture, the recommended dosage is only about 11-13 kg P/ha; in India, it varies between 26 and 35 kg P/ha (Kpeglo et al. 1980).

Of all the root crops, cassava is probably the least responsive to P, but, as mentioned, this is highly dependent on the P status and the mycorrhizal population of the soil. In an Oxisol in Hawaii with only 3 ppm NaHCO₃-extractable P, cultivar Ceiba produced a yield of 42 t/ha (Vander Zaag et al. 1979), while in a Dystropept in Colombia yields of 40-50 t/ha have been reported in a soil with only 324 ppm Bray II-extractable P (CIAT 1988). Still, in soils with equally low levels of available P but with less efficient VAM populations, P application can markedly increase yield. Phosphorus application increased yields from about 6.5 to 25 t/ha in an Oxisol in Carimagua, Colombia. Banded triple superphosphate (TSP) and broadcast basic slag were the most effective sources, while partially acidulated phosphate rock and a 5:1 mixture of phosphate rock with elemental S were also highly effective. The locally produced single superphosphate was least effective. Considering the average response to the six sources, increasing levels of P application increased cassava top growth almost linearly, while root yields increased quadratically, resulting in an initial increase and then a decrease in harvest index (CIAT 1977). Greater responsiveness to P application in top growth than in root growth was also reported by Vander Zaag (1979).

Simple NPK trials throughout Colombia indicated a significant response to P at 13 of 24 locations (Howeler 1985a), mainly in the Oxisols of the Eastern Plains (Llanos Orientales) and the Andepts of Cauca Department. These areas not only have low levels of available P—generally less than 3 ppm Bray II-P—but they often have low VAM populations as well. Thus, P deficiency was found to be the main limiting factor in most short-term fertility trials (Fig. 6). However, with continuous cassava cultivation, K deficiency invariably becomes the main limiting factor (Howeler 1985b).

In highly P-fixing soils, relatively high P rates must be applied to supply the plant’s P requirement. Attempts to increase the efficiency of applied P by frequent applications of small quantities to the soil, by dipping stakes in P solutions before planting, or by foliar applications were all unsuccessful (CIAT 1985). Only soil applications of 50 kg P/ha, either as banded TSP or broadcast basic slag, increased cassava yields significantly at 2 locations in Colombia. Basic slag was also found to be a highly effective P source for cassava in southern India, while Mussoorie rock phosphate was very effective for sweet potato (Ghosh et al. 1988). These less soluble P sources should be broadcast and incorporated before planting, while water-soluble P sources generally should be band-applied full dose, at planting or shortly after planting of cassava (Howeler 1985a), taro (De la Peña and Plucknett 1967, Ghosh et
Conclusions

Tropical root and tuber crops vary greatly in their P requirements. Irish potato is a high-yielding crop of short growth duration that requires a high external P concentration and generally heavy application of soluble P sources. Yam, taro, and sweet potato are intermediate in P requirements and generally require relatively high soil-P levels or modest applications of P fertilizers. Cassava is highly variable in P requirement because of its dependence on an effective association with mycorrhizal fungi. The same is probably true for sweet potato and yam, which were also found to be mycorrhizal. Without mycorrhizal infection, cassava has an extremely high P requirement. In natural soils, however, the crop is always associated with VAM fungi, which greatly enhance P absorption. Thus, in soils with a highly effective native VAM population, cassava has a very low P requirement and often can
produce high yield without P application, even in low-P soils; in soils with low P and low VAM populations, the crop responds well to P, but relatively modest applications are required for continuous production because of the relatively low level of P removal by the crop.

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Van Rossem C (1917) De hoeveelheid der voornaamste voedingsstoffen die door de rijstooast aan de grond worden onttrokken (Quantity of the principal nutrients absorbed from the soil by the rice harvest). Mededeelingen Agric. Chem. Lab. Buitenzorg No. 17.


**Notes**

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*Citation information:* International Rice Research Institute (1990) Phosphorus requirements for sustainable agriculture in Asia and Oceania. P.O. Box 933, Manila, Philippines.
Phosphorus requirements of fiber crops—cotton, jute, and kenaf

LIN BAO AND P.N. TAKKAR

This paper briefly reviews the research on N, P, and K uptake by cotton, jute, and kenaf as well as research in China on the absorption percentage of those elements at the various growth stages of cotton. Using experimental results from China and India, the authors evaluate the response of fiber crops to P fertilization and discuss the proper dosage of P fertilizer under varying conditions. They conclude that rational application of P fertilizer to fiber crops is an important measure for sustainable agriculture.

Cotton, jute, and kenaf are major fiber crops in Asia, particularly in China and India. From 1984 to 1986, the average annual area planted to cotton in China and India reached 13.04 million ha, and the average annual output was 18.28 million t of seed cotton, constituting three quarters of the total output of Asia. At the time, Asia accounted for half of the world cotton area and output. India is the largest jute producer in the world in terms of both total yield and area, followed by Bangladesh (FAO 1986).

Nutrient uptake by cotton, jute, and kenaf

The amount of nutrients absorbed by plants and the percentage of nutrient uptake at various growth stages vary with cultivar, yield, climate, soil, and fertilizer rate, which must all be considered in determining the amount of fertilizer required by the crops.

Total amounts of nutrients absorbed by cotton, jute, and kenaf

The nutrient uptake by cotton at various yield levels in China is listed in Table 1. At a high yield level, cotton plants absorbed more nutrients per ton of cotton production than at a relatively low yield level. The ratio of N:P:K absorbed by cotton plants is about 100:13:83 but varies with the following factors:

- Application of N at a high rate increases N absorption and decreases P and K uptake.
- In southern regions with high temperature and precipitation, the vegetative growth of cotton plants is very active; therefore N uptake is higher and proportions of P and K lower than in the north.
- Some newly developed high-yielding cotton cultivars (e.g., Shandong cotton No. 1) absorb around 50% more nutrients than the local cultivar (Dai zi 15) (CAAS 1983, Li 1979).
Table 1. Nutrient uptake by cotton at various yield levels from 1959-79 data (CAAS 1983).

<table>
<thead>
<tr>
<th>Lint yield (t/ha)</th>
<th>Nutrient uptake (kg/ha)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>N</td>
</tr>
<tr>
<td>0.75</td>
<td>53-135</td>
</tr>
<tr>
<td>1.13</td>
<td>75-158</td>
</tr>
<tr>
<td>1.50</td>
<td>150-278</td>
</tr>
<tr>
<td>1 t lint needs</td>
<td>150</td>
</tr>
</tbody>
</table>

Less information is available in the literature on nutrient uptake by other fiber crops. Data on the nutrient uptake of jute and kenaf (Table 2) come from the Fiber Crop Institute, Chinese Academy of Agricultural Sciences (CAAS) (Lang et al 1982). Phosphorus uptake by jute is significantly higher than that by kenaf. The amounts of N and K absorbed by jute were approximately the same, but significantly more K than N was required when high yield was expected. For kenaf, the requirement for K was also significantly higher than that for N (CAAS 1981).

Proportions of nutrients absorbed during the growth stages of cotton

The pattern of nutrient uptake in cotton is very different at various growth stages (Table 3). Maximum uptake of P occurred at the “blossom to boll bursting” stage, and that of N and K at the “bud emergence to blossom” stage. A large portion of N and K uptake by cotton occurs at the early and middle growth stages, with an early absorption peak, while P uptake occurs at the middle and late growth stages, with a later peak.

Although the absolute amount of P needed is not high, P uptake is critical at the emergence of the second and third leaves. At this time, a P deficiency will greatly restrict growth and development, and injuries cannot be cured even with P treatment at a later stage. If only a limited amount of fertilizer is applied, total nutrient uptake will be very low, since a large portion of the nutrient is absorbed at an early stage, and the crop senesces early. Conversely, if excessive fertilizer is applied, more nutrient will be absorbed, and a greater proportion of the nutrient will be absorbed at a later stage, resulting in excessive vegetative growth (Li et al 1981).

The maximum nutrient uptake of jute is at the “vigorous growth stage” (from plant height of 30-40 cm to bud appearance). The cumulative uptake of N, P, and K in 50 d or so accounts for about 60% of the total uptake of the nutrients during the whole growing period (CAAS 1981).

Phosphorus requirements of cotton, jute, and kenaf as related to management

In both India and China, response of cotton and jute to P fertilizer and P management have been studied under field conditions. The salient results are discussed below.
Table 2. Nutrient requirements for producing 1 t of fiber (Lang et al 1982).

<table>
<thead>
<tr>
<th>Crop</th>
<th>Nutrient requirement (kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>N</td>
</tr>
<tr>
<td>Jute</td>
<td>140</td>
</tr>
<tr>
<td>Kenaf</td>
<td>75</td>
</tr>
</tbody>
</table>

Table 3. Percentage of nutrients absorbed at different growth stages of cotton (Li et al 1981).

<table>
<thead>
<tr>
<th>Growth stage</th>
<th>Nutrients (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>N</td>
</tr>
<tr>
<td>Seeding to bud emergence</td>
<td>5</td>
</tr>
<tr>
<td>Bud emergence to blossom</td>
<td>67</td>
</tr>
<tr>
<td>Blossom to boll bursting</td>
<td>23</td>
</tr>
<tr>
<td>Boll bursting to harvest</td>
<td>5</td>
</tr>
</tbody>
</table>

**Yield response of fiber crops to phosphorus application**

Fiber crops are most sensitive to N, although K application can increase yield and fiber quality. Generally speaking, P has a smaller effect on fiber crops, especially when applied alone, because most soils lack N.

In a series of experiments in India from 1963 to 1973 no yield increase was attributed to P application, probably because the soils supplied sufficient available P to the crop; unfortunately, the soil-available P was not recorded (Kairon et al 1986). In subsequent experiments, as a result of introducing modern agricultural technology and utilizing high-yielding cultivars and heavy N applications, a great amount of soil P was removed. Therefore, a significant response of cotton to P application was found. Cotton grown on newly reclaimed soils that were low in available P showed dramatic yield increases with P application.

The traditional jute-growing alluvial soils in India were not deficient in P and K. Even in the late 1960s, N fertilization was considered the key factor for successful jute production, although P application improved fiber quality. A 9-yr experiment at the Jute Agricultural Research Institute (JARI) farm showed very little increase in fiber yield of cultivar JRQ-632 with P application at 9 kg P/ha; in fact, 18 kg P/ha depressed yield.

Results of 23 fertilizer trials in China in 1958 on soils with continuous application of organic manure and relatively low yield levels showed that cotton was most sensitive to N fertilizer; only one-third of the trials showed P effects. The yield increase of unginned cotton per kilogram of P was only one-half of that per kilogram of N (Table 4) (Soil and Fertilizer Institute 1958).

**Phosphorus requirements of fiber crops**

From 1981 to 1983, research workers associated with the All-India Coordinated Agronomic Research Project conducted 365 dryland field trials to determine the N,
Table 4. Response of cotton to fertilizer application (CAAS 1986).

<table>
<thead>
<tr>
<th>Fertilizer</th>
<th>Trials (no.)</th>
<th>% of total trials showing yield response</th>
<th>Yield increase (kg/kg nutrient)</th>
</tr>
</thead>
<tbody>
<tr>
<td>N</td>
<td>23</td>
<td>78.3</td>
<td>8.4</td>
</tr>
<tr>
<td>P</td>
<td>23</td>
<td>34.8</td>
<td>4.2</td>
</tr>
<tr>
<td>K</td>
<td>20</td>
<td>40.0</td>
<td>4.3</td>
</tr>
</tbody>
</table>

P, and K requirements of Hirsutum cotton (species B332, CJ 73, and G 1946). The experimental plots had medium black soils (Vertisols) with pH 7.5-8.6, 0.3-7% organic C, cation exchange capacity (CEC) 35-50 meq/100 g, and clay content 40-60%. The soil texture ranged from silty clayey loam to clay. Pooled statistical analysis of certain N and P treatments in the 365 trials indicated that seed cotton yield was significantly increased by application of N and P (Table 5). Phosphorus application at 26 kg P/ha showed better yield responses than at 13 kg P/ha, with an average yield increase of 0.43 t/ha, irrespective of location and year. Since no higher rates were included in the experiment, 26 kg P/ha was recommended for Hirsutum cotton as the optimum rate for dryland medium black soil in India (AICARP 1981-83).

In 1982-83, field experiments in a Balsamand loamy sand alluvial soil with low P (Olsen P 1.8 kg P/ha, pH 7.5, 0.3% organic C) showed that cotton yield was significantly increased by P application at 7 and 13 kg P/ha compared with the control, but the difference between the two levels was not significant. Further increase of the application rate to 20 and 26 kg P/ha reduced yields to levels close to the no-P treatment (Table 6). The recommended rate of P application under these conditions was 7-13 kg P/ha (Sharma et al 1988).

Experiments in China showed a negative relationship between the effect of P on yield increase and available P content in the soil. Table 7 lists data from 27 experiments conducted by the Cotton Research Institute of Shandong Province. It is believed that if the available P (Olsen P) is above 16 ppm, no cotton yield response to P will occur (Li et al 1979). Results from 40 field experiments jointly conducted by the Hebei Agricultural Academy and the Agricultural Bureau of Xinji City also

Table 5. Seed cotton yield as influenced by 30, 60, and 90 kg N/ha and P application to medium black soils of India, 1981-83.\(^a\)Control yield of unfertilized plots = 0.39 t/ha.

<table>
<thead>
<tr>
<th>P rate (kg/ha)</th>
<th>30</th>
<th>60</th>
<th>90</th>
<th>Mean</th>
</tr>
</thead>
<tbody>
<tr>
<td>13</td>
<td>0.87</td>
<td>0.79</td>
<td>0.82</td>
<td>0.83</td>
</tr>
<tr>
<td>26</td>
<td>-</td>
<td>1.04</td>
<td>1.48</td>
<td>1.26</td>
</tr>
<tr>
<td>Mean</td>
<td>0.87</td>
<td>0.92</td>
<td>1.15</td>
<td>–</td>
</tr>
</tbody>
</table>

\(^a\)LSD (0.05) for P = 0.149, for N = 0.206.
support the preceding finding that P response is closely related to soil available P (Table 8). The soils at the experimental sites were calcareous alluvial soils with pH 8.2, 0.5-0.7% organic C, soil texture silty loam to loam, well-irrigated, and drained. The seed cotton yield ranged from 2.7 to 3.6 t/ha. The local recommended P application rate was 44-53 kg P/ha when the soil available P was equal to or less than 5 ppm, and 26 kg P/ha when available P was around 7 ppm (Lui Zongheng and Ai Wei, 1987, pers. comm.).

The rates of P application to cotton differed with variety, plant spacing, and rainfed or irrigated condition in Gujarat State, India (Table 9).

On 15 different Indian soils, Olsen P proved to be the best test for available P, and the critical level for jute was 11 kg P/ha. The effect of P on jute increased with lowered soil available P (Doharey et al 1979, Goswami et al 1971). Therefore, P application must be on the basis of soil test results.

### Table 6. Effect of P application rate on seed cotton yield (Sharma et al 1988).

<table>
<thead>
<tr>
<th>P rate (kg/ha)</th>
<th>Seed cotton yield (t/ha)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1982</td>
</tr>
<tr>
<td>0</td>
<td>2.13</td>
</tr>
<tr>
<td>7</td>
<td>2.39</td>
</tr>
<tr>
<td>13</td>
<td>2.41</td>
</tr>
<tr>
<td>20</td>
<td>2.27</td>
</tr>
<tr>
<td>26</td>
<td>2.26</td>
</tr>
<tr>
<td>LSD (0.05)</td>
<td>0.25</td>
</tr>
</tbody>
</table>

### Table 7. Range of soil available P, and cotton yields as a result of p application (Li et al 1979).

<table>
<thead>
<tr>
<th>Soil available P (ppm)</th>
<th>Cotton yield increase</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>kg/ha</td>
</tr>
<tr>
<td>1.5-4.4</td>
<td>278</td>
</tr>
<tr>
<td>4.5-7.4</td>
<td>102</td>
</tr>
<tr>
<td>9.4-11.8</td>
<td>65</td>
</tr>
</tbody>
</table>

### Table 8. Relationship between soil available P content and response of cotton to P application (Lui Zongheng and Ai Wei, 1987, pers. comm.).

<table>
<thead>
<tr>
<th>Soil available P (ppm)</th>
<th>Trials (no.)</th>
<th>Trials (no.) showing response</th>
<th>% of total trials showing response</th>
</tr>
</thead>
<tbody>
<tr>
<td>&lt;5</td>
<td>11</td>
<td>10</td>
<td>91</td>
</tr>
<tr>
<td>6-8</td>
<td>12</td>
<td>8</td>
<td>67</td>
</tr>
<tr>
<td>&gt;9</td>
<td>17</td>
<td>4</td>
<td>24</td>
</tr>
</tbody>
</table>
Agronomists at JARI conducted 456 simple fertilizer trials in farmers’ fields to assess the N, P, and K requirements of *Capsularis* variety JRC-212 and *Olitorius* variety JR0-632 in normal to slightly acidic jute-growing soils in the West Bengal, Assam, Orissa, Uttar Pradesh, and Bihar States of India (Dargan 1971). The response of jute to P was significant in the majority of districts, and the response was often greater than 100 kg/ha. Furthermore, the response to P was by and large greater when applied with NK than with N alone, except in Assam. This effect was more marked in JRC-212 than in JR0-632, indicating more synergistic interaction between P and K as well as response to P in the former variety. The greater response of jute to P in some districts and states than in others appears to have stemmed from the degree of P deficiency in the soil.

To obtain target yields of 2.5 and 3.5 t jute/ha on alluvial soils having a soil test value of 10 kg Olsen P/ha, Ghosh (1983) computed P requirements of 9 and 18 kg P/ha, respectively.

In experiments at the Zhejiang Agricultural Research Institute, P application not only increased yield, but also improved fiber strength (Table 10). With application of 113 kg N/ha and 93 kg K/ha, adding 18 kg P/ha increased raw jute fiber by 0.5 t/ha. No further yield increase was found at higher P rates (Agriculture Department of Zhejiang Province 1959).

For kenaf production in China, a basal application of 300-450 kg/ha of single superphosphate (SSP) mixed with organic manure is common. Unfortunately, no experimental data in the literature show yield responses.

### Phosphorus fertilizer application techniques

Phosphorus application is relatively simple compared with N fertilization. Phosphorus is used mostly as basal fertilizer or as an early sidedressing. The keys to P fertilization are early application and deep placement. It is traditional to broadcast a mixture of P fertilizer (SSP) and organic manure, and then plow. Another effective way to use P fertilizer is banding. Sometimes farmers apply P as a sidedressing at seeding or at the early seedling stage. The efficiency of P fertilizer applied at later stages is usually low; therefore the early application of P is strongly recommended.

Attention must be paid to the cropping system of fiber crops for rational P application. In recent years, monocropping in irrigated land has been gradually
replaced by a cotton - wheat rotation. The cotton - wheat system is becoming more and more popular in the alluvial soils and calcareous soils in Punjab and Haryana States of India as a result of modern agricultural technology and irrigation facilities. In 57 field experiments in light-textured soils with low or medium P levels in Punjab, 9 kg/ ha or more of P applied to cotton after fallow significantly increased yield, but P applied to cotton following wheat produced no yield response, due to the residual effect of P applied to wheat. After 3 yr of continuous P fertilizer application to wheat in a rotation, no P fertilizer may be needed for the following cotton crop (Rana et al 1984).

The Northern China Plain is the most important cotton-growing area in China. At present, both total cotton area and cotton yield in this region account for more than 50% of those in the whole country. About 53% of the land in the Plain is well irrigated. Changing the cotton monocrop into wheat - cotton double cropping (intercropping or relay cropping) is considered one of the key measures to fully utilize the climate and land resources, stabilize cotton production, increase wheat yield, and raise economic returns. Cotton - wheat rotation can produce 3 t wheat/ ha, plus cotton yields of 80-90% of those in a monocrop. South of 38° N, the cotton - wheat system is rapidly becoming popular. In 1988, around 1.12 million ha were under this system. In this system, wheat usually shows a very good yield response to P. One kilogram of P can increase wheat grain by 20 kg. Therefore, the recommendation is to supply adequate P fertilizer to wheat and omit or reduce P application to cotton (CAAS 1986).

For many cropping systems in China and India involving jute, cotton, and kenaf in combination with rice, wheat, mustard, peanut, rape, green manure crops, sorghum, etc., further research is needed on the efficiency of P use.

**Discussion and conclusions**

The effect of P fertilizer on fiber crops is becoming more and more significant. This results from the combination of high-yielding varieties with high N fertilizer use and varietal improvement. The application of P has an effect on yield and fiber quality.

The response of fiber crops to P is closely related to soil available P content. Consideration must be made not only of crop P uptake, but also of the P-supplying power of soils when the rate of P fertilization is to be determined. In the large area

<table>
<thead>
<tr>
<th>P rate (kg/ha)</th>
<th>Jute fiber yield (t/ha)</th>
<th>Fiber strength (kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>4.18</td>
<td>43.2</td>
</tr>
<tr>
<td>6</td>
<td>4.45</td>
<td>43.6</td>
</tr>
<tr>
<td>18</td>
<td>4.64</td>
<td>44.5</td>
</tr>
<tr>
<td>36</td>
<td>4.60</td>
<td>47.7</td>
</tr>
</tbody>
</table>
planted to cotton in the Northern China Plain, P-deficient soils (Olsen P 5 ppm) account for 67% of the land, and P application is a very effective way to increase yield. The rate of P application should not be less than the amount needed by the crop, and even a little more P should be added to reduce the P-deficient area and improve N efficiency. Hence, the total amount of P needed by cotton and other fiber crops can be roughly estimated.

To realize high and stable yields, attention must be paid not only to the P requirement of fiber crops, but also to the needs and rational distribution of P fertilizers in cropping systems.

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Notes

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Citation information: International Rice Research Institute (1990) Phosphorus requirements for sustainable agriculture in Asia and Oceania. P.O. Box 933, Manila, Philippines.
Vegetables produce high biomass in a short time and remove larger quantities of P than many other crops. The use of large amounts of chemical and organic fertilizers leads to high values of available soil P on vegetable farms. Band placement of small doses of water-soluble P may be advantageous to vegetable crops, even on lands containing high soil P. Steps should be taken to prevent the buildup of soil P, since this may lead to chemical and biological imbalances in soil that can reduce its productivity.

With the approaching self-sufficiency in cereal production in many countries of Asia, considerable attention is being directed to vegetable production. The chief reasons for this interest are the needs to provide a better balanced diet to an expanding population, increase the income levels of farmers, generate employment, and earn foreign exchange from exports.

Vegetables can be grown on a wide array of soils and in a variety of climates and are thus found in numerous farming systems, ranging from shifting cultivation to sophisticated greenhouse culture. Most vegetables are annuals, with a short growth period that may last only 1-2 mo for certain species. They generate high biomass rapidly and remove comparatively large quantities of plant nutrients in a short time (Table 1). Unlike most other annuals, vegetables are harvested succulent, while the plant is still in a physiologically active state. For example, harvest of luffa, eggplant, okra, and tomato may be simultaneous with flowering.

Crop yields, inputs, costs of cultivation, and profits— from a survey of 50 farmers engaged in rice cultivation—are compared in Table 2 with those for potato and tomato cultivation. Chemical and organic fertilizers are used abundantly in vegetable cultivation, often in amounts considered in excess of need. A primary reason for the overuse of chemical fertilizer in vegetable cultivation is its low cost compared with the high cost of cultivation and high income. Consequent to this excessive use, vegetable-growing soils are rich in P compared with soils in other farming systems (Table 3). Pesticides are also commonly used in vegetable cultivation, many farmers adding them as a protective measure whether pests are present or not.

This paper focuses on P management in intensive vegetable cultivation where farmers use large quantities of chemical and organic fertilizer, soils are already high
in available P from past fertilization, and profits are quite substantial. The paper will also examine some of the undesirable effects of excessive P fertilization on the production environment.

Table 1. Phosphorus removed by crops.

<table>
<thead>
<tr>
<th>Crop</th>
<th>Dry matter yield (t/ha)</th>
<th>P removed (kg/ha)</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vegetables</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bean</td>
<td>7.0</td>
<td>22</td>
<td>Greenwood et al (1980)</td>
</tr>
<tr>
<td>Cabbage</td>
<td>5.9</td>
<td>22</td>
<td>Greenwood et al (1980)</td>
</tr>
<tr>
<td>Carrot</td>
<td>13.7</td>
<td>38</td>
<td>Greenwood et al (1980)</td>
</tr>
<tr>
<td>Cereals</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Maize</td>
<td>4.0</td>
<td>14</td>
<td>Amarasiri and Perera (1975)</td>
</tr>
<tr>
<td>Rice</td>
<td>5.0</td>
<td>18</td>
<td>Amarasiri and Perera (1975)</td>
</tr>
<tr>
<td>Grain legumes</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cowpea</td>
<td>1.5</td>
<td>5</td>
<td>Amarasiri and Perera (1975)</td>
</tr>
<tr>
<td>Mungbean</td>
<td>1.2</td>
<td>3</td>
<td>Amarasiri and Perera (1975)</td>
</tr>
<tr>
<td>Peanut</td>
<td>1.8</td>
<td>6</td>
<td>Amarasiri and Perera (1975)</td>
</tr>
<tr>
<td>Plantation crops&lt;sup&gt;a&lt;/sup&gt;</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Coffee</td>
<td>1.0</td>
<td>8</td>
<td>Cooke (1985)</td>
</tr>
<tr>
<td>Rubber</td>
<td>1.1</td>
<td>1</td>
<td>Cooke (1985)</td>
</tr>
<tr>
<td>Tea</td>
<td>1.3</td>
<td>5</td>
<td>Cooke (1985)</td>
</tr>
</tbody>
</table>

<sup>a</sup>Removal estimated for the harvested product.

Table 2. Cost of cultivation and inputs, and profit obtained from rice, potato, and tomato in Sri Lanka (Division of Agricultural Economics and Projects, Department of Agriculture, Sri Lanka 1988).

<table>
<thead>
<tr>
<th>Item</th>
<th>Rice</th>
<th>Potato</th>
<th>Tomato</th>
</tr>
</thead>
<tbody>
<tr>
<td>Yield (t/ha)</td>
<td>4.4</td>
<td>19</td>
<td>19.8</td>
</tr>
<tr>
<td>Chemical fertilizer (kg/ha)&lt;sup&gt;a&lt;/sup&gt;</td>
<td>151</td>
<td>595</td>
<td>275</td>
</tr>
<tr>
<td>Organic fertilizer (t/ha)&lt;sup&gt;b&lt;/sup&gt;</td>
<td>0</td>
<td>20</td>
<td>4</td>
</tr>
<tr>
<td>Cost of fertilizer ($/ha)&lt;sup&gt;c&lt;/sup&gt;</td>
<td>39</td>
<td>772</td>
<td>301</td>
</tr>
<tr>
<td>Cost of pesticides ($/ha)</td>
<td>12</td>
<td>193</td>
<td>309</td>
</tr>
<tr>
<td>Cost of cultivation ($/ha)</td>
<td>355</td>
<td>34.28</td>
<td>1459</td>
</tr>
<tr>
<td>Net return ($/ha)</td>
<td>107</td>
<td>4235</td>
<td>2882</td>
</tr>
</tbody>
</table>

<sup>a</sup>N + P + K. <sup>b</sup>Farmyard manure for potato, and poultry litter for tomato. <sup>c</sup>Includes both chemical and organic fertilizers.

Table 3. Range of available P in farming systems in Sri Lanka.

<table>
<thead>
<tr>
<th>Cropping system</th>
<th>NaHCO₃-extractable P (ppm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rice - rice</td>
<td>10-25</td>
</tr>
<tr>
<td>Rice - vegetable</td>
<td>25-50</td>
</tr>
<tr>
<td>Rice - vegetable - vegetable</td>
<td>50-100</td>
</tr>
<tr>
<td>Vegetable - vegetable - vegetable</td>
<td>100-400</td>
</tr>
</tbody>
</table>
Phosphorus supply to plants

The pool of available P in soil and its supply to plants are influenced by weathering of minerals; solubilization of P-containing inorganic compounds, which may be the reaction products of soil and fertilizer; mineralization of organic matter; and the action of mycorrhizae. The effect of mycorrhizae, both naturally present in soil and inoculated, on plant growth and P uptake has been well documented (Tinker 1975). In fact, Pacovsky and Fuller (1986) showed that P uptake by soybean growing in a low-P soil inoculated with *Glomus fasciculatum* or *G. mossae* was four to five times greater per day than by uninoculated plants.

Conventional soil test procedures using chemical extractants, adsorption isotherms, and radioactive isotopes are efforts at estimating the P-supplying capability of soils. This information, along with field experimentation, helps in devising recommendations to farmers on P requirements. Although organic manure is added by nearly all vegetable growers, experiments designed to compare the effects of organic with chemical fertilizers or to assess their complementary effects are scarce. Consequently, chemical P fertilizer recommendations that take into account the contribution of P from organic sources are not very common.

Phosphorus supply from animal wastes

Animal wastes are the most common form of organic manure used in vegetable cultivation in Asia. The benefits of adding animal wastes to soil—such as slow plant nutrient release, reduction of P fixation in soil (Khanna and Stevenson 1962, Struthers and Sieling 1950), improvement of soil physical properties, and increase of water-holding capacity and cation exchange capacity—are well known. Additionally, organics may improve the quality of vegetables (Asano 1984) and provide substances that impart disease resistance to plants (Flaig 1984).

An interesting consideration is whether the increase of soil temperature during the breakdown of farmyard manure (FYM) can increase P availability to plants growing on cold soils. In fact, Singh and Jones (1977) showed that the higher P uptake by lettuce as temperature was raised from 17 to 29 °C was due to greater release of P to the soil solution than to any physiological effects of temperature on the plant itself.

It is not clear why farmers continue to add costly organic manure to soils already rich in plant nutrients, possessing desirable physical properties, and free of moisture stress. When asked why they consistently add organics, farmers often state quite simply their belief that crop yield will decrease substantially if they are excluded.

Since 20-30 t/ha of animal wastes may be added to each vegetable crop, it is essential to know the amount of P added thereby and its plant availability, at least in comparison with inorganic P fertilizers. Chemical analyses of buffalo, cattle, goat, sheep, pig, and poultry dung are shown in Table 4. Pig and poultry dung have the highest P content. Dung is usually mixed with the stable bedding material, which may be straw in the case of cattle or rice husk in the case of poultry. The P content of the resulting manure will be often less than that of the dung itself, being about 0.3-0.4% on a fresh weight basis. Even when 3 vegetable crops are grown per year, it
Table 4. Mean P content of animal wastes (dry basis) (S. Maraikar and S. L. Amarasiri, Department of Agriculture, Sri Lanka, unpubl. data).

<table>
<thead>
<tr>
<th>Source</th>
<th>Samples (no.)</th>
<th>Dry matter (%)</th>
<th>P content(^a) (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Buffalo</td>
<td>106</td>
<td>18.0</td>
<td>0.57 (0.03)</td>
</tr>
<tr>
<td>Cattle</td>
<td>220</td>
<td>16.7</td>
<td>0.74 (0.02)</td>
</tr>
<tr>
<td>Goat</td>
<td>126</td>
<td>43.9</td>
<td>0.70 (0.04)</td>
</tr>
<tr>
<td>Sheep</td>
<td>103</td>
<td>40.6</td>
<td>0.67 (0.04)</td>
</tr>
<tr>
<td>Pig</td>
<td>105</td>
<td>38.0</td>
<td>1.46 (0.07)</td>
</tr>
<tr>
<td>Poultry</td>
<td>110</td>
<td>29.3</td>
<td>1.52 (0.05)</td>
</tr>
</tbody>
</table>

\(^a\) Standard errors within parentheses.

is common to add FYM for 2 of them, each application amounting to 20-30 t/ha. An annual input of about 120 kg P/ha may enter the fields this way.

The effect of incubating monocalcium phosphate, cattle manure, and poultry manure for 6 wk in a soil with pH 6.4 at a temperature of about 25 °C is shown in Table 5. All three sources led to an increase in Olsen P. Soil P values increased as more manure was added. Although poultry manure gave higher soil P values than cattle manure, the P availability index, calculated as the increase in available soil P as a percentage of P added, was higher for cattle manure. The availability index of the latter was nearly equal to that of monocalcium phosphate. Similar results have been reported by Elias-Aazar et al (1980), who compared the effect of organic manure with KH₂PO₄ when added to two alkaline soils.

From a 6-yr experiment where equal amounts of P were added as single superphosphate (SSP) and FYM, Sharma et al (1980) found that available soil P as well as yield and P uptake of potato were higher with FYM than with SSP. They concluded that chemical fertilizer need not be added to potato if heavy applications of FYM are made.

**Phosphorus supply from chemical fertilizer**

The type of chemical fertilizer, the amount to be added, and the manner of its placement must be determined so that the proper balance of agronomic effectiveness and economic benefits is realized. The preference is usually for phosphate rocks (PRs), since they are cheaper per unit of P and are available locally in many countries. For most perennials and for some annuals, PRs have been found suitable, particularly in acidic soils. Some plant species have greater capability of solubilizing PRs by their relatively higher cation uptake and consequent acidification of the rhizosphere, or by an excessive Ca²⁺ uptake, thereby shifting the mass-action equilibria in favor of dissolving PRs (Bekele et al 1983). Information on the relative agronomic effectiveness of vegetable species in utilizing PRs in the tropics is scarce.

Field experiments indicate that water-soluble phosphates are preferable to PRs in meeting the P requirements of potato, even in acid soils (Kathirgamathiyah and Caesar 1964). The response of cabbage to triple super-phosphate (TSP), a high citric acid-soluble (4.4% P) PR, and a low citric acid-soluble (1.5% P) PR in an Ultisol of pH 4.3 and 18.0 ppm Olsen P is shown in Figure 1. Although the soil was strongly
Table 5. Effect of adding monocalcium phosphate, cattle manure, and poultry manure to soil on available P content after 6 wk (S. Maraikar and S. L. Amarasiri, Department of Agriculture, Sri Lanka, unpubl. data).

<table>
<thead>
<tr>
<th>Material</th>
<th>P added (mg/kg)</th>
<th>Soil available P&lt;sup&gt;a&lt;/sup&gt; (mg/kg)</th>
<th>P availability index</th>
</tr>
</thead>
<tbody>
<tr>
<td>Control</td>
<td>0</td>
<td>12.6</td>
<td>−</td>
</tr>
<tr>
<td>Monocalcium phosphate</td>
<td>37</td>
<td>27.7</td>
<td>41</td>
</tr>
<tr>
<td>Cattle manure</td>
<td>90</td>
<td>52.6</td>
<td>44</td>
</tr>
<tr>
<td></td>
<td>179</td>
<td>108.4</td>
<td>54</td>
</tr>
<tr>
<td></td>
<td>359</td>
<td>175.5</td>
<td>45</td>
</tr>
<tr>
<td>Poultry manure</td>
<td>457</td>
<td>118.6</td>
<td>23</td>
</tr>
<tr>
<td></td>
<td>913</td>
<td>278.7</td>
<td>29</td>
</tr>
<tr>
<td></td>
<td>1826</td>
<td>472.0</td>
<td>25</td>
</tr>
</tbody>
</table>

<sup>a</sup>NaHCO<sub>3</sub>-extractable.

acidic, the PRs could not match the P-supplying ability of TSP to meet the P needs of cabbage. Under these conditions, TSP is the most profitable source.

The optimal amount of P fertilizer to be added depends on the available P status of the soil, crop species, season, and prices of both inputs and product. Usually the P content of vegetable-growing soils is on the high side, and one would therefore expect low or no response to added P. However, yield increases have been reported on high-P soils. Tomato yield increased from 21 to 26 t/ha with the addition of 8.7

1. Effect of adding triple superphosphate (TSP), high citric acid-soluble phosphate rock (HCPR), and low citric acid-soluble phosphate rock (LCPR) on cabbage yield.
kg P/ha in a soil having 227 ppm P (Bray No. 2) (Blatt and McRae 1986). In another study, Peck et al (1987) showed that cabbage yields increased with the addition of TSP, although the soil had been fertilized with it at the rate of 70 kg P/ha per yr for 9 yr. These reports as well as the continued use of high doses of chemical fertilizer by farmers on soils even exceeding 300 ppm P (Olsen) suggest economic advantages with a starter dose of water-soluble P to facilitate the early rapid growth of vegetables. The P in the soil may effectively take care of the subsequent needs of the plant.

The available experimental evidence on placement of P fertilizer for vegetables is overwhelmingly in support of band placement. Blatt and McRae (1986) compared broadcast (15 cm from row) and band placement (10-12 cm deep) of TSP on the growth of tomato in two soils having high and low available P. On the high-P soil, banding P at 8.7 kg P/ha and broadcasting 35 kg P/ha gave similar fruit yields while on the low-P soil, banding at 17 kg P/ha was as effective as broadcasting 70 kg P/ha.

Effects of high soil phosphorus content on crop production

Unless farmers know that the P content of vegetable-growing soils is usually high, P values will continue to rise with time, since the P input from FYM and chemical fertilizers is likely to exceed that removed in the harvest. Although direct adverse effects of excess soil P on plant growth have not been widely reported, P-induced Zn deficiencies are known (Peck et al 1987, Singh et al 1986). Yet the influence of high soil P levels on the biological processes taking place there has not received much attention in discussions on soil fertility management and crop production.

Many low-input agricultural systems depend on the action of mycorrhiza to obtain the P requirements of plants. Much evidence shows that high P content in soil can reduce the effect of mycorrhiza. Hirata et al (1988) showed that when soil P exceeded 8 ppm (Bray No. 2), the mycorrhizal population began to decrease. Similar results were shown by Cooper (1975) and Strzemska (1975). Hayman (1975) showed from a long-term experiment involving addition of different levels of P over a 12-yr period that vesicular-arbuscular mycorrhiza (VAM) infection in potato was reduced sevenfold as Olsen’s P increased from 8 to 39 ppm. From the high values of soil P in most vegetable soils, it seems that VAM is almost nonfunctional there.

While intensive cultivation with high fertilizer additions may not have to depend on contributions by VAM, many unfavorable effects on plant growth may arise from elimination or reduction of VAM in soil. Schonbeck (1979) states that VAM infection reduces fungal soil-borne diseases in tomato, cucumber, onion, and lettuce. Sikora (1978) reported that distribution of Meloidogyne incognita galls in mycorrhizal tomato plants was negatively correlated with G. mossae levels in the roots. He suggests that the reduction in nematode population of mycorrhizal plants may be caused by the inability of a large number of larvae to penetrate roots populated by the fungus.

These observations show that nutrient imbalances, such as in the P-Zn ratio, are but a part of the numerous, varied, and complex unfavorable situations that may result from P excesses in soil. While inorganic imbalances can be readily detected...
and often easily corrected, biological imbalances may not be apparent and can lead to serious crop losses. That addition of excessive inputs may reduce soil productivity may be suspected from the potato tuber yields obtained in 12 farmers’ fields on a fairly homogeneous tract of land totaling about 50 ha. A yield decline from 22 to 16 t/ha with increases in available P content from 30 to 110 ppm (Olsen) was observed. Since no other soil parameter apart from P was considered, the above relationship may not have been a cause and effect. If one assumes that farmers who added high P fertilizer also added large quantities of other plant nutrients, as well as fungicides, weedicides, and insecticides, these results may have been the effects of overall chemical or biological soil degradation. In fact, many farmers in intensive farming systems complain of a productivity decrease over time. Some farmers in Sri Lanka, after adding very high doses of chemical inputs, have experienced declining yields and have begun to purchase and apply tractorloads of uncultivated soils to their lands as a corrective measure.

Outlook

These observations show the importance of maintaining correct chemical and biological balances in soil. An important consideration in intensive cultivation systems in so far as P is concerned seems to be the prevention of a P buildup or the use of farming practices that can lower soil P values where they are already very high. A primary requirement to achieve this is soil testing of farmers’ fields. The tests should be simple, rapid, reliable, useful, and inexpensive. Since large quantities of organic fertilizers are commonly added, chemical P additions may be kept to a minimum. Where soil P values are very high, crops that remove much P may be included in the rotation.

References cited


Notes

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Citation information: International Rice Research Institute (1990) Phosphorus requirements for sustainable agriculture in Asia and Oceania. P.O. Box 933, Manila, Philippines.
Management of fertility, variety, planting density, and irrigation for maximum yield

H.L.S. TANDON AND D.K. KUNDU

The maximum yield concept—along with its practical derivative, maximum economic yield—is discussed with special reference to the importance of fertility, variety, density, and irrigation in building high productivity systems. Maximum yield research demands the best interdisciplinary efforts, and an understanding of the factors affecting yield and the management of interactions. Crop yields of 6-10 times the average levels have been achieved in food grains and commercial crops. Modern varieties show large variations in yield potential. Manipulation of plant density is an important tool for maximizing yields, the optimum density being determined largely by water availability, fertility, and plant growth habit. Although single-factor studies are numerous, little research has integrated the various factors. Maximum yield research is relevant for Asian agriculture if it responds to the special features and needs of Asian farmers. In addition, maximum yield technology packages should ensure the long-term preservation of soil productivity and of the environment so that farmers are able to obtain high yields year after year without side effects. Some suggestions are made for maximum yield research in the Asian context.

The maximum yield is the highest attainable yield that a constraint-free crop production system can produce in a given environment. In tropical and subtropical climates, where it is possible to grow up to four crops per year on the same field, the maximum attainable yield (MAY) should be evaluated on the basis of the cropping system as a unit or in terms of yield per hectare per year. Where systems include crops that differ substantially in caloric or monetary value (cereals, legumes, oilseeds, tubers), MAY can perhaps be better evaluated in terms of energy or monetary units rather than physical yield alone.

Maximum yield research contains a built-in challenge in that it calls for the development and demonstration of production technologies for obtaining MAY out in the field. Such research demands the best interdisciplinary efforts, a thorough understanding of the factors that affect yield, and the skill to manage various interactions. To quote Cooke (1982), “The purpose of research on maximum yields is to identify the factors that limit yield, to show how they interact, and how they may be overcome. Research to understand and control crop production is not complete until a package of practices has been assembled that will reliably achieve the yield that crop variety, soil, and climate make possible on a site.”
This paper is confined to the importance of management factors such as fertility, variety, planting density, and irrigation. A discussion of a few selected technology packages and the need for maximum yield research that takes into account special features of Asian agriculture is also included.

Definitions

A distinction between MAY and maximum economic yield (MEY) is necessary for relevance to practical agriculture. MAY is of interest primarily to

- the researcher aiming to establish the production potential of a crop or variety,
- the farmer aiming to win a maximum yield competition, and
- the innovative farmer wanting to know MAY under his conditions.

For most farmers having access to adequate resources, MEY is associated with maximum net returns and lowest per unit production cost. MEY is thus somewhat lower than MAY, since it rejects that part of the yield response curve that is not economical for the farming enterprise. The relationship between MEY and MAY depends on and varies with crops, production factors, and prices.

The production package for MEY must, however, flow from MAY research. Some aspects of maximum yield research have been outlined (Bosshart and Von Uexkull 1986). MAY → MEY research is relevant for Asian agriculture, since improvement in yields has already been accepted in most countries as the major route for producing adequate food and other farm-based commodities to meet the needs of increasing populations. For commercial crops, the need to maximize yields to lower the per unit production cost and gain competitiveness in export markets has been discussed (Das 1985).

The realization of maximum yields depends upon the optimization of many factors; it leaves little room for making mistakes. The idea, however, is not to maximize yields at any cost. The technology for the maximization of production should be fully accountable for the preservation of soil productivity and the environment in the long run.

Maximum attainable yields

When compared with the highest yields achieved, let alone theoretical production potentials, average crop yields at present appear low. The yield gap is indicative of both missed opportunities as well as hope for the future.

Theoretical dry matter production potential under optimum management in the tropics has been reported to be 281 t/ha or 770 kg/ha per d (Loomis and Williams 1973). Theoretical maximum yield of maize is 38 t grain/ha; yield levels >23 t/ha have already been achieved. In India, grain yields of >10 t/ha have been obtained with irrigated wheat and flooded rice in the dry season, while yields up to 15 t rough rice/ha per yr have been achieved with multiple cropping (Mahapatra et al 1974).

In coconut, the best yields achieved are 4 times the average yield, although exceptional single palms yielding 470 nuts/palm per yr (equivalent to 16 times the average yield in India) have been identified (Bavappa 1985). In Pakistan, sugarcane
yields of 324-370 t/ha have been recorded, as compared with the average yield of 37 t/ha (Husain 1982). Under nonirrigated conditions, a sorghum grain yield of 8.4 t/ha has been obtained in southern India, as compared with the average yield of <1 t/ha (Kudasommannaar et al 1980).

The prerequisites for harvesting maximum yields have been described by Bosshart and Von Uexkull (1986), Brownell and Van Elswyk (1987), and Cook (1982). The approach is well stated by Bavappa (1985): “If we are to integrate the various independent pieces of know-how which already exist on how to improve crop yields into a unified or integrated system, substantial increases in production are possible.” The importance of internutrient and interinput interactions in building maximum yields has been stressed (Tandon 1987, Tandon and Sekhon 1988, Wagner 1979).

Key ingredients for harvesting 23.3 t maize grain/ha included selection of the best hybrid, a high planting density (90,720 plants/ha at harvest), 610 mm rainfall during crop growth in the midwestern USA, and integrated use of organic manure, liming material, and inorganic NPK fertilizer (Bosshart and Von Uexkull 1986).

Citing an example of maize production in Kenya, Arnon (1978) reported a fourfold increase in yield over control with adoption of a complete package of improved practices. The package included monetary as well as nonmonetary inputs. A package for harvesting 185 t sugarcane/ha in Pakistan has been reported (Husain 1982); it uses hot water-treated young planting material, potash application, density of 14,000 holes/ha, hilling, plant protection, and use of sterilized implements.

**Selected management factors**

Each of the four factors under consideration (fertility, variety, planting density, and irrigation) exerts considerable influence on crop yields, individually and collectively. The appropriate level and management of essential plant nutrients is one of the factors required for optimum crop yields (Pretty and Sanders 1982). Nutrient requirements vary with cropping sequence, cropping intensity, nature of component crops, and productivity levels attained. A large number of published data showed that intensive annual cropping systems removed 27-67 kg P/ha per yr (Table 1). Inadequate fertility clearly limits crop production, but the other three factors also cause substantial yield differences and may contribute 4.2-5.7 t/ha to grain yield (Table 2). While the superiority of hybrids or other modern varieties (MVs) over traditional varieties cannot be emphasized, careful choices need to be made within the broad group of MVs for specific conditions. Yield differences between low-ranking and top-ranking maize hybrids can be as much as 5.7 t/ha (Potash and Phosphate Institute 1988), which is 1.5 times the average world maize yield. A hybrid that may outperform another hybrid without irrigation can turn out to be a “low” yielder under irrigated conditions (Flannery 1982).

High yields are quite often associated with a high planting density if water, nutrients, and mutual shading do not operate as constraints. Maize yields of more than 20 t/ha are usually associated with densities of around 90,000 plants/ha (Bosshart and Von Uexkull 1986). In coconut plantations, as against a normal stand
Table 1. Nutrient removal by some intensive annual cropping systems (Tandon and Sekhon 1988).

<table>
<thead>
<tr>
<th>Cropping system</th>
<th>Yielda (t/ha)</th>
<th>Nutrient removal (kg/ha per yr)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>N</td>
</tr>
<tr>
<td>Rice - wheat</td>
<td>8.8</td>
<td>235</td>
</tr>
<tr>
<td>Maize - wheat</td>
<td>7.7</td>
<td>220</td>
</tr>
<tr>
<td>Pigeonpea - wheat</td>
<td>4.8</td>
<td>219</td>
</tr>
<tr>
<td>Rice - rice</td>
<td>6.3</td>
<td>139</td>
</tr>
<tr>
<td>Soybean - wheat</td>
<td>7.7</td>
<td>260</td>
</tr>
<tr>
<td>Rice - berseem</td>
<td>5.7 + 66 (fo)</td>
<td>274</td>
</tr>
<tr>
<td>Maize - wheat - green gram</td>
<td>8.2</td>
<td>306</td>
</tr>
<tr>
<td>Rice - wheat - green gram</td>
<td>11.2</td>
<td>328</td>
</tr>
<tr>
<td>Maize - potato -wheat</td>
<td>8.6 + 11.9 (t)</td>
<td>268</td>
</tr>
<tr>
<td>Maize - rapeseed -wheat</td>
<td>8.6</td>
<td>250</td>
</tr>
<tr>
<td>Rice - wheat - jute</td>
<td>6.9 + 2.3 (fi)</td>
<td>170</td>
</tr>
<tr>
<td>Soybean - wheat - maize (fodder)</td>
<td>5.8 + 5.1 (fo)</td>
<td>334</td>
</tr>
<tr>
<td>Rice - wheat - cowpea (fodder)</td>
<td>9.6 + 3.9 (fo)</td>
<td>272</td>
</tr>
</tbody>
</table>

a fo = fodder, fi = fiber, t = tuber, all others grain yield.

Table 2. Contribution of variety, planting density, and irrigation to increasing maize grain yield, USA (Potash and Phosphate Institute 1988).

<table>
<thead>
<tr>
<th>Factor</th>
<th>Level</th>
<th>Grain yield (t/ha)</th>
<th>Difference</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>t/ha</td>
</tr>
<tr>
<td>Variety</td>
<td>Low-ranking hybrids</td>
<td>8.3</td>
<td>5.7</td>
</tr>
<tr>
<td></td>
<td>Top-ranking hybrids</td>
<td>14.0</td>
<td></td>
</tr>
<tr>
<td>Density</td>
<td>30,000 plants/ha</td>
<td>8.7</td>
<td>4.2</td>
</tr>
<tr>
<td></td>
<td>90,000 plants/ha</td>
<td>12.9</td>
<td></td>
</tr>
<tr>
<td>Irrigation</td>
<td>Without</td>
<td>7.1</td>
<td>4.9</td>
</tr>
<tr>
<td></td>
<td>With</td>
<td>12.0</td>
<td></td>
</tr>
</tbody>
</table>

of 175 palms/ha, high density multistorey cropping systems can accommodate 13,000 plants/ha of a variety of crops (Bavappa 1985).

In an interesting 7-yr experiment with pea, the highest yield was obtained with 132 plants/m²; but when the cost of seed was taken into account, the highest economic return was obtained with 88 plants/m² (Saimbhi and Dhillon 1985). Results with pineapple in India show that yield levels of 100 t/ha or more could be attained only if the planting density was increased from 64,000 to 73,000 plants/ha. The fertility level that produced a yield of 90 t/ha at 64,000 plants/ha resulted in a yield of 110 t/ha with 73,000 plants/ha (Table 3). Yields generally increase with increasing irrigation up to the optimum depending upon the soil, climate, water table, and season. However, proper scheduling of irrigation in relation to stages of crop growth is very important to get the highest productivity out of available water resources. Results with wheat show that if water is available, say, for 4 irrigations, the yield difference between the best irrigation schedule and the worst one could be
Table 3. Impact of planting density on pineapple yield in relation to applied nutrients, India (Roy 1986).

<table>
<thead>
<tr>
<th>Attainable yield (t/ha)</th>
<th>Economical N+K combination</th>
<th>Attainable yield (t/ha)</th>
<th>Economical N+K combination</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>64,000 plants/ha</td>
<td>73,000 plants/ha</td>
<td>70</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>80</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>90</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>100</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>110</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

\[a\] In the presence of optimum P application. \[b\] Yield always >70 t/ha.

as much as 1.4 t/ha, worth US$180/ha at current prices (Bhardwaj et al 1975). In sugarcane, at any level of available irrigation water per season, a yield gain of 10 t/ha could be achieved just by proper distribution of this water during the crop season (Singh et al 1981). Increase in the supply of irrigation water did not compensate for yield loss due to late planting.

**Fertility-variety relationships**

Genotypic differences in the utilization of absorbed P are well known. Varieties differ in ability to make efficient use of absorbed P for grain production. This is illustrated in Table 4 for five rice cultivars that absorbed similar amounts of P but produced dissimilar amounts of grain. More efficient varieties in this regard will be increasingly sought for sustaining high yields and high profits.

**Fertility-irrigation relationships**

Benefits from variable rates of irrigation and fertility are either additive or synergistic (Tandon 1987). There is generally an optimum combination of both, which is determined primarily by the degree of nutrient deficiency and moisture availability. In the arid region of Rajasthan, India, results of a 3-yr study indicated the following fertilizer-water combinations for wheat production (Singh et al 1976):

- For maximum yield (6.3 t/ha): 156 kg N + 17 kg P + 89 cm water/ha
- For maximum profit: 132 kg N + 17 kg P + 75 cm water/ha
- For minimum acceptable yield (3 t/ha): 80 kg N + 17 kg P + 36 cm water/ha

Table 4. Yield differences among 5 rice cultivars that absorbed similar amounts of P (Lal et al 1982).

<table>
<thead>
<tr>
<th>Variety</th>
<th>P uptake (kg/ha)</th>
<th>Rough rice yield (t/ha)</th>
</tr>
</thead>
<tbody>
<tr>
<td>RP-79-7</td>
<td>11.3</td>
<td>4.4</td>
</tr>
<tr>
<td>RP-79-5</td>
<td>10.7</td>
<td>4.3</td>
</tr>
<tr>
<td>IET-826</td>
<td>10.5</td>
<td>4.1</td>
</tr>
<tr>
<td>RP-79-14</td>
<td>11.0</td>
<td>3.7</td>
</tr>
<tr>
<td>MTU-17</td>
<td>10.7</td>
<td>3.6</td>
</tr>
</tbody>
</table>
In field experiments with lentil, the positive interaction between irrigation and P application accounted for 35% of the total yield response to these two inputs, as shown below (Singh et al 1983):

- Response to irrigation without P = 250 kg grain/ha
- Response to P without irrigation = 500 kg grain/ha
- Response to P plus irrigation = 1150 kg grain/ha
- Interaction component = 400 kg grain/ha

**Fertility-density relationships**

Results of field experiments with pigeonpea showed that it was worth increasing plant population if the same was accompanied by P application. The following picture emerged from the experiments reported by Ahlawat and Saraf (1981):

- Increasing plant population from 50 to 100 thousand/ha = 9% extra yield
- 50 thousand plants/ha plus 17 kg P/ha = 47% extra yield
- 100 thousand plants/ha plus 17 kg P/ha = 82% extra yield

**Fertilizers and amendments for sustaining yields**

Technology packages for sustaining high yields always include fertilizer application. The results of a series of long-term fertilizer experiments initiated by the Indian Council of Agricultural Research during the early 1970s clearly show that in several environments, high yields could be sustained only if soil amendments, organic manures, and needed micronutrients were applied along with the major nutrients (Table 5). Results from another long-term experiment in Ludhiana, India, with a maize - wheat rotation showed how application of N alone could not sustain yields, but balancing N with P did so over 15 yr (Table 6).

**Variety-density relationships**

Variety-density relationships are determined primarily by the availability of water and by plant growth habit, especially with respect to mutual shading. In experiments in New Jersey, USA, increasing plant stand from 90,000 to 102,000/ha decreased make yield without irrigation (Flannery 1982). In a deep Vertisol in south India cropped to rainfed sorghum, the highest grain yield of 8.4 t/ha was obtained at the highest population density of 666,000/ha, the seasonal rainfall being 509 mm (Kudasomannavar et al 1980). In environments where the rainfall is poorly distributed, a balance between optimum plant density and available moisture may have to be worked out based on rainfall probability analyses to minimize risks.

In transplanted lowland rice, raising planting density from 100,000 to 250,000 hills/ha added 0.8 t/ha to rice yield (Zia 1987); higher populations were not tried in this experiment. In other results from Pakistan, planting density and fertility appeared to strike a balance so that rice yield at low planting density + high fertility was comparable to the yield at higher density + medium fertility (Table 7).

In population density studies with cotton varieties, highest yields of around 1.7 t lint/ha were obtained at a density of 77,500 plants/ha both with CA 491 and Paymaster 10IA (Fowler and Ray 1977). CA 491 produced this yield through
Table 5. Contribution of different inputs to the total yield increase due to NPK + farmyard manure (FYM) application in long-term fertilizer experiments, India, 1971-85 (Nambiar and Ghosh 1984, Tandon 1989). \(^a\)

<table>
<thead>
<tr>
<th>Location (soil)</th>
<th>Crop</th>
<th>Total response to NPK + FYM addition (kg/ha)</th>
<th>Contribution (%) of FYM</th>
<th>N</th>
<th>PK</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ludhiana</td>
<td>Maize</td>
<td>2796</td>
<td>24</td>
<td>36</td>
<td>18</td>
</tr>
<tr>
<td>(alluvial)</td>
<td>Wheat</td>
<td>3848</td>
<td>3</td>
<td>49</td>
<td>30</td>
</tr>
<tr>
<td>Barrackpore</td>
<td>Rice</td>
<td>2757</td>
<td>0</td>
<td>79</td>
<td>13</td>
</tr>
<tr>
<td>(alluvial)</td>
<td>Wheat</td>
<td>1579</td>
<td>2</td>
<td>82</td>
<td>8</td>
</tr>
<tr>
<td></td>
<td>Jute</td>
<td>938</td>
<td>0</td>
<td>76</td>
<td>3</td>
</tr>
<tr>
<td>Hyderabad</td>
<td>Rice (kharif)</td>
<td>2446</td>
<td>23</td>
<td>45</td>
<td>22</td>
</tr>
<tr>
<td>(red)</td>
<td>Rice (rabi)</td>
<td>2627</td>
<td>29</td>
<td>56</td>
<td>14</td>
</tr>
<tr>
<td>Ranchi</td>
<td>Soybean</td>
<td>735</td>
<td>37</td>
<td>-ve</td>
<td>24</td>
</tr>
<tr>
<td>(red)</td>
<td>Wheat</td>
<td>1218</td>
<td>10</td>
<td>-ve</td>
<td>74</td>
</tr>
<tr>
<td>Bangalore</td>
<td>Finger millet</td>
<td>1806</td>
<td>5</td>
<td>0</td>
<td>78</td>
</tr>
<tr>
<td>(red)</td>
<td>Maize</td>
<td>4545</td>
<td>31</td>
<td>19</td>
<td>37</td>
</tr>
<tr>
<td>Palampur</td>
<td>Wheat</td>
<td>2772</td>
<td>24</td>
<td>11</td>
<td>50</td>
</tr>
<tr>
<td>(submontane)</td>
<td>Rice</td>
<td>2566</td>
<td>27</td>
<td>57</td>
<td>0</td>
</tr>
<tr>
<td>Pantnagar</td>
<td>Wheat</td>
<td>2544</td>
<td>17</td>
<td>82</td>
<td>0</td>
</tr>
</tbody>
</table>

\(^a\) NPK was applied to each crop. FYM was applied only to the kharif crop. Contributions of inputs were straight effects, not accounting for interactions. At Ranchi and Bangalore, contribution of P was a combined NP effect because in these highly P-deficient soils, N alone was ineffective in raising yield.

Table 6. Impact of P application on sustaining grain yield of an annual maize-wheat rotation over 15 yr in Ludhiana, India (Singh and Brar 1986).

<table>
<thead>
<tr>
<th>Treatment</th>
<th>Mean annual grain yield (t/ha)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Years 1-5</td>
</tr>
<tr>
<td>No fertilizer added</td>
<td>2.5</td>
</tr>
<tr>
<td>100 kg N</td>
<td>4.9</td>
</tr>
<tr>
<td>100 kg N + 22 kg P/ha</td>
<td>7.3</td>
</tr>
<tr>
<td>100 kg N + 44 kg P/ha</td>
<td>8.0</td>
</tr>
</tbody>
</table>

Table 7. Effect of variety and planting density on yield of rice at 2 fertility levels, Pakistan (Tahir Saleem et al 1986).

<table>
<thead>
<tr>
<th>Nutrients applied (kg/ha)</th>
<th>Rough rice yield (t/ha)</th>
</tr>
</thead>
<tbody>
<tr>
<td>N</td>
<td>P</td>
</tr>
<tr>
<td>---</td>
<td>---</td>
</tr>
<tr>
<td>57</td>
<td>13</td>
</tr>
<tr>
<td>84</td>
<td>25</td>
</tr>
<tr>
<td>57</td>
<td>13</td>
</tr>
<tr>
<td>114</td>
<td>25</td>
</tr>
</tbody>
</table>
greater number of fruits per square meter and Paymaster 101A through more lint per boll. A significant negative interaction between plant population and plant height was reported in cotton by Kittock et al (1986). Within the range of 20,000-200,000 plants/ha, the optimum plant population for maximum yield decreased by about 11,000 plants/ha for every 10cm increase in plant height. Taller plants would be expected to reach a given level of leafshading at a lower planting density, resulting in reduced photosynthesis and greater square and boll abscission.

Conflicting results regarding varietal response to changes in plant density, so often encountered in the literature, can probably be attributed to differences in plant architecture and to inadequate description of the factors that influence their relationship at a given site.

In maize, the grain yield of hybrids having upright leaves increased with increasing plant population, whereas the yield of horizontal-leaved hybrids was less responsive to increase in planting density. Horizontal-leaved hybrids yielded 15% more than upright-leaved hybrids at 32,110 plants/ha, but 27% less at 128,440 plants/ha (Anonymous 1970).

**Variety-irrigation relationships**

Crop varieties having high yield potentials normally respond more to irrigation water and fertilizer, because they have the ability to use these inputs for producing high yields. This is illustrated by numerous results with MVs and in the MEY trials (Flannery 1982).

Results from India show that coconut and areca nut MVs made more productive use of irrigation water, resulting in higher yields and lower production costs per unit of crop (Table 8). Such results indicate that application of irrigation water, a purchased input in many cases, is most remunerative in high-productivity systems.

**Density-irrigation relationships**

With access to abundant irrigation water, planting density can be raised until yields are maximized, provided that matching fertility levels are applied. Manipulation of plant density becomes an important tool for maximizing yield as well as nutrient use efficiency. Where water is limited, the optimum plant density must be worked out to

<table>
<thead>
<tr>
<th>Variety</th>
<th>Irrigation status</th>
<th>Yield</th>
<th>Production cost per unit of crop</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Coconut</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Local (WCT)</td>
<td>Rainfed</td>
<td>10,500 nuts/ha</td>
<td>Rs 1.05/nut</td>
</tr>
<tr>
<td>Local (WCT)</td>
<td>Irrigated</td>
<td>15,700 nuts/ha</td>
<td>Rs 0.90/nut</td>
</tr>
<tr>
<td>MV (D×T)</td>
<td>Irrigated</td>
<td>21,000 nuts/ha</td>
<td>Rs 0.60/nut</td>
</tr>
<tr>
<td><strong>Areca nut</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Local</td>
<td>Rainfed</td>
<td>1,400 kg nuts/ha</td>
<td>Rs 13.40/kg</td>
</tr>
<tr>
<td>Local</td>
<td>Irrigated</td>
<td>2,200 kg nuts/ha</td>
<td>Rs 12.65/kg</td>
</tr>
<tr>
<td>MV (Mangala)</td>
<td>Irrigated</td>
<td>3,500 kg nuts/ha</td>
<td>Rs 7.70/kg</td>
</tr>
</tbody>
</table>

*Rs 16 = approximately US$1.*
match water availability. An interaction between irrigation and planting density is presented in Table 9 (after Karlen and Camp 1985). Higher planting density was worthwhile only at higher levels of applied water.

In nonirrigated, dryland systems, the management of soil water depletion becomes important. When a crop is grown in a dry area without irrigation, the rate at which roots extract water from the soil can be manipulated by changing planting density (Bond et al 1964). The maximum yield of a crop in such environments can be obtained by regulating the plant population so that excessive depletion of soil moisture does not occur early in the season and adequate moisture is available for the crop to complete the reproductive phase satisfactorily. Under limited water conditions, high plant density may result in more dry matter but less grain yield, whereas low plant density may give a higher grain yield in spite of comparatively lower dry matter production. The effect of fewer plants per area in the low-density stands can be compensated, within limits, by better tiller survival and higher yield per plant (Azam-Ali et al 1984).

**Variety-density-irrigation relationships**

Not many studies have evaluated all three factors simultaneously. One example, directly related to maximum yield research, is that of Flannery (1982) (Table 10).

### Table 9. Water management and plant population interaction effects on grain yield of maize on a loamy sand soil (Karlen and Camp 1985).

<table>
<thead>
<tr>
<th>Water applied (mm) a</th>
<th>Grain yield b (t/ha)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>67,000 PPH 1980</td>
</tr>
<tr>
<td>297</td>
<td>5.5</td>
</tr>
<tr>
<td>581</td>
<td>12.8</td>
</tr>
<tr>
<td>745</td>
<td>12.9</td>
</tr>
<tr>
<td></td>
<td>71,000 PPH 1981</td>
</tr>
<tr>
<td>330</td>
<td>5.8</td>
</tr>
<tr>
<td>524</td>
<td>11.3</td>
</tr>
<tr>
<td>583</td>
<td>11.5</td>
</tr>
</tbody>
</table>

*a Rainfall plus irrigation water, b PPH = plants per hectare. LSD (0.05) was 0.7 t/ha in both years.

### Table 10. Integrated effect of variety, planting density, and irrigation on maize yield, USA (Flannery 1982).

<table>
<thead>
<tr>
<th>Irrigation</th>
<th>Plant population (X 1000/ha)</th>
<th>Hybrid Agway 849X</th>
<th>Hybrid Pioneer 3382</th>
</tr>
</thead>
<tbody>
<tr>
<td>Not Irrigated</td>
<td>90</td>
<td>7.1</td>
<td>8.4</td>
</tr>
<tr>
<td></td>
<td>102</td>
<td>6.3</td>
<td>8.1</td>
</tr>
<tr>
<td>Irrigated</td>
<td>90</td>
<td>17.0</td>
<td>11.9</td>
</tr>
<tr>
<td></td>
<td>102</td>
<td>17.5</td>
<td>12.7</td>
</tr>
</tbody>
</table>
Although irrigation was a must for getting highest yields, decisions regarding the best variety to be planted and the optimum planting density depended upon whether irrigation was available or not. Even without irrigation, the value of selecting the most appropriate hybrid and planting density was equivalent to 2 t grain/ha.

In experiments with 2 sunflower varieties grown at 3 plant populations with and without irrigation, the contribution of irrigation to yield was maximum. A 45,000/ha plant stand was near optimum, and no significant difference was observed between the 2 hybrids NK 212 and CW 894 with or without irrigation (Miller et al 1984). Planting densities higher than 45,000/ha were detrimental to the performance of NK 212.

**Maximum yield concept in the Asian context**

Although attempts to harvest maximum yields have been made by individual farmers in Asian countries, the concept of setting maximum net returns as the prime goal has been developed primarily in North America. The concept is relevant to Asian agriculture for the simple reason that all farmers would like to maximize their net income. However, agriculture in Asia has its own special features, wherein most farmers do not have the facilities to operate a constraint-free crop production system, even if they wanted to. In our assessment, the development of maximum yield production packages for smallholder Asian farmers should be based on the following:

- Agricultural production programs must be fully geared toward producing enough food for an expanding Asian population. The goal of sustainable agriculture, therefore, should be to increase agricultural production to levels necessary to meet the increasing needs and aspirations of an expanding world population without degrading the environment.
- Yield and profit maximization should be seen in terms of the cropping system as a unit, although it is recognized that a strong system is built up of strong individual components.
- The technology for maximum yield must not lead to any long-term deterioration in soil productivity or the environment. It should enable the farmer to produce maximum sustainable yield and profit levels year after year. This implies that maximum yield research should be conducted on a medium- to long-term basis with provision for adequate monitoring of the soil, water, pests, diseases, etc.
- In future research programs on yield maximization, as many interacting factors should be evaluated simultaneously as are possible.
- The MAY-MEY approach should take into account not only the main product but also by-products such as straw, stover, and sticks. These have definite commercial value and are traded, and their prices rise when fodder and fuel wood are scarce. At similar grain prices, a 3 t pigeonpea crop/ha is far more valuable than a 3 t chickpea crop/ha, for example, because the former is accompanied by at least 10 t fuel wood/ha.
Fertility, variety, planting density, and irrigation

- MEY research should find ways and means of including appropriate studies on postharvest crop care so that the maximum yield harvested is actually translated into maximum net returns by reducing postharvest losses.
- Since farmers have different investment capacities, which are usually suboptimal, yield maximization packages for more than one level of investment should be developed. This would provide much-needed information for a vast majority of farmers. There is, for example, hardly any crop production research in which treatment levels are in terms of investment levels ($/ha) rather than the traditional quantity levels (kg/ha).
- Maximum yield research should be conducted on well-characterized, benchmark sites through long-term experiments so that the results can be transferred with greater confidence across locations. The sites selected should be representative of sizable agricultural areas.
- Research on MAY should serve as the first step toward MEY research, with the latter having a built-in provision for responding to changes in the prices of inputs and outputs. It will essentially have to be agroeconomic research.

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Notes

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Citation information: International Rice Research Institute (1990) Phosphorus requirements for sustainable agriculture in Asia and Oceania. P.O. Box 933, Manila, Philippines.
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