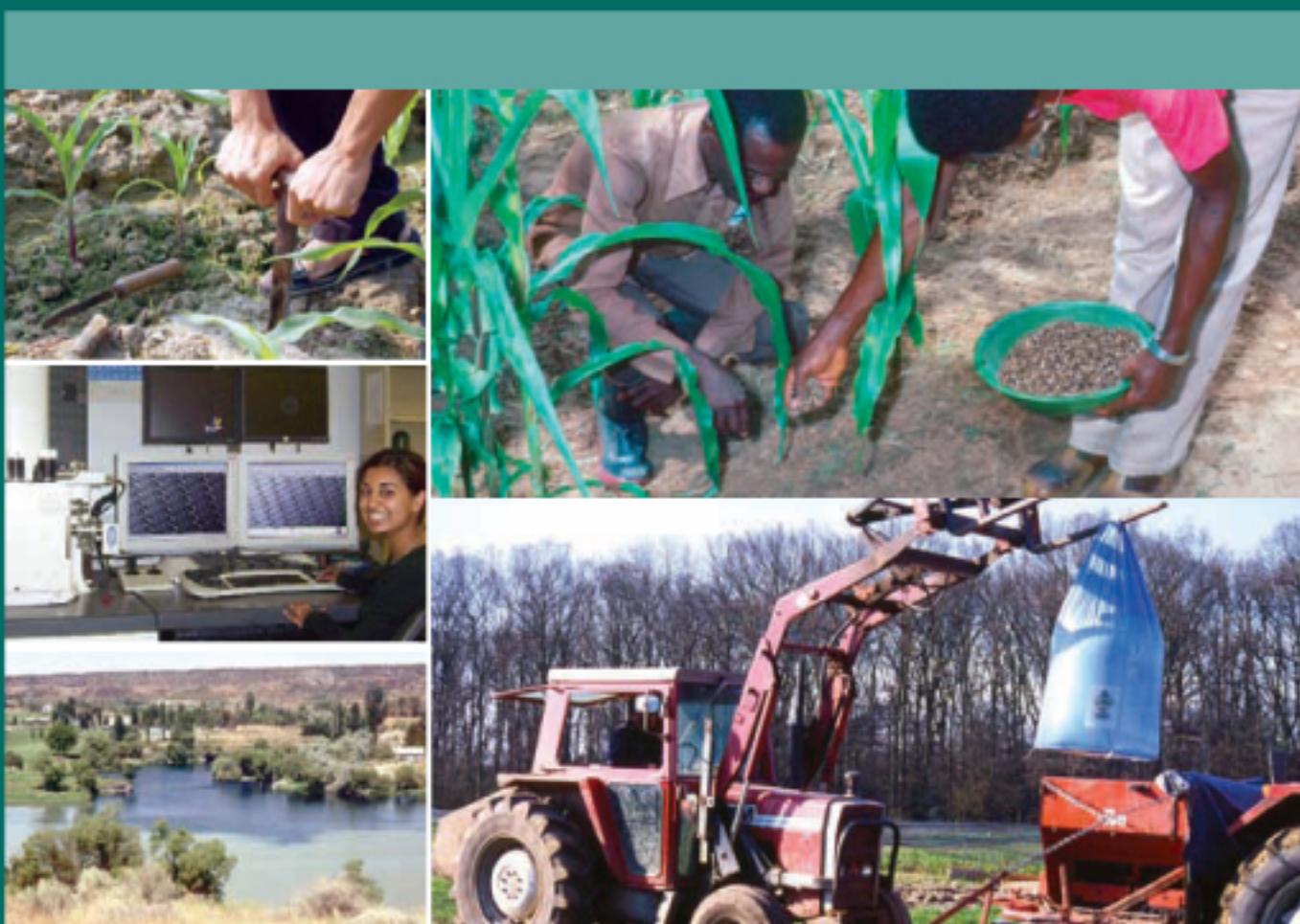


# Efficiency of soil and fertilizer phosphorus use

Reconciling changing concepts of soil phosphorus behaviour with agronomic information



The Fertilizer Institute  
Nourish. Replenish. Grow.



# Efficiency of soil and fertilizer phosphorus use

Reconciling changing concepts of soil phosphorus behaviour with agronomic information

18

by

**J.K. Syers**

Dean, School of Science  
Mae Fah Luang University  
Thailand

**A.E. Johnston**

Lawes Trust Senior Fellow  
Rothamsted Research  
United Kingdom

**D. Curtin**

Scientist  
New Zealand Institute for Crop & Food  
Research Limited  
New Zealand

The designations employed and the presentation of material in this information product do not imply the expression of any opinion whatsoever on the part of the Food and Agriculture Organization of the United Nations (FAO) concerning the legal or development status of any country, territory, city or area or of its authorities, or concerning the delimitation of its frontiers or boundaries. The mention of specific companies or products of manufacturers, whether or not these have been patented, does not imply that these have been endorsed or recommended by FAO in preference to others of a similar nature that are not mentioned.

ISBN 978-92-5-105929-6

All rights reserved. Reproduction and dissemination of material in this information product for educational or other non-commercial purposes are authorized without any prior written permission from the copyright holders provided the source is fully acknowledged. Reproduction of material in this information product for resale or other commercial purposes is prohibited without written permission of the copyright holders. Applications for such permission should be addressed to:

Chief  
Electronic Publishing Policy and Support Branch  
Communication Division  
FAO  
Viale delle Terme di Caracalla, 00153 Rome, Italy  
or by e-mail to:  
[copyright@fao.org](mailto:copyright@fao.org)

# Contents

<b>Acknowledgements</b>	<b>vii</b>
<b>List of acronyms and abbreviations</b>	<b>viii</b>
<b>Executive summary</b>	<b>ix</b>
<b>1. Introduction</b>	<b>1</b>
Rationale for the report	1
Background	2
<b>2. Plant availability of soil and fertilizer phosphorus</b>	<b>5</b>
Soil-plant interactions	5
Concentration of phosphorus in the soil solution	5
Movement of phosphorus to roots	7
Plant root systems and phosphorus uptake by roots	8
Phosphorus uptake, root systems and soil conditions	10
<b>3. Changing concepts of the behaviour of soil and fertilizer phosphorus and reconciling these with agronomic information</b>	<b>15</b>
Work in the nineteenth century	15
Work in the early part of the twentieth century	16
From 1950 to 1980: a period of change	17
A major change in direction	20
An overall assessment	23
Reconciling current concepts with agronomic information	23
<b>4. Measuring the recovery of soil and fertilizer phosphorus and defining phosphorus-use efficiency</b>	<b>27</b>
Introduction	27
Assessing the recovery of added phosphorus from crop yields	29
Direct method	31
Difference method	32
Balance method	34
The difference and balance methods compared	35
Efficiency determined in relation to yield per kilogram of phosphorus applied or taken up by the crop	36

Summary of methods for estimating the recovery of phosphorus fertilizers	37
Soil analysis	38
Assessing the increase in readily plant-available soil phosphorus	39
Optimizing the use of soil phosphorus reserves	39
Sequential analysis of soil phosphorus	40
Using omission plots to assess the need for phosphorus	43
Summary	44
<b>5. Improving the efficiency of soil and fertilizer phosphorus use in agriculture</b>	<b>45</b>
Modifying surface soil properties	46
Managing surface soil and its phosphorus content	47
Managing phosphorus sources	49
Investment to optimize soil phosphorus status and availability	50
<b>6. Conclusions</b>	<b>53</b>
<b>References</b>	<b>55</b>
<b>Annex 1 - Case studies</b>	<b>63</b>

# List of tables

1. Effect of soil organic matter on the relationship between the yield of three arable crops and Olsen P in a silty clay loam soil, Rothamsted
2. Interactive effects of soil phosphorus and applied nitrogen on maize grain yields
3. Total phosphorus at different depths where superphosphate was applied for many years to a silty clay loam surface soil at pH 6.5
4. Recovery of P by the difference method in a greenhouse experiment with P added as MCP at four rates to soils with a range of plant-available P values
5. Change in P recovery over time determined by the difference method, Broadbalk, Rothamsted
6. Effect of level of plant-available soil P on the recovery of P applied to three arable Rothamsted
7. Change in P recovery over time determined by the balance method, Broadbalk, Rothamsted
8. Percentage recovery of three amounts of applied P at two levels of Olsen P, sandy clay loam soil, Saxmundham
9. Efficiency of P applied as MCP when expressed as unit of DM per unit of P applied or unit of DM per unit of P uptake
10. Effect of Olsen P and N on the yield and efficiency/recovery of P by winter wheat, Broadbalk, Rothamsted, 1985–2000
11. Relationship between P balance at the end of each treatment period and the change in soil P fractions, Exhaustion Land, Rothamsted

## List of figures

1. Daily P uptake by spring barley after emergence
2. Olsen P values over 16 years in eight soils having different initial Olsen P values and with no further additions of phosphorus (left) and development of a coincident decline curve by making horizontal shifts (right)
3. Conceptual diagram for the forms of inorganic P in soils categorized in terms of accessibility, extractability and plant availability
4. Response to Olsen P of sugar beet, barley and winter wheat grown on different soils at three sites in the southeast of the United Kingdom
5. The theoretical relationship between crop yield and the level of readily-plant-available P and K in soil
6. The relationship between Olsen P and the yield of wheat grain on a silty clay loam soil
7. The relationship between Olsen P and the yield of grass DM on a silty clay loam soil

# Acknowledgements

This report has benefited from the valuable inputs provided at all stages of its preparation by the other joint sponsors: The Fertilizer Institute; the International Fertilizer Industry Association; the International Plant Nutrition Institute; and the World Phosphate Institute.

A number of people from a range of countries have supplied data and information, and contributed to the thinking that has formed the basis of the present report. They include: Robert Brinkman, Limamoulaye Cisse, Achim Dobermann, Paul Fixen, Allan Gillingham, Wenceslau Goedert, Liang Guo-qing, Patrick Heffer, Bill Herz, Li Shutian, Jin Ji-yun, Terry Roberts, John Ryan Malcolm Sumner, and Holm Tiessen.

# List of acronyms and abbreviations

Al	Aluminium
AM	Arbuscular mycorrhiza
Ca	Calcium
Cu	Copper
DAP	Di-ammonium phosphate
DCP	Dicalcium phosphate
DCPD	Dicalcium phosphate dihydrate
DM	Dry matter
Fe	Iron
FYM	Farmyard manure
GPS	Global Positioning System
IFA	International Fertilizer Industry Association
IPI	International Potash Institute
IPNI	International Plant Nutrition Institute
K	Potassium
LDC	Least-developed country
M	Mol
MAP	Mono-ammonium phosphate
MCP	Monocalcium phosphate
Mg	Magnesium
N	Nitrogen
Na	Sodium
OCP	Octacalcium phosphate
P	Phosphorus
Pi	Inorganic phosphorus
Po	Organic phosphorus
PR	Phosphate rock
RPR	Reactive phosphate rock
SDC	Swiss Development Cooperation
SOM	Soil organic matter
SP	Superphosphate
SSNM	Site-specific nutrient management
SSP	Single superphosphate
TCP	Tricalcium phosphate
TSP	Triple superphosphate

# Executive summary

The efficient use of fertilizer phosphorus (P) is important for three main reasons. First, phosphate rock, from which P fertilizers are manufactured, is a finite, non-renewable resource, and it must be used efficiently in order to maximize its life span. Second, there is a need to maintain and improve the P status of many soils for the growth of crops for food, fibre and bioenergy. This is particularly important in least-developed countries (LDCs) that need to increase food production and improve rural livelihoods. Third, the transfer of soil P (derived from fertilizers and organic manures) is a major cause of P-induced eutrophication in surface waters. This causes undesirable changes in their ecology, resulting in a decline in the provision of eco-services, often with serious economic consequences.

This report reviews, analyses and synthesizes information on the efficient use of soil and fertilizer P. It presents information on the plant availability of soil and fertilizer P, with an emphasis on soil-plant interactions. The focus is on the changing concepts of the behaviour of both soil and fertilizer P and on the need to define and assess their recovery and, thus, P-use efficiency, more appropriately. The report also outlines strategies for improving P-use efficiency.

The main conclusion of this report is that the efficiency of fertilizer P use is often high (up to 90 percent) when evaluated over an adequate time scale using the balance method.

The two main factors controlling the availability of soil P to plant roots are the concentration of phosphate ions in the soil solution and the ability of the soil to replenish these ions when plant roots remove them, i.e. the P-buffer capacity of the soil. Root length and diameter and the efficiency of P uptake by the roots determine the rate and extent of P uptake.

Understanding of the behaviour of P in soils has improved substantially in recent years. Research indicates that inorganic P exists in most soils in adsorbed forms, which can become absorbed by diffusive penetration into soil components. This may result in only a temporary decrease in plant availability (i.e. there is a reversible transfer of P between available and non-available forms). These findings have largely been responsible for the re-assessment developed in this report. It is concluded that P is largely retained by soil components with a continuum of bonding energies, resulting in varying degrees of reversibility. This conclusion is consistent with the often high values (up to 90 percent) for the recovery of fertilizer P over an appropriate time scale. This implies a high efficiency of use over time.

An important outcome of these findings is that soil P can exist in a series of “pools”, which can be defined in terms of the extractability of P in different reagents. In turn, the P in these pools can be related to the availability of P to plants, recognizing that there is a continuum of both extractability and availability. If the readily-extractable pool provides most of the plant-available P in soils, then it is only necessary to accumulate and maintain a certain amount of P in it in order to obtain an optimal crop yield. This concept of a “critical value” for a given soil and farming system has important practical implications for efficient P use. Maintaining the soil at or close to the critical value has important benefits to the farmer (in terms of economic return) and to the environment (in terms of reducing the risk of P transfers to surface waters). This concept is less relevant in LDCs as soils usually contain small amounts of available P.

It is possible to define a critical value for readily plant-available soil P for individual soil types and farming systems. This report provides examples and methods to achieve and maintain the critical value. Where adequate information is lacking, it is possible to use an “omission plot” technique to establish whether the soil contains sufficient available P for economically viable yields. Where P limits plant growth, field experiments must determine the amount required.

Phosphorus-use efficiency depends on soil P status, but measurements of P recovery also depend on crop yield, which can be affected by many factors, including other inputs (e.g. fertilizer nitrogen). To build up soil P to the critical value, it may be necessary to accept a lower recovery of added P for some years. In many arable cropping systems, the amount of P required to maintain the critical value is often similar to that removed in the crop (i.e. there is a very high P-use efficiency). Where soil P levels are well above the critical value, P applications can be withheld until soil analysis shows that the value has fallen to near the critical value. Animal production systems can have a positive P balance and an apparent inefficient use of added P. This is largely because of the inefficient recycling of P in dung.

Part of the P added to soil in fertilizer and manure is used by the plant in the year of application. A varying but often substantial part accumulates in the soil as “residual P”. This reserve can contribute to P in the soil solution and be taken up by crops for many years. Thus, it is essential to measure this continuing uptake of P over several years in order to obtain reliable results for the recovery and efficiency of use of P. Where the amount of readily-plant-available soil P is below the critical value, the rate of P release from residual P may not be sufficiently rapid to supply enough P to produce optimal yields of the high-yielding cultivars of many crops. In these situations, P must be added in order to achieve the critical value required.

Of the methods for calculating the recovery and efficiency of fertilizer P, the “balance method” is preferred because it takes residual P in the soil into account. It

---

expresses total P uptake by the crop as a percentage of the P applied. The “difference method” considers the difference in P uptake by crops with and without added P as a percentage of the applied P. However, the P taken up by the crop comes partly from freshly-applied P and partly from residual P in the soil from previous applications. Replacing the P taken up from residual P (to prevent P mining and loss of soil fertility) is an integral part of the efficient use of an application of P fertilizer. Therefore, the balance method is preferable to the difference method.

The fact that crops can recover previously applied fertilizer P over quite long periods demonstrates that P is not irreversibly fixed in unavailable forms in soils. It also implies the reversible transfer of P between readily plant-available and less-readily plant-available forms, and that this is an important process influencing the long-term availability of P in soils. Therefore, it is suggested that the design of some existing long-term experiments be modified in order to measure the availability of residual P over a number of years.

Strategies for improving the efficiency of use of soil and fertilizer P include: (i) modifying surface soil properties; (ii) managing surface soil; (iii) managing P sources; and (iv) optimizing P use through economically appropriate rates and timing. Some of these strategies are site-specific and cropping system specific. Although they may have only a small impact individually, in combination their benefits may be significant. However, their costs and benefits will largely determine their adoption.

