

Efficiency of soil and fertilizer phosphorus use

Reconciling changing concepts of soil phosphorus
behaviour with agronomic information



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Reconciling changing concepts of soil phosphorus behaviour with agronomic information

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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

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Contents

Acknowledgements	vii
List of acronyms and abbreviations	viii
Executive summary	ix
1. Introduction	1
Rationale for the report	1
Background	2
2. Plant availability of soil and fertilizer phosphorus	5
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
3. Changing concepts of the behaviour of soil and fertilizer phosphorus and reconciling these with agronomic information	15
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
4. Measuring the recovery of soil and fertilizer phosphorus and defining phosphorus-use efficiency	27
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
5. Improving the efficiency of soil and fertilizer phosphorus use in agriculture	45
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
6. Conclusions	53
References	55
Annex 1 - Case studies	63

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 ara 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

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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.

Chapter 1

Introduction

RATIONALE FOR THE REPORT

The essential need to increase the plant availability of phosphorus (P) in soils to produce adequate yields of crops was demonstrated some 200 years ago, and P fertilizer use has increased in response to the need to feed an increasing population. In the developed countries, the increase in the annual use of P fertilizers was gradual from the mid-1850s; it then increased rapidly between the early 1950s and the mid-1970s before stabilizing or declining slightly thereafter. However, there is still a need for P inputs to maintain crop production in the developed countries. Perhaps the greater need today is to increase the use of P fertilizers in the least-developed countries (LDCs), where many soils are deficient in P and increased food production is essential to feed their increasing population.

Improving the efficiency of P use in agriculture is a contribution to many agricultural and environmental issues. These include maintaining or improving the P fertility of soils by the judicious use of P fertilizers and other sources of P, such as organic manures including animal manures, composts and biosolids. There is also the need to conserve the finite global P resource. However, in the developed countries (and increasingly in LDCs), there is the additional need to minimize the transport of P to water, by various pathways, because of the adverse effect of P on water quality in some situations. A major contribution to these issues can come from improving the understanding of the fate of P added to soils and its effective use in crop production. In turn, this could result in an economic benefit for farmers if it were possible to demonstrate that using less P fertilizer does not have an adverse impact on the financial viability of the farm enterprise and does not lead to a decline in soil fertility.

Although there has been much research and extension work on P fertilizer use since commercial production of single superphosphate (SSP) first began in the United Kingdom in 1843, a review is timely. This is because in the last four decades there have been major changes in the understanding of the properties and behaviour of soil and fertilizer P and their interrelationships with crop yield. This report seeks to provide a sound technical basis for improving P-use efficiency in agriculture, so that the best possible advice is available to agricultural scientists, extension workers, farmers and environmental managers.

Following a brief background review in this chapter, Chapter 2 outlines the role of P in crop nutrition. The main focus of the report is in Chapter 3, which discusses changing concepts of the behaviour of soil and fertilizer P. Partly as a result of these changing concepts, there is a need to define and measure the

recovery of fertilizer P. Chapter 4 addresses these aspects and discusses indicators of the efficiency of soil and fertilizer P use. It also illustrates the recovery of soil and fertilizer P, supported by data from nine detailed case studies from different agro-ecological zones (Annex 1). These studies have measured P recovery over a number of years. Chapter 5 discusses ways for improving the efficiency of soil and fertilizer P use in agriculture, and Chapter 6 presents the conclusions drawn from this report.

BACKGROUND

Phosphorus is an essential element for all living organisms. As a component of every living cell, P is indispensable because no other element can replace it in its vital role in many physiological and biochemical processes. As a consequence, the production of crops for food, feed, fuel and fibre requires an adequate supply of P in the soil. Of the plant nutrients required by crops in large amounts, P is of most concern because of the rate of exploitation of this non-renewable resource to meet current demand.

Phosphorus is a common element, ranking 11th in order of abundance in the earth's crust. However, the concentration in many rocks is usually very small. Globally, phosphate deposits consist of reserves and resources (or potential reserves). Reserves are deposits that are currently exploitable in an economically viable way. Resources are deposits that could be used subject to advances in processing technology or their use becoming economically viable. Both the reserves and resources have a finite life span. In 2006, the US Geological Survey estimated the world phosphate rock (PR) reserves at about 18 000 million tonnes, while resources were about 50 000 million tonnes (Jasinski, 2006). The International Fertilizer Industry Association (IFA) estimated world PR production at 171 million tonnes in 2005 (Prud'homme, 2006). At this rate of use, the reserves and resources could last between 105 and 470 years. However, it is difficult to ascertain the true extent of world P reserves and resources (IFDC/ UNIDO, 1998). Based on some estimates of potential resources, the global P supply could last between 600 and 1 000 years at the current rate of use (Isherwood, 2003). These estimates do not include the possibility of finding as yet unknown P deposits. However, the fact remains that the total global P supply is finite and that it is necessary to use it efficiently in order to maximize its life span.

Besides recognizing the essential need to apply P to many soils in order to increase crop production, soil scientists have been intrigued by the fate of P added to soils in fertilizers since the first publication of a study by Way in 1850. Currently, the role of the scientist in increasing the life span of world P reserves lies in increasing the efficiency of use of P in agriculture. This may be P applied in mineral fertilizers, in organic manures, e.g. animal manures, composts and biosolids, but also soil P reserves accumulated as residues from past applications of fertilizers and manures. Currently, of the total global production of PR,

mineral fertilizers account for about 80 percent, animal feeds about 5 percent, while 15 percent goes to industrial uses, such as detergents (12 percent) and metal treatment (3 percent) (Heffer *et al.*, 2006).

As noted above, environmental issues are now a driver of the need to improve the efficient use of P in agriculture. Enrichment of surface waterbodies with P causes their eutrophication, on which their own biological productivity depends. This relies on the transfer of P from land, which may be both undisturbed and human-managed, and from urban and industrial effluents discharged to water, e.g. from sewage treatment works. However, excessive nutrient enrichment of surface freshwater bodies can cause undesirable changes in their ecology, including the balance of species of plants, fish and other aquatic organisms. In many cases, these changes in the biological balance are seen first as algal blooms, which usually occur owing to an increase in the concentration of bio-available P in the water and, in some cases, nitrogen (N). Widespread problems associated with the eutrophication of freshwaters came to the fore in the 1960s, most notably in the Great Lakes Basin of Canada and the United States of America (Rohlich and O'Connor, 1980). In the following two decades, studies found that many other lakes had varying degrees of eutrophication, i.e. in the United States of America (Federico *et al.*, 1981), in Finland (Rekolainen, 1989), in Ireland (Foy and Withers, 1995), and in Germany and the Netherlands. Sharpley and Rekolainen (1997) later reviewed the role of P in agriculture and the environment.

Initially, studies linked eutrophication in lakes primarily to sewage-derived P inputs. Jenkins and Lockett (1943) estimated that as much as 40–60 percent of the total P in crude sewage entering treatment works was discharged as effluent to rivers in the United Kingdom. Much of the P in the effluent was water-soluble and, therefore, immediately bio-available for use by aquatic plants and animals. By the 1970s, although steps had been taken to limit P discharges to rivers from larger sewage treatment works, water quality had not improved in many lakes. This led to the suggestion that P from agriculture was a contributing factor to the P load in rivers and lakes. In consequence, there has since been much research on P and water quality in both North America and Europe. However, even in many developed countries, there are few sewage treatment plants with tertiary treatment facilities to remove P from the effluent. In LDCs, large volumes of untreated wastewater are usually discharged directly to surface waters.

It now appears that much of the P transferred from agriculturally-managed land to streams, rivers and lakes derives from specific areas (“hot spots”) within a river catchment and that these are related to farming system, soil type, and hydrology (Gburek *et al.*, 2002). It is possible to consider these areas as: (i) critical source areas – permanent features within a catchment from which P may be lost readily; and (ii) variable source areas – temporary features, often near streams, that lead to overland water flow carrying P, often associated with mineral or organic particles. Most of the P transported from soil to water is in eroded soil particles enriched with P (Ryden, Syers and Harris, 1973) or from excessive amounts of P fertilizer

or animal manure applied to soil when conditions are not suitable (Johnston and Dawson, 2005).

This report recognizes the need to consider both the agricultural and the environmental dimensions of the use of P applied in fertilizers and organic manures to benefit crop growth, and it explores the basis of the concept of P-use efficiency and the rationale and prospects for its improvement.

Chapter 2

Plant availability of soil and fertilizer phosphorus

SOIL-PLANT INTERACTIONS

Phosphorus is taken up from the soil solution by plant roots as orthophosphate ions, principally H_2PO_4^- and to a lesser extent HPO_4^{2-} . Several factors can influence both the rate and amount of P taken up by the plant and, therefore, can affect the recovery of a single application of P fertilizer. The same factors can also affect the recovery of P reserves accumulated in the soil from past additions of P as fertilizer or manure.

The most important factors controlling the availability of P to plant roots are its concentration in the soil solution and the P-buffer capacity of the soil. The latter controls the rate at which P in the soil solution is replenished, i.e. the rate of desorption of P from the solid phase of the soil, which is faster in soils with a high buffer capacity. Also important are the size of the root system and the extent to which roots grow into the soil, and the efficiency with which roots take up P. When considering a single application of P fertilizer, the efficiency with which it is used also depends on how well it was mixed with the volume of soil exploited by roots. Other factors that affect crop yield, and hence the requirement for P, can influence P uptake by the crop and thus the recovery of P and the efficiency with which the applied P was used. These factors include soil moisture and the extent to which weeds, pests and diseases have been controlled. Because the effects of these factors vary from year to year, it is essential to average estimates of P recovery over a number of years in order to obtain reliable data.

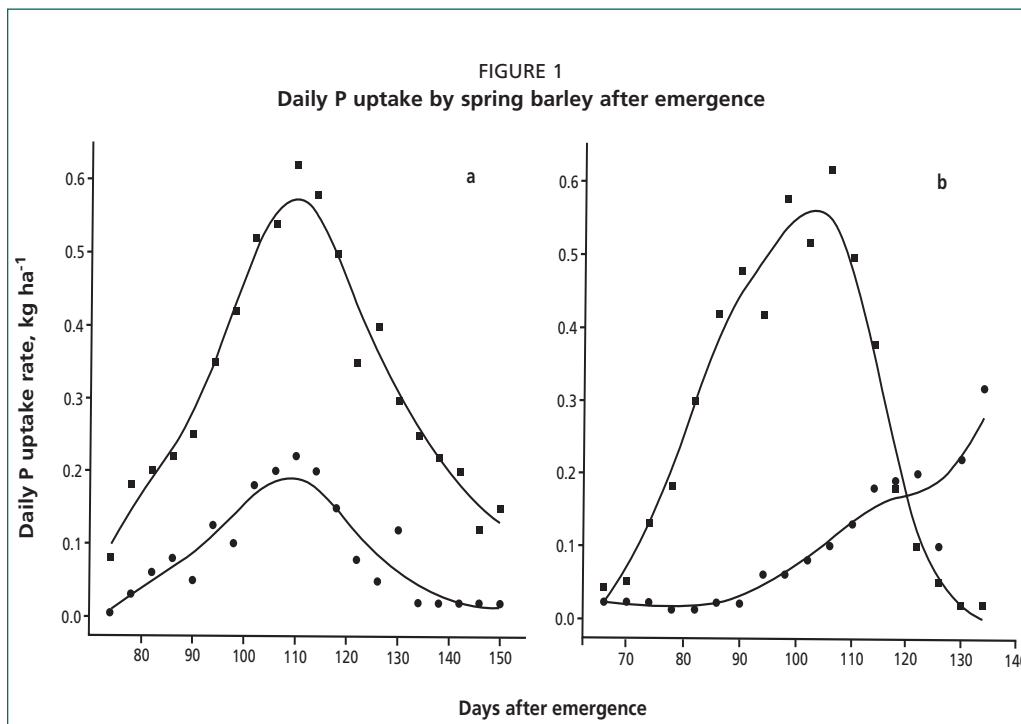
CONCENTRATION OF PHOSPHORUS IN THE SOIL SOLUTION

The concentration of P in the soil solution can range from 10^{-4} M, very high, to 10^{-6} M, deficient, to as low as 10^{-8} M in some very low-fertility tropical soils. These concentrations can be related to the amount of P in the soil solution and crop uptake of P. For example, a concentration of 10^{-5} M corresponds to 0.31 mg P per litre in the soil solution. Assuming that the top 30 cm of soil holds 6 cm of water (equivalent to 600 m³ per hectare) there will be less than 0.2 kg P ha⁻¹ in the soil solution to that depth. If a crop uses 37 cm of water during its growth, there will only be about 1 kg P ha⁻¹ dissolved in the soil solution, yet it may take up 20–40 kg P ha⁻¹ during the growing season. This much larger uptake is possible because roots can absorb P from solutions with very small P concentrations and P is maintained in solution by desorption from the solid phase of the soil. Provided

that there is sufficient P on adsorption sites, from which it can be desorbed readily, and that the rate of release is adequate, plants will obtain enough P to meet their changing demand during the growing season. The rate of P release is an important factor (Frossard *et al.*, 2000), but it is difficult to measure routinely because radioisotopes and expensive counting equipment are required.

The minimum concentration of P to which the roots of soil-grown plants can deplete the external concentration of P in the rhizosphere soil solution is about 1 μM (Hendriks, Claassen and Jungk, 1981). The amount of P in the bulk soil solution required to replenish this concentration of P in the root hair cylinder can be estimated as follows. If the concentration of P is 5 μM , equivalent to 0.15 mg P per litre, and the amount of solution in the top 30 cm of soil is 500 000 litres per hectare, then the quantity of P is 0.075 kg ha^{-1} . However, the crop requirement for P during its phase of rapid growth can range between 0.3 and 0.5 kg P ha^{-1} per day. To meet this requirement for P during the period of maximum demand, the P in the root hair cylinder has to be replenished at least 10–20 times each day. This is because roots explore only about 25 percent of the topsoil in any one growing season (Jungk, 1984), but this depends on the crop grown.

Figure 1 illustrates the importance of maintaining an adequate supply of readily-plant-available P in soil to satisfy the maximum daily demand of a crop for P. Spring barley, given sufficient N and K, was grown in 1980 and 1981 on two soils, one well supplied with readily-plant-available P, the other with little. Figure 1a shows that in 1980 the maximum daily P-uptake rate occurred some 106–114 days after sowing and differed by a factor of three for the crops grown on the two soils. After the 114th day, the daily uptake rate declined on both soils. This large difference in P uptake was reflected in the final grain yield: the yield on the soil with adequate P was 6.88 tonnes ha^{-1} but it was only 2.88 tonnes ha^{-1} on the P-deficient soil. The following year (1981), the same cultivar was grown on the plots but the results were slightly different (Figure 1b). On the soil adequately supplied with P, maximum uptake occurred between the 94th and 106th day, and reached a maximum value of just under 0.6 kg P ha^{-1} per day, a difference in timing but similar in the amount of P to the previous year. On the soil with too little P, daily P-uptake rate by the crop continued to increase until the onset of senescence, but at the maximum the rate was less than 0.3 kg P ha^{-1} . As in 1980, the difference in soil P availability, and the effect on the daily P-uptake rate, resulted in a large difference in grain yield at harvest, namely 5.07 and 2.48 tonnes ha^{-1} on soil with and without an adequate supply of readily-plant-available P, respectively. The different pattern of P uptake between years on the P-deficient soil probably reflected the available moisture. In 1980, rainfall was less than average in May and, apparently, there was too little root activity to take up what P was available. In 1981, rainfall was more than average and the roots continued to take up the small amounts of P that were available. The difference in rainfall patterns did not affect P-uptake rates with adequate amounts of available soil P.



Note: The two crops were grown in the same experiment on soils with adequate (■) and less than adequate (●) amounts of plant available P in 1980 (a) and 1981 (b).

Source: Adapted from Leigh and Johnston (1986).

MOVEMENT OF PHOSPHORUS TO ROOTS

Plant root systems have two main functions; first, to provide an anchor for the plant in the soil, and second, to take up water and nutrients from the soil solution. Roots do not grow throughout the whole volume even of the surface soil and, as noted above, roots explore perhaps as little as 25 percent of the topsoil in one growing season. Roots can intercept nutrients (Barber, Walker and Vasey, 1963) but less than 1 percent of the available soil nutrients are supplied in this way (Barber, 1984). Nutrients are taken up from the soil in the region of the root, and this process is largely dependent on nutrients moving to the root by two distinct processes, mass flow and diffusion (Barber, 1984).

The amount of nutrient transported by mass flow is related to the amount and rate of water movement to the root, the water use by the crop, and the concentration of the nutrient in the soil solution. For example, assuming the concentration of P in the soil solution is 0.15 mg per litre and a crop transpires 3 million litres of water per hectare during its growth, then the total amount of P delivered to the roots is about 0.45 kg P per hectare. This quantity is only 2–3 percent of the total amount of P required by many crops to produce acceptable yields.

Diffusion is the main process by which P moves to the root surface. Diffusion involves the movement of ions along a concentration gradient, i.e. from a higher to a lower concentration. Thus, when plant roots remove nutrient ions from the soil solution and the concentration is lowered relative to that in the bulk solution, a concentration gradient develops and nutrient ions move down this gradient. The extent of depletion at the root surface depends on the balance between the supply from the soil and the demand by the plant. If the “absorbing power” of the root is large, this creates a sink to which nutrients diffuse (Tinker and Nye, 2000). The root-absorbing power is not constant but depends on root metabolism and the nutrient status of the plant (Barber, 1984). The amount of P required at the root surface depends on the depletion profile that develops with time. The shape of this profile will depend on the balance between P uptake by roots, the rate at which P is replenished in the soil solution, and the mobility of the phosphate ions by diffusion.

The mobility of an ion is defined in terms of a diffusion coefficient, which is usually orders of magnitude smaller in soils than in homogeneous media, such as water, because of the tortuosity (complexity of shape and length) and small diameter of most water-filled pores in the matrix of the heterogeneous soil system. Marschner (1995) gives estimated diffusion coefficients of H_2PO_4^- (the most common form of inorganic orthophosphate in solution in weakly-acid aqueous systems) in water as $0.9 \times 10^{-9} \text{ m}^2 \text{ s}^{-1}$, but in soil estimated values range from 10^{-12} to $10^{-15} \text{ m}^2 \text{ s}^{-1}$. At an average value of $1 \times 10^{-13} \text{ m}^2 \text{ s}^{-1}$, the movement of H_2PO_4^- would be about 0.13 mm per day. This very limited movement of phosphate ions explains why it is necessary to have a sufficient supply of readily-available P throughout the volume of soil explored by roots if the demand for P by a crop is to be met during its most active period of growth. It also explains why good responses are often obtained to placing P fertilizer near where the roots of a crop are expected to grow.

PLANT ROOT SYSTEMS AND PHOSPHORUS UPTAKE BY ROOTS

Plant roots take up P from the soil solution as orthophosphate ions, principally H_2PO_4^- and to a lesser extent HPO_4^{2-} , except in calcareous and saline soils. Plant roots can absorb P from soil solutions having very low P concentrations (Loneragan and Asher, 1967), in which case P uptake is against a very steep P concentration gradient. This is because the P content of root cells and xylem sap is 100–1 000 times larger than that of the soil solution (Mengel and Kirkby, 1987). The transport of P across the cell membrane varies between plant species. Cultivars within the same species can differ in their capacity for active P uptake, and these differences are probably largely genetically controlled.

Many plants have extensive root systems, which frequently have root hairs that extend out into the rhizosphere (the cylinder of soil surrounding the root), thereby increasing the effective surface area of the root system for the uptake of water and nutrients. Root hair formation is modified by environmental factors such as nutrient supply, especially that of N and P, and it differs between species.

In non-mycorrhizal plants, the extent of the zone of P depletion in the soil as a result of active P uptake by roots is often closely related to root hair length. For example, the extent of the P-depletion zone around maize and oilseed rape roots is nearly the same as the maximum root hair length, 1.8 mm for maize and 2.6 mm for rape, respectively (Hendriks, Claassen and Jungk, 1981). Itoh and Barber (1983) found a strong positive correlation between P-uptake rate per unit root length and the volume of the root hair cylinder. Caradus (1982) also showed differences in the efficiency of P uptake between genotypes of white clover that were related to root hair length.

Root hairs are more effective in absorbing P than is the root cylinder when the influx per unit area of each is compared because the smaller diameter and geometric arrangement of the root hairs maintain higher diffusion rates for P (Jungk and Claassen, 1989; Claassen, 1990). In soils with little readily-available P, uptake by root hairs can account for up to 90 percent of total P uptake by the plant (Föhse, Claassen and Jungk, 1991).

However, a close relationship between root hair length and the extent of the P-depletion zone in the rhizosphere is not always found. For example, the P-depletion zone around cotton, with short root hairs (about 0.2 mm) greatly exceeds the root hair cylinder (Misra, Alston and Dexter, 1988). For non-mycorrhizal plants, this suggests root-induced changes in the rhizosphere, e.g. the release of root exudates (particularly low-molecular-weight organic acids), pH changes, or a higher efficiency of uptake per unit length of root.

Many plants have developed a symbiotic association with arbuscular mycorrhizal (AM) fungi. The spores, which are found in many soils, develop hyphae that penetrate the root, remove carbohydrates from it, and grow out into the soil immediately surrounding the root, extending the capacity of the root to take up water and nutrients, especially P and micronutrients (Tinker, 1984). In soils with adequate plant-available P, this fungal association is usually not well developed, suggesting that mycorrhizae are not important in such soils. In mycorrhizal plants, the extent of the P-depletion zone greatly exceeds the diameter of the root hair cylinder (Jungk and Claassen, 1989), and it can be as large as 11 cm in white clover (Li, George and Marschner, 1991). Some plants do not have a mycorrhizal association. These include species of the order Chenopodiaceae, which includes agriculturally-important crops such as sugar beet. Compared with crops with mycorrhizae, such crops can be disadvantaged considerably when grown on soils with very small amounts of readily-available P (Johnston *et al.*, 1986).

Differences between genotypes in P-use efficiency may be caused by differences in P uptake by roots, P transport within roots, P transport from root to shoot and between organs within shoots, and the utilization of P within the plant (Marschner, 1995). Perhaps the most important factor causing differences between genotypes is the acquisition of P by roots. Differences in P uptake per unit root length may be caused by higher influx rates, longer root hairs or differences in root/shoot ratios relative to the availability of P in the soil solution. As these differences are genetically controlled, there should be good prospects for developing more

P-efficient genotypes. If such genotypes become available, it should be possible to maintain soils at lower critical P concentrations than those required for current cultivars. Such P-efficient genotypes, whether produced by conventional breeding techniques or genetic manipulation, would have to be high-yielding and not more susceptible than current cultivars to other nutrient deficiencies and abiotic and biotic stress. Brown, Clark and Jones (1977) showed that some P-efficient genotypes are more susceptible to iron (Fe) and copper (Cu) deficiencies.

There may be reasonably good prospects for improving the efficiency of P use by plants by selecting appropriate genotypes with characteristics for root hair length, organic acid production in the rhizosphere, and mycorrhizal associations for soils with low P status. This approach to improving P-use efficiency may be more appropriate than seeking to modify root architecture, i.e. the shape and branching of the root system, which is often suggested as a way of improving nutrient uptake. Field evidence shows that root distribution in soil is much more dependent on soil physical characteristics than on the inherent shape of the root system. Almost 30 years ago, Drew and Saker (1978) showed that plant roots proliferated in soil zones that are enriched in P rather than following some specific pattern of spatial distribution.

PHOSPHORUS UPTAKE, ROOT SYSTEMS AND SOIL CONDITIONS

For nutrients such as P that are taken up by roots from the soil solution, the size of the root system and the efficiency with which it takes up nutrients are important in nutrient acquisition. The size of the root system is genetically controlled and varies between species. However, external factors also affect root growth and function. These factors include soil properties (such as acidity), depth, structure, stoniness, moisture retention, and composition of the soil atmosphere. Root diseases and nematodes also decrease the size of the root system, limiting the opportunity for nutrient uptake.

Many plants have extensive root systems, a feature possibly related to the time when they had to acquire nutrients from soils with very low concentrations of plant-available nutrients. Although both ryegrass and winter wheat have large root systems, they differ greatly in that ryegrass has fine roots, most of which are in the surface soil, while the roots of winter wheat are coarser and many are found below a depth of 1 m. A crop of winter wheat yielding 10 tonnes of grain per hectare can have a root system weighing about 1.5 tonnes ha⁻¹ (dry matter) and extending to 300 000 km ha⁻¹, or about 100 m of root for each plant. Although the root system can be so large, root tips can only enter soil pores of larger than a certain diameter. For example, cereal roots cannot enter pores that are narrower than about 0.05 mm (Johnston *et al.*, 1998).

The rhizosphere, extending about 1–2 mm from the root surface into the bulk soil, is particularly important for plant nutrient availability. Estimates suggest that as much as half of the organic carbon translocated from the topsoil to the roots passes into the soil during the period of active growth. Much of this carbon is in excreted mucilage and dead cells (sloughage) shed by the root. This organic

material ensures close contact between the root surface and the soil, and facilitates nutrient uptake. These materials, together with other organic compounds excreted by roots, are an energy source for micro-organisms living in the rhizosphere. Microbial activity in the rhizosphere can increase P availability by both lowering the pH and solubilizing iron-bound and aluminium-bound P, probably by complexing (or chelating) the Fe and aluminium (Al). Plant roots can also excrete organic acids that could solubilize considerable amounts of P in hydroxylapatite. Many species of brassicas, such as oilseed rape, and some legumes are particularly effective at doing this. Applying N as ammonium sulphate, or N sources such as urea that are converted to ammonium, can lower the pH in the rhizosphere by as much as 1 pH unit, and this also helps to solubilize P.

Soil pH has a controlling influence on the release of Al from various clay minerals as well as the dissolution of Al hydroxy compounds in soil. Soil acidity has adverse effects on plant growth and these are more the consequence of the free Al in the soil solution than the large concentration of H^+ ions. At elevated Al concentrations in the soil solution, root tips and lateral roots become thickened and turn brown, and P uptake is reduced. A large concentration of Al within the upper parts of the plant decreases the translocation of P and also interferes with P metabolism. Where liming materials are not readily available in the large quantities needed to increase soil pH, then adding sufficient material to remove free Al ions from the soil solution is generally adequate to ensure unhindered P uptake.

The composition of many soils is such that there are approximately equal volumes of mineral material and voids or pores in a complex array. The pores are important because they contain both air and water, and both are essential for root function. The relation between the water and air content in the pores is important because roots respire and an adequate level of oxygen in the soil air is required to ensure adequate root respiration for active P uptake. The diameter of the pores varies greatly. They tend to be larger in coarse-textured sandy soils than in clayey soils. In the latter, the mineral particles can be aggregated, and this creates larger pores. Excess water drains through larger pores, while smaller-diameter pores retain water to supply the needs of the plant. Compaction, for example by heavy traffic on soil with a small load-bearing capacity, tends to eliminate larger pores, and roots cannot grow in severely compacted soil because the pore diameter is too small. Compaction also decreases the diffusion of phosphate ions in soil by increasing the path length or tortuosity (complexity) of the system, with a further reduction in P uptake by the roots.

The slow movement of P by diffusion is frequently ascribed to the tortuosity of the pore system (above). However, the reactive sites for P adsorption on soil minerals lining the sides of the pores can also retain phosphate ions, temporarily or permanently, slowing or preventing their movement along the pore.

Soils devoid of air in the pores, for example as a result of waterlogging, become anaerobic. Reducing conditions in the soil as a result of anaerobic conditions, defined by the redox potential, affect many inorganic and biological processes. For example, the end products of the anaerobic microbial decomposition of

organic matter can be toxic to higher plants. However, there can be benefits in relation to P nutrition for some specialized plants, including paddy rice, that grow in waterlogged soil. Oxygen required by the root for respiration passes to the root through air-filled channels (aerenchyma) in the stems and roots. Under anaerobic conditions, the reduction and dissolution of ferric oxides typically releases P into solution from sites where it is strongly adsorbed, e.g. on hydrous ferric oxides. This P is available for uptake by the roots. As the soils dry after harvest and ferrous iron reverts to ferric iron, hydrous ferric oxides in the soil will again retain readily plant-available P. In addition, PR can be used on paddy soils because anaerobic decomposition of organic matter produces soluble organic compounds that can increase the solubility of P in apatite materials through their ability to complex calcium (Ca) during the dissolution of apatite. Even in normally aerobic soils, it is probable that at certain times of the year there will be anaerobic microsites, especially in small-diameter pores, where the reduction of ferric to ferrous iron will release adsorbed P.

It is difficult to demonstrate the effects of soil structure on the response of a crop to an application of P fertilizer. However, in an experiment on a silty clay loam soil in the United Kingdom, there was a relationship between the content of soil organic carbon and the response of three crops to different levels of Olsen P (Table 1). For each of the three crops (spring barley, potatoes, and sugar beet), the percentage variance accounted for in the relationship between crop yield and Olsen P was appreciably larger for the soil with more soil organic matter (SOM). Moreover, much less Olsen P was required to achieve optimal yield when the crops were grown on the soil with more SOM. When a soil sample was taken from

TABLE 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

Crop	Soil organic matter (%)	Yield at 95% of the asymptote (tonnes ha ⁻¹)	Olsen P associated with the 95% yield (mg kg ⁻¹)	Variance accounted for (%)
Field experiments				
Spring barley	2.4	5.00	16	83
Grain (tonnes ha ⁻¹)	1.5	4.45	45	46
Potatoes	2.4	44.7	17	89
Tubers (tonnes ha ⁻¹)	1.5	44.1	61	72
Sugar beet	2.4	6.58	18	87
Sugar (tonnes-ha ⁻¹)	1.5	6.56	32	61
Pot experiments in the greenhouse				
Grass dry matter	2.4	6.46*	23	96
(g pot ⁻¹)	1.5	6.51*	25	82

* The response curves at the two levels of soil organic matter were not visually different.

Source: Adapted from Johnston and Poulton (2005).

each plot in the field experiment and cropped with ryegrass in the greenhouse under controlled conditions, the relationship between yield and Olsen P showed the same critical value for Olsen P, irrespective of the level of SOM. This suggests strongly that the different critical Olsen P values, observed for each crop grown in the field, on the different soils was a consequence of the effect of the difference in SOM on soil structure. Similar effects of SOM have also been reported in an experiment with a sandy loam soil (Johnston, 2001).

Thus, the process of P diffusion in soil and the factors that influence diffusion substantially influence soil–plant P interactions. Root distribution and particularly the presence of root hairs, also play an important role in P acquisition by plant roots. All of these factors contribute to the recovery of P from soils and, thus, influence the efficiency with which plants use soil and fertilizer P.

A major factor that affects crop yield, and hence the requirement of the crop for P, is the adequacy of all other nutrients required in order to produce optimal yields. The sufficiency or insufficiency of other nutrients *per se* does not necessarily affect the uptake of P from the soil solution, but there can be important interactions between nutrients that affect yield. Two or more nutrients are said to interact when their individual effect is modified by the presence of one or more of the other nutrients. If the combined effect exceeds the sum of the individual effects then the interaction is positive or synergistic; if less than the sum of the individual effects, the interaction is negative or antagonistic.

Sumner and Farina (1986) discuss the agronomic implications for crop yield of interactions between P and other nutrients. They point out that many studies on nutrient interactions have been done in the laboratory or the greenhouse, but few in the field. They give a diagrammatic representation of the response of a crop to a number of limiting factors to show how replacing them, one by one, can affect yield. This effect is illustrated by the interaction between plant-available soil P (Olsen P) and N applied to maize (Table 2). The response to both P and N was

TABLE 2

Interactive effects of soil phosphorus and applied nitrogen on maize grain yields

Olsen P (mg kg ⁻¹)	N applied (kg ha ⁻¹)			
	0	60	120	180
	Maize grain yield (tonnes ha ⁻¹)			
3	2.31	2.22	3.11	3.41
16	4.74	6.68	7.91	7.84
27	4.06	7.14	9.12	9.74
46	4.54	8.17	9.42	9.96

Source: Adapted from Sumner and Farina (1986).

small at deficient levels of the other nutrient but increased markedly as soil P and applied N increased. Sumner and Farina (1986) also discuss, in detail, P by lime interactions, where there are considerable contradictions in the published literature. Many references are given to each of three possibilities, i.e. liming increased, decreased, or did not change soil P availability, as measured by various soil extraction techniques. There are similar contradictory reports for the effect of modifying soil pH on the recovery of P by plants.

Chapter 3

Changing concepts of the behaviour of soil and fertilizer phosphorus and reconciling these with agronomic information

WORK IN THE NINETEENTH CENTURY

The landmark field experiments established at Rothamsted, the United Kingdom, in the mid-nineteenth century revolutionized thinking on soil fertility and plant nutrition. These experiments tested the effects of fertilizers supplying N, P, potassium (K), magnesium (Mg), and sodium (Na), applied singly and in various combinations, and compared their effects with those of farmyard manure (FYM) on the growth of a range of arable crops (Johnston, 1994). They soon demonstrated that it was necessary to apply more P than was removed in the harvested crop to achieve an acceptable yield on what were then P-deficient soils (Johnston, 1970).

The need to apply more P than was removed in the harvested crop raised the question as to what happened to the residual phosphate. In the early 1870s, Liebig received samples of soil from some of the plots from the Broadbalk Winter Wheat experiment (started at Rothamsted in 1843), which had treatments with and without P since the beginning. On extracting the soils with dilute mineral acids, Liebig showed that the P-treated soils contained more readily soluble P than the untreated soils (Liebig, 1872). Later, Dyer (1894) produced a P balance (P applied minus P removed) for the first 38 years of the Hoosfield Continuous Barley experiment at Rothamsted. Where superphosphate (SP) had been applied annually at 33 kg P ha⁻¹, the P balance was positive. Most of this positive P balance could be accounted for by the extra total P accumulated in the 0–23 cm soil layer.

Subsequently, Dyer (1902) estimated a P balance for the first 50 years of the Broadbalk Winter Wheat experiment where P had been applied annually as SSP at a rate of 33 kg P ha⁻¹. Dyer related the positive P balance where P had been applied to the change in both total and 1 percent citric acid soluble P in the 0–23, 23–46, and 46–69 cm layers of soil sampled in 1893. Dyer calculated that, on the five plots receiving N and P fertilizer, 80–90 percent of the positive P balance had been retained in the top 23 cm of soil. Dyer assumed that the P that could not be accounted for (3.7 kg P ha⁻¹ each year, or about 10 percent of that added in SSP)

had moved downwards in the soil profile. However, the variability in both total and 1 percent citric-acid-soluble P in the 23–46 and 46–69 cm soil layers did not allow Dyer to demonstrate, with certainty, any subsoil enrichment with P. While recognizing that some of the P could have moved below 69 cm, Dyer concluded that errors in sampling and analysis of the soil precluded the possibility of obtaining a more accurate estimate of the amount of residual P in the soil. A very important consequence of this pioneering work was the thinking that, because only a small proportion of the P balance could not be accounted for as an increase in total P in the soil, most of the residual P was retained or “fixed” in the surface soil.

Further interest in residual fertilizer P in soil was stimulated in the United Kingdom at the beginning of the twentieth century. There was considerable discussion as to whether, when a tenant farmer left a farm, the owner of the land should pay the tenant compensation for the residual value of any fertilizers the tenant had applied but had not had the time to obtain any benefit from by way of increased crop yields. For each nutrient, the residual value was determined by measuring the increase in crop yield in the years following the initial application, compared with the yield on soil that had not received that nutrient. For fertilizer P, the residual benefit was estimated to be small and short-lived. In part, this was because the experiments attempted to measure the residual value of only one or a few applications of small amounts of P fertilizer added to very P-deficient soils, and sufficient N and K were not always applied to ensure that these nutrients were not limiting yield. The lack of response to residual P was taken as further evidence that if P was applied to a soil to grow a crop and it was not taken up by that crop, then the P was fixed in soil in unavailable forms. This stimulated interest in developing an understanding of the forms, amounts and availability to plants of P in soils, particularly of inorganic P.

WORK IN THE EARLY PART OF THE TWENTIETH CENTURY

Early studies, dating back to the mid-nineteenth century, e.g. Way (1850), demonstrated that soils could remove phosphate ions from solution. This process was called “P fixation” or “P retention” (Sample, Soper and Racz, 1980), the two terms often being used synonymously. The reaction was usually attributed to specific soil components, e.g. calcium carbonate in calcareous soils, and hydrous iron and aluminium oxides in acid soils (Wild, 1950). This early work, which started in earnest in the 1920s, stimulated subsequent interest in the interactions of phosphate solutions with pure minerals, and the mechanisms involved. The review by Wild (1950) indicates that although precipitation of calcium, iron and aluminium phosphates was widely suggested, up to that time the dominant mechanism was thought to involve the removal of phosphate ions from solution by adsorption. This is supported by much of the work reviewed by Kurtz (1953), where adsorption received a degree of prominence, although Kurtz made the observation that “in many respects, a distinction between the reactions in which phosphate ions are precipitated from solutions of iron and aluminium, and

reactions in which phosphate ions are removed from solution by hydrated oxides is arbitrary, because the final products, if both reactions went to completion, would be identical.” With hindsight, if the final product of these two very different processes were identical then the subsequent rate and extent of release of P would be the same, and there is no evidence for this. In addition to the review by Wild (1950), Pierre and Norman (1953), Khasawneh, Sample and Kamprath (1980), and Larsen (1967) provide summaries of the earlier work.

Most of the early studies produced conflicting results and conclusions, in part related to the conditions used in the experiments, and also because insufficient attention was directed to the actual plant availability of soil P, as measured by plant uptake of P and crop response. Although some researchers did pay due attention to the plant dimension, most of their work did not receive adequate recognition. Of the studies prior to the 1950s, that by Coleman (1942) is particularly interesting. It had commonly been assumed that the failure of a crop to respond to fertilizer P was because of the rapid fixation of P by the soil. Coleman showed that this could also be due to a sufficiency of plant-available P already in the soil and that large amounts of P “formerly considered fixed” are available to plants. Kurtz (1953) concluded that P reacts quickly in acid and neutral soils by becoming adsorbed but is still readily available to plants. With time, this initial form of P is converted gradually to less extractable and less plant-available forms. Kurtz argued that the explanation that P is held in soil by simple precipitation “sometimes leads to rather questionable conclusions.” Kurtz asserted that if the P in a given soil were present as a series of insoluble phosphate compounds, then there would be a stepwise decrease in “solubility” when the same reagent was used for sequential extractions of the soil. The observed solubility showed no such stepwise changes; rather, solubility decreased very gradually with repeated extractions or dilutions. Kurtz concluded that the gradual decrease in extractability of added P provides evidence, but not necessarily proof, that definite phosphate compounds are not present in a fertilized soil.

A further complicating factor, in retrospect, has been the rather loose terminology used initially, and some still persists today. As mentioned previously, some workers in this field frequently used the terms fixation and retention interchangeably. However, others used the term fixation to indicate an irreversible removal of phosphate ions from solution, and retention to describe only the removal of phosphate from solution, regardless of the mechanism involved. Both terms ignore the implications for the availability of added P for uptake by plants. In retrospect, it was also incorrect to regard fixation and precipitation of P as being one and the same thing because precipitated phosphates are usually metastable, or transient, as discussed below.

FROM 1950 TO 1980: A PERIOD OF CHANGE

The 1950s saw a major shift in thinking, especially in the United States of America, regarding the reactions that occur when water-soluble phosphates are added to soil. These studies may be divided into laboratory studies and modelling.

Many laboratory studies focused on the formation of “discrete-phase”, “water-insoluble” compounds, particularly variscite (aluminium phosphate) and strengite (iron phosphate) under acid conditions, and a range of calcium phosphates under near-neutral and alkaline conditions. This led to the thinking that these compounds were the products of interactions between water-soluble P added in fertilizer and soil components. It was claimed that the very large concentrations of P (1.5 to in excess of 6 M) and cations (as large as 12 M) in the soil solution following the addition of a highly water-soluble P fertilizer react rapidly to form phosphate minerals with low water-solubility, and that this explained why the plant-availability of fertilizer P was so low in many soils. Much of this work was done in the United States of America by Jackson and co-workers at Wisconsin (Jackson, 1963) and by an active group at the Tennessee Valley Authority (Huffman, 1962, 1968). Early work in this area was reviewed by Kurtz (1953) and Hemwall (1957); subsequent work was reviewed by Larsen (1967) and Sample, Soper and Kamprath (1980), among others. There is strong evidence to suggest that, under the conditions used in many of the laboratory experiments, i.e. very large phosphate concentrations, often in reactions with pure minerals and sometimes at elevated temperatures, phosphate minerals having very low water solubility can form. Whether such insoluble reaction products commonly form in the heterogeneous environment of the soil is debatable (Barrow, 1983a). Furthermore, even if strengite and variscite do form as reaction products, they are unlikely to persist in soils having pH values higher than 1.4 and 3.1, respectively (Bache, 1964), and thus are unlikely to explain the chemistry of P in fertilized soils.

Much work was done on the reactions of P with calcium carbonate, used as a model system for calcareous soil, beginning more than 50 years ago but continuing subsequently (Kuo and Lotse, 1972). The early work of Cole, Olsen and Scott (1953) showed that adsorption reactions were dominant when dilute P solutions were added to calcium carbonate in the laboratory, but that dicalcium phosphate (DCP), or a compound with similar properties to DCP, precipitated when more concentrated P solutions were added. Lindsay, Frazier and Stephenson (1962) concluded that DCP and dicalcium phosphate dihydrate (DCPD) were formed as initial reaction products when a saturated solution of monocalcium phosphate (MCP) was reacted with calcium carbonate or calcium magnesium carbonate. These compounds were also thought to form in calcareous soils when highly water-soluble triple superphosphate (TSP), containing MCP, was added to soil. However, Sample, Soper and Racz (1980) have pointed out that there have been very few studies conducted with moist soil in which reaction products have been isolated and identified successfully. Most of the compounds considered to form as reaction products have been inferred from simulation of the chemical environment near a fertilizer granule or from solubility isotherm data, the limitations of which are discussed below. For example, using data from experiments in Colorado, the United States of America, Fixen, Ludwick and Olsen (1983) inferred – but did not demonstrate – that in two calcareous soils with extractable P concentrations of more than 35 mg kg⁻¹, octocalcium phosphate (OCP) was controlling solution

P concentrations, whereas with less-extractable P (concentrations in the range of 10 to 25 mg kg⁻¹), tricalcium phosphate (TCP) or a similar mineral dominated the concentration of P in the soil solution. However, Fixen, Ludwick and Olsen (1983) concluded, as did many other workers, that most P minerals are too soluble to persist in many soils. For example, it was earlier believed that DCPD reverted to OCP and even to colloidal hydroxylapatite relatively quickly (Lehr and Brown, 1958; Larsen, 1967), although this was not always the case. For example, Larsen, Gunary and Devine (1964) could not demonstrate the formation of a new crystalline phase when DCPD was incubated in both acid and alkaline soils for periods of up to 26 months. As suggested by Mattingly and Talibudeen (1967), the rate of removal of P from solution by soil components in acid and neutral soil is faster than OCP can be formed, indicating that OCP, if formed, is unlikely to persist. A similar conclusion was reached by Bache (1964) for the stability of strengite and variscite in most soils. Even if these compounds form, which seems unlikely in most soil environments, their persistence is doubtful. Thus, secondary, discrete-phase P compounds are unlikely to control solution P concentrations in soils and the availability of P to plants, except for short periods in some soils receiving water-soluble P fertilizer.

The preoccupation with precipitation reactions and the likely importance of solid-phase reaction products had an important side-effect. Much time and effort was spent in attempting to find methods for fractionating soil inorganic P using sequential extraction with a series of reagents of increasing extraction severity (Dean, 1938; Chang and Jackson, 1957). It was thought that the different chemical reagents, when used sequentially, would extract different forms of discrete-phase inorganic P. If this proved to be the case, it would support the view that added water-soluble P was precipitated in soil in a range of chemical compounds related to iron, aluminium and calcium phosphates, depending on soil pH. However, as discussed later, an alternative explanation is that these chemical reagents remove P associated with soil components with varying bonding energies. Today, soil P fractionation is being used in an attempt to identify soil P fractions associated with the plant-availability of soil P. This has led to a less prescriptive terminology that reflects the improved understanding of the behaviour of phosphate ions at the surfaces of soil and soil components (Chapter 4 and Annex 1). The preoccupation with P precipitation also ignored the fact that much P would be sorbed on particulate matter in soil and involve both adsorption and absorption reactions.

In a comprehensive review of the reactions of fertilizer phosphate added to soil, Sample, Soper and Racz (1980) concluded that both sorption reactions and precipitation are likely to occur simultaneously. However, it was recognized that it is difficult to assess sorption reactions in the presence of precipitation. Some of the initial reaction products undergo dissolution, and the P released may be taken up by plant roots or be adsorbed by soil components. The initially adsorbed P may be replaced and moved to new adsorption sites. According to Sample, Soper and Racz, the overall trend with time is for both initially precipitated and adsorbed forms of P to slowly become more stable and support progressively lower

concentrations of P in the soil solution. The mechanisms involved are complicated and, to a significant extent, this explains the rather slow progress in developing an adequate understanding of the P fertilizer–soil system.

In the late 1950s and in the 1960s, modelling studies made extensive use of thermodynamic models, particularly solubility isotherms, to explain the behaviour of P in soil. Much of this work was done by Lindsay and co-workers (e.g. Lindsay and Moreno, 1960; Huffman, 1962; Lindsay, Frazier and Stephenson, 1962) and has been reviewed by Larsen (1967) and subsequently by Lindsay (1979). Using solubility isotherms for pure, crystalline phosphate compounds, Larsen (1967) concluded that the solubility of “hydroxylapatite” controls phosphate equilibria in soils, a view that now finds little acceptance. Although such models can produce elegant descriptions of products that might form, they largely ignore the kinetics of reactions and the fact that it is necessary to achieve a given level of supersaturation (defined by the supersaturation index) before a particular reaction product actually forms. Barber (1984) has indicated that a major limitation of using solubility isotherms is that they are constructed assuming that pure crystalline compounds are in equilibrium with phosphate ions in solution. Barber suggests that P compounds in soils are not pure crystalline forms but are rather impure with an unknown solubility. Most importantly, the fit of data-points to a solubility isotherm does not constitute proof that a particular compound controls phosphate solubility. This puts a question mark against the significance of much of the earlier evidence, inferred from solubility isotherms, that claimed to support the precipitation of P added to soil in fertilizer.

A MAJOR CHANGE IN DIRECTION

Pioneering work in Australia in the late 1960s and 1970s by Posner and co-workers (Posner and Barrow, 1982) and later by Barrow (1983b) on P adsorption in soils and its reversibility (desorption) led to a change in thinking. The slow reaction between phosphate and soil was attributed to the diffusive penetration of adsorbed phosphate ions into soil components. This would explain the decrease in extractability, isotopic exchangeability, and plant availability of P with time (Barrow, 1980). Earlier, Evans and Syers (1971) used the stable P isotope, ^{31}P , and the low-energy (0.25 Mev) radioactive ^{33}P isotope with a longer half-life (25 days) relative to ^{32}P to study the distribution of P added to soil. Using autoradiography on a medium-grained film, Evans and Syers (1971) showed that when P was added to aggregates of an iron-rich, Brazilian Oxisol (Syers *et al.*, 1971), the surface sorption of P was initially rapid and this was followed by diffusive penetration (or absorption) over time. Significantly, phosphate was not concentrated in discrete areas. This suggested that P was retained by a sorption reaction, presumably initially by adsorption at external surfaces, followed by absorption, which may be thought of as adsorption at internal surfaces. If the P removed from solution had been precipitated as strengite (in this goethite/hematite-rich soil), then the volume of soil occupied by phosphate would have been appreciably less than that indicated on the autoradiograms. Significantly, the exchangeability (even in 1 hour) of the

sorbed, added P was small and decreased between 7 and 21 days of contact with the soil aggregates. The small exchangeability of the sorbed, added P and its spatial distribution, in conjunction with changes in P penetration into soil components over time, substantiate the hypothesis that the penetration of added P and the isotopic exchange of that sorbed, added P are diffusion-controlled processes.

Barrow (1980) suggested that the P that had become absorbed could be released over time; in other words the adsorption or absorption of P was largely reversible over time, but that testing for complete reversibility might involve a period of years. Barrow used results from Leamer (1963) to support this view. In an irrigated rotation experiment in the southwest of the United States of America, two-thirds of an addition of 235 kg P ha⁻¹ had been recovered after growing alfalfa for four years and sorghum for one year. Subsequent crops responded to freshly added fertilizer P, but there continued to be a slow, cumulative increase in the proportion of the original fertilizer recovered, up to almost 80 percent after nine years. At lower levels of P application, the recovery was even larger and was essentially complete after nine years.

Barrow (1980) acknowledged useful discussions with Mattingly (Rothamsted), and some of the topics reviewed by Barrow would have been supported by data supplied by Mattingly. Among these were data on the residual value of P when different P sources had been applied to soil; the work reported in Mattingly (1971) was especially relevant. Mattingly probably drew Barrow's attention to the recovery of P residues more than 70 years after the last application of P fertilizer in the Exhaustion Land experiment at Rothamsted. Annex 1 provides a full discussion of these results in the case study on arable cropping in the United Kingdom. Furthermore, at about this time, a number of research workers were considering how P was retained in soil if it was not precipitated as discrete-phase inorganic phosphates.

Further evidence that fertilizer P is sorbed reversibly comes from experiments at Rothamsted. In these experiments, Olsen P was used to monitor P availability over time. In the Exhaustion Land experiment, SSP was applied annually at 33 kg P ha⁻¹ from 1856 to 1901. The P balance was positive but the increase in Olsen P (167 kg P ha⁻¹) accounted for only 14 percent of the positive P balance (1 217 kg P ha⁻¹). After 1901, no more P was applied, and between 1901 and 1974 there was a negative P balance of 509 kg P ha⁻¹. However, the decrease in Olsen P in the top 23 cm accounted for only 182 kg P ha⁻¹ or 36 percent of the total P removed in the crops grown in this period (Johnston and Poulton, 1977). This shows that P was retained at sites in the soil from which it was not extracted by the Olsen reagent when the P balance was positive. However, it was released from these sites when the P balance was negative, indicating a degree of reversibility of sorbed P (details in Annex 1).

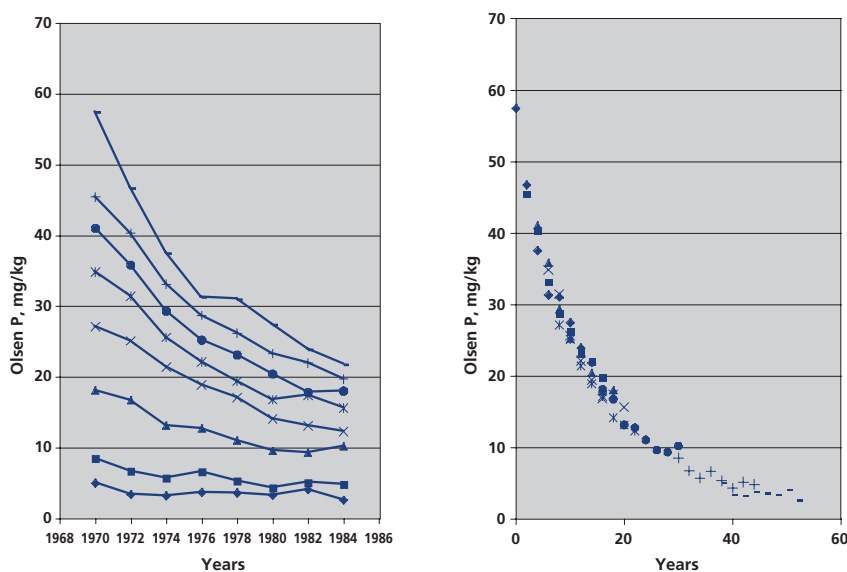
In another experiment started in 1899 on a silty clay loam soil at Saxmundham in Suffolk, the United Kingdom, treatments with and without P were applied annually to eight plots. By 1967, these eight plots had soils with Olsen P values ranging from 3 to 67 mg kg⁻¹. Potatoes, sugar beet, spring barley, winter wheat

and field beans (*Vicia faba*) were grown in rotation without further addition of P but with adequate N and K between 1968 and 1984. The harvested crops were analysed for P while the soils were sampled in alternate years and analysed for Olsen P. On the soils with most Olsen P, the decline in Olsen P accounted for 26–46 percent of the P uptake. On the soils with 21 and 28 mg kg⁻¹ Olsen P, the decline in Olsen P accounted for 12 and 21 percent, respectively, of the P uptake. On the soils with the least Olsen P, the change in Olsen P was less than 10 percent of the P uptake (Johnston, Poulton and Syers, 2001).

Although the data from this experiment at Saxmundham are only for a period of 16 years, it was observed that the decline curve for Olsen P on each of the eight plots appeared to be a segment of a single decay curve. It proved possible to bring the eight individual decay curves into coincidence and this unified curve (Figure 2) described the decline in Olsen P over a 50-year period (Johnston, Poulton and Syers, 2001).

From this curve, it was possible to calculate that it took nine years for the amount of Olsen P to halve as a result of P removal in the harvested crops. Similar unified decay curves have been found for experiments on silty clay loams growing arable and grass crops at Rothamsted.

FIGURE 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)



Source: Adapted from Johnston and Poulton (1992).

These results are critically important to the present discussion because this type of decay curve would be expected if there were different soil P pools in equilibrium with one another, with the readily-plant-available pool of P being buffered by one or more pools of less readily-available soil P. It also suggests that there are no specific, well-defined and discrete fractions of soil P, as previously widely believed, because these would become available in a stepwise progression.

AN OVERALL ASSESSMENT

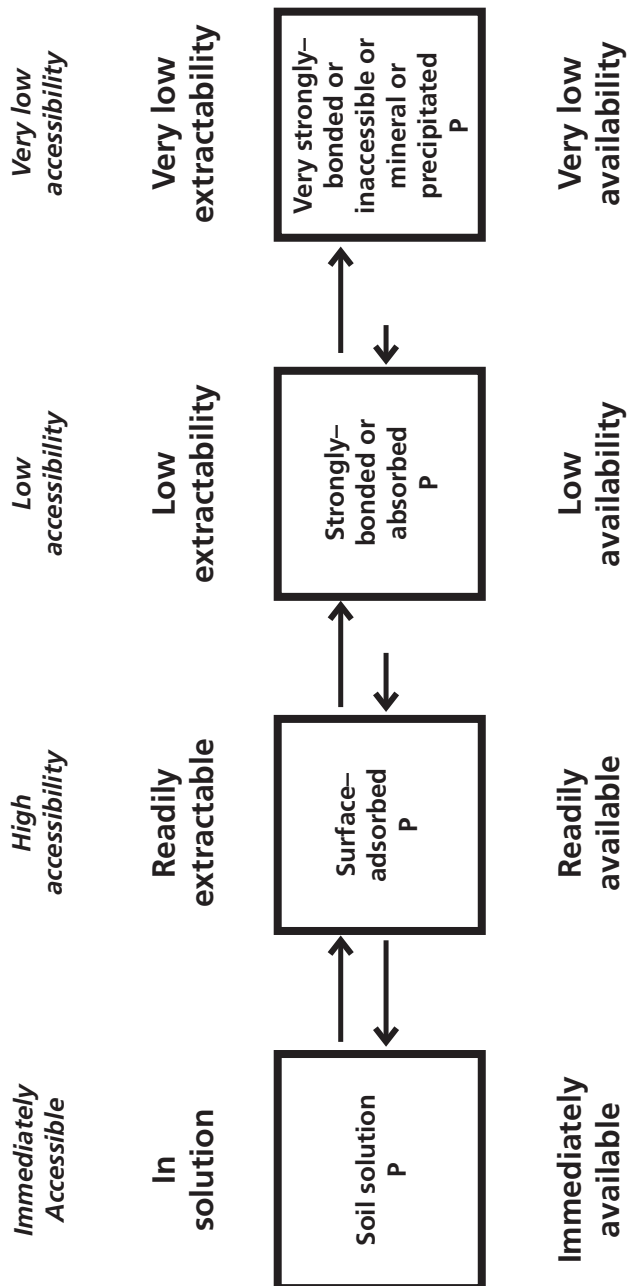
As discussed above, much of the work done up to about 1980 led to a preoccupation with the concept of P fixation and, hence, to an underestimate of the likely recovery over time of fertilizer P residues in soil. In retrospect, the persistence of the notion that fertilizer P residues are fixed irreversibly in soil may seem somewhat surprising, given that as early as 1953 Kurtz (1953) noted that: “Contrary to the apparent belief of two decades ago, more recent evidence indicates that the reactions of phosphate with soils are not entirely irreversible and that for most soils the term fixation is an exaggeration.” The present understanding among most researchers is that changes in the extractability of soil and fertilizer P, and the decrease in plant availability of added P with time, can be explained reasonably well by current concepts relating to P equilibria in soils. These primarily involve adsorption and absorption reactions, which may be largely reversible with time. What now requires attention is the extent to which this concept of reversible adsorption can be reconciled with agronomic information when assessing P residual effects and the efficiency of P fertilizer use. This is a major thrust of the present report.

RECONCILING CURRENT CONCEPTS WITH AGRONOMIC INFORMATION

Using the ideas presented above, the concept that inorganic P is more likely to be retained by soil components with a continuum of bonding energies was developed and substantiated. This concept suggests that the more strongly bound the P is, the less available it is for uptake by plant roots. Moreover, sorbed P has a varying extractability or availability, related to the nature of its physical association with retaining components in the soil. However, this concept of the behaviour of P in soil needs to be reconciled with information on crop response to P. This can be done by categorizing soil P in terms of its availability to plants, i.e. by describing soil P as being readily and less-readily available to plants. These descriptions are essentially operational definitions and relate to the ability to characterize them by chemical extractants because it is important to have a methodology that is suitable for routine advisory purposes. This approach can be conceptualized and expressed diagrammatically, as in Figure 3, in which soil P is represented as being in four pools. Analytical procedures such as equilibration with resin and 0.5 M NaHCO₃, which remove weakly-bonded P that equates to P that is readily plant-available, can be used to assess the response of a crop to an application of P fertilizer.

Phosphorus is considered to be in the four different pools shown in Figure 3 on the basis of its accessibility and extractability, and thus its availability to the plant.

FIGURE 3
Conceptual diagram for the forms of inorganic P in soils categorized in terms of accessibility, extractability and plant availability



In the soil solution, P is immediately available for uptake by plant roots. The second pool represents readily-extractable P held on sites on the surface of soil components. This P is considered to be in equilibrium with P in the soil solution, and it can be transferred readily to the soil solution as the concentration of P in the latter is lowered by P uptake by plant roots. The P in the third pool is less readily extractable and is the P that is more strongly bonded to soil components or is present within the matrices of soil components as absorbed P (i.e. P adsorbed on internal surfaces) but can become plant-available over time. The P in the fourth pool has a low or very low extractability. This is because the P is very strongly bonded to soil components, or it has been precipitated as slightly soluble P compounds, or it is part of the soil mineral complex, or it is unavailable because of its position within the soil matrix. Whatever the reason, this P is only very slowly available (often over periods of many years) for plant uptake.

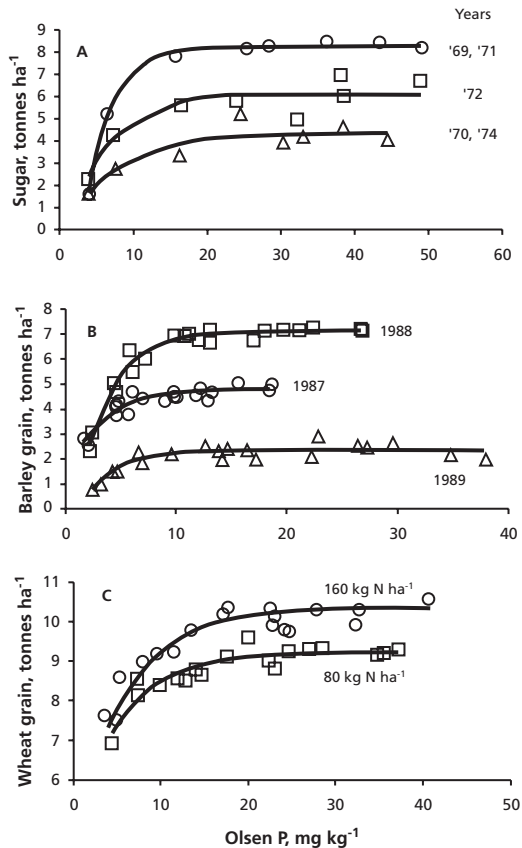
Electron microprobe analysis has shown that P may also be dispersed within certain minerals (presumably through isomorphous substitution reactions at the time of initial crystallization) or is present as apatite inclusions within other minerals (Cescas, Tyner and Syers, 1970). However, these modes of occurrence are of little direct interest to the behaviour of fertilizer P, even though they may affect the availability of soil P over extended periods of time (Syers *et al.*, 1967) and be important in certain natural ecosystems.

Routine soil tests measure P that is in the soil solution and in the readily plant-available soil pool. Thus, it is not a definite quantity but will vary with the reagent used. However, provided that there is a strong relationship between the amount of P extracted and the response of a crop to an application of P fertilizer, then this fraction of soil P can be thought of as being reasonably well defined.

The most important concept illustrated in Figure 3 is the reversible transfer of P between the first three pools. It is in this respect that current thinking about the behaviour of P in soil is fundamentally different from the belief that P is irreversibly fixed in soil. Irreversible fixation of P cannot be invoked to explain satisfactorily this behaviour of P added to soils in fertilizers.

When a fertilizer containing water-soluble P is added to soil, a very small proportion remains in the soil solution, and a small part may undergo initial precipitation reactions in some calcareous soils. However, the majority of the P rapidly becomes distributed between the readily-available and less readily-available pools by processes of adsorption and then absorption. For example, in the long-term (40+ years) experiments at Rothamsted, Woburn and Saxmundham, in the United Kingdom, where P has been applied as fertilizer and organic manure, only about 13 percent of the increase in total soil P is extracted by the Olsen reagent, which is used routinely to estimate readily-available P in soils. This experimental observation offers an explanation as to why attempts to estimate the value of residual P were not successful in the early twentieth century. If less than 15 percent of any residual P remains immediately available to plants, then it is unlikely that the small increase in Olsen P from any positive P balance resulting from a few small applications of P fertilizer would have a measurable effect on yield.

FIGURE 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



Source: Adapted from Johnston (2005)

An important outcome from the above analysis is that, if the P in the readily-extractable pool (pool 2) supplies the bulk of available P for plants, then it is only necessary to accumulate a certain amount of P in this pool in order to achieve optimal yield; this is consistent with the concept of a “critical P” value for a particular crop in a given situation. This point is well illustrated by the data in Figure 4. Figure 4 shows that when sugar beet, barley and winter wheat were grown on contrasting soils at three sites, there was a critical P value for each crop. This was about 15 mg kg⁻¹ Olsen P for sugar beet, 10 mg kg⁻¹ Olsen P for spring barley, but nearer 20 mg kg⁻¹ Olsen P for

wheat. Compared with values for wheat from other soils, this value for wheat was rather large, probably because the soil on which this experiment was conducted had a poor structure and root growth was restricted. Above this critical value, there was no further increase in crop yield with further increases in Olsen P.

It is concluded that applying the concept of a critical P value for a specific soil growing a given crop can lead to a more efficient use of P from an agronomic standpoint. If this minimizes the excessive use of P, there will also be environmental benefits. The erosion of excessively P-enriched soil into surface freshwater bodies is a major cause of the increasing load of P in these waterbodies. Such P enrichment (eutrophication) leads to adverse effects on the biological balance in the aquatic environment (Johnston and Dawson, 2005).

Chapter 4

Measuring the recovery of soil and fertilizer phosphorus and defining phosphorus-use efficiency

INTRODUCTION

The outcome of any discussion about the recovery and efficient use of soil and fertilizer P is partly dependent on the definitions adopted and whether crop yield, P uptake and soil analysis data are used in making the calculation. A large percentage recovery of added P is taken to imply an efficient use of P by the plant.

There are a number of agronomic indices and methods for measuring the efficiency of plant-nutrient use in agriculture. In summary, the methods and indices, based on those of Cassman *et al.* (1998), are: direct method; difference method; partial factor productivity index; physiological efficiency index; and balance method.

The direct method can only be used for those nutrients where the fertilizer can be labelled, e.g. using ^{32}P -labelled or ^{15}N -labelled fertilizer, to measure nutrient uptake from the fertilizer directly. The index is the proportion of added nutrient recovered in the crop.

Results obtained by this method are often expressed as percentages.

The difference method can be used in two ways:

- Using yield, $(Y_N - Y_O)/F_N$, where Y_N and Y_O , are the crop yields with and without the nutrient being tested, and F_N is the amount of nutrient applied, all in kg ha^{-1} . This is frequently considered to be the “agronomic efficiency” of the applied nutrient.
- Using nutrient uptake, $(U_N - U_O)/F_N$, where U_N and U_O are the nutrient uptake by crops with and without the applied nutrient, all in kg ha^{-1} . This is frequently considered to be the “apparent recovery” or “apparent efficiency” of the applied nutrient.

Results obtained by this method are often expressed as percentages.

The partial factor productivity of the applied nutrient is calculated in terms of kilograms of product produced per kilogram of nutrient applied, Y_N/F_N (Y_N and F_N as above).

The physiological efficiency of the applied nutrient is calculated in terms of kilograms of product increase per kilogram of increase in nutrient taken up, $(Y_N - Y_O)/(U_N - U_O)$. (Y_N , Y_O , U_N and U_O as above).

In all the above, P can replace N (nutrient) in the formulae. Examples are given below.

In addition, a balance method is used here, i.e. total P in the crop divided by the P applied (U_P/F_P), expressed as a percentage. This method has been used occasionally (e.g. Chambers, 1953). It is an appropriate method for calculating P recovery and efficiency for a number of important reasons. For N fertilizers, the difference method, which has been used widely for many years, is appropriate because very little of an N application remains in the soil as mineral N in autumn to benefit a subsequent crop. However, where P is added to soil in fertilizers or manures, there can be a large P residue, which may increase the yields of subsequent crops for a number of years. When P in a fertilizer or manure is added to the heterogeneous and complex biological, chemical and physical environment of the soil, it can undergo several biological and chemical reactions that remove phosphate ions from the soil solution. However, this does not imply that the P becomes unavailable to plants. As measured by the direct method, rarely is more than 25 percent of the added fertilizer P taken up by the crop to which it was applied. The remainder of the P in the crop must come from soil P reserves, and this P must be returned if the existing level of plant-available P in the soil is to be maintained. Thus, P-use efficiency can be measured by expressing total P uptake as a percentage of the P applied. In one sense, Dobermann *et al.* (2005) have used this approach by suggesting that nutrient management and efficiency of nutrient use can be considered at a system level where changes in all nutrient pools are taken into account.

In this report, the direct and balance methods have mainly been used to assess the efficiency of use of P based on the recovery of added and soil-derived P, but other methods have also been considered to illustrate how they may be used.

Soil analysis can also be used to assess any residual value of applied P. This approach is not sensitive to the other factors that can affect crop yields but an appropriate method of soil analysis is required. Some suggestions are discussed below.

If the recovery of added P is of interest not only in the year of application but in subsequent years as well, this raises two questions:

- Over what time scale should recovery be measured?
- Can the residual P produce yields that are economically viable for the farmer?

Both of these issues are discussed below (with examples in Annex 1).

Where very large amounts of P are added to soil, they can have a residual effect over many years (Kamprath, 1967). However, it is more important to consider the residual effect and hence recovery over time of smaller, annual applications of P more similar to those used in normal farming practice. However, assessing the residual effect of P should only be done relative to that of an application of “fresh”

(i.e. newly-applied) P in the year of the experiment (Mattingly, 1971). Thus, a welldefined response curve to freshly-applied P is required, and the response to it can be measured as yield or P uptake. In pot experiments, these two measures give similar indications of residual value (Barrow and Campbell, 1972), but this is not always the case in field experiments (Mattingly and Widdowson, 1963). In field experiments, P uptake may indicate a larger residual value than that indicated by yield alone.

The ultimate measure of the recovery of a P fertilizer, determined as its continued uptake over many years, is time-consuming; this may explain why there is a paucity of such data. Of equal interest is whether residual P is able to produce acceptable yields over a period of years. This is why other methods of estimating P efficiency (but not recovery) have been suggested. These include: the quantity of added P that remains in a labile form in the soil over time (Larsen, Gunary and Sutton, 1965); the effect of P additions on P-sorption isotherms (Fox and Kamprath, 1970); and changes over time in Olsen P values (Power *et al.*, 1964; Fitter, 1974). More recently, changes in the various pools of P extracted sequentially from soil have been used (Beck and Sanchez, 1996; Aulakh *et al.*, 2003; Blake *et al.*, 2003); this approach is discussed in more detail below.

ASSESSING THE RECOVERY OF ADDED PHOSPHORUS FROM CROP YIELDS

This section provides assessments of the recovery of applied P by the direct, difference and balance methods together with a comparison of the difference and balance methods.

Yield can be used in the calculations using the latter two methods, and P uptake in all three methods. Both the yield of a crop and the amount of P it takes up can be affected not only by the availability of soil P, but also by a range of other factors that vary from year to year. These factors include: climate (e.g. rainfall and sunshine) during the growing season; agronomy, including the availability of other essential plant nutrients, especially N and K; biotic stress (e.g. pests and diseases); and soil factors, such as soil structure. For annual experiments, the result will also depend on how well the added P was incorporated into the volume of soil explored by the roots.

For longer-term experiments, the result will depend on the number of years the experiment lasts. This is particularly important for P because, for soils where P can be accumulated in plant-available forms, plants may continue to take up the residual P from one or more applications of P fertilizer for many years. Thus, the recovery of residual P will depend on the time scale over which it is measured. Often, this residual effect has either been ignored or considered simply to be a benefit to yield by building up soil P reserves, without considering the recovery of residual P as part of the efficiency with which the initial application has been used over time.

There are two major problems with measuring P recovery over a number of years. The first is having the guarantee that the experiment will continue for an

appropriate period of time; this explains why the most useful data for assessing the efficiency of P fertilizer use are usually obtained from experiments conducted on research stations where there is “security of tenure”. The second relates to the distribution of P within the soil profile where plant roots are taking up nutrients actively, and the risk of loss of P from the soil. In long-term experiments, it is not correct to assume that all the residual P will be in the topsoil, which is usually the only soil horizon sampled and analysed. The data in Table 3 show that soil P has increased at different depths in some long-term experiments. However, little is known about the relative contribution of the P from different soil horizons to the total uptake of P by plants, because there is no information on root activity at different depths in these experiments.

Estimates of P recovery in long-term experiments can also be affected where P has been lost in surface runoff, especially in eroded soil (Sharpley and Syers, 1979; Tunney *et al.*, 1997; Johnston and Dawson, 2005) and also in subsurface runoff (Ryden, Syers and Harris, 1973). Both dissolved and particulate forms of P can be lost by any of these routes. Where P is lost from the soil, then the amount of P available for crop uptake will be less than that added originally. Thus, the recovery, when calculated as a percentage of the total P added, will be underestimated, whereas the recovery would be larger if it were calculated on the basis of the actual amount of residual P in the volume of soil explored by the roots.

Losses of P by movement down through and out of the soil profile are likely to occur on coarse-textured soils (Neller *et al.*, 1951; Ozanne, Kirton and Shaw, 1961). Mattingly (1970) observed that residual P from applications of SSP was leached from a coarse-textured, sandy surface soil but was retained by a clayey horizon in the subsoil. The amount of P recovered from this clayey layer would depend on the concentration and proliferation of roots in this soil layer, and the amount of P recovered would influence substantially the estimated P recovery. Similarly, Russell (1960) calculated the P balance for the period 1919–1957 for a permanent pasture grazed by sheep at Kybybolite, Australia. The soil was a light grey loamy sand passing to very light grey sand. Less than half of the increase in the P balance was found as an increase in total P in the top 20 cm of soil, and Russell presumed that much P had leached below this depth on this coarse-textured soil.

TABLE 3

Total phosphorus at different depths in long-term experiments at Rothamsted where superphosphate was applied for many years to a silty clay loam surface soil at pH 6.5

Soil depth (cm)	Arable crops		Permanent grassland	
	None	P	None	P
	(mg kg ⁻¹)			
0–23	780	1 295	575	1 425
23–30	465	525	555	785
30–46	415	450	500	600
< 46	400	395	n.d.	n.d.

Source: Adapted from Johnston and Poulton (1992).

Reviewing results from other experiments in Australia, Russell noted that, on other coarse-textured soils, P appeared to have been lost from the surface soil although the magnitude of the loss was not consistent. Unlike the results reported by Mattingly (1970), where P leached from the sandy surface soil was retained in the heavier-textured subsoil, the P leached from the surface soil described by Russell could well have been transported out of the soil profile.

Improving P-use efficiency on coarse-textured soils requires considerable management skills and a greater understanding of the progressive “saturation” of soil with P, as well as the role of maintenance applications, especially on permanent pastures, from which little P is removed in animal products. One potential option is to use a slow-release P fertilizer in these situations; a second option is to try to increase soil organic matter but this is not easy on coarse-textured soils.

Direct method

Labelling a P fertilizer with a radioactive isotope of P (usually ^{32}P) is the main direct method of estimating the recovery by a crop of P from a single application of P fertilizer. The half-life of ^{32}P is too short (14.3 days) for it to be used over periods longer than about three months, so most studies are inevitably short-term. The method is also expensive. A second radioisotope of P, ^{33}P (Evans and Syers, 1971), has a longer half-life (25 days) but it is appreciably more expensive than ^{32}P .

A large number of studies on the uptake by plants of P from fertilizers labelled with ^{32}P were reported in the 1950s (Mattingly, 1957). Before then the difference method (below) had been used (Russell and Watson, 1940; Crowther *et al.*, 1951). However, the difference and radiochemical methods do not always give the same result; the reasons for this, which are related mainly to technique, were discussed by Mattingly (1957).

In a greenhouse experiment in 1952, Mattingly (1957) used soil samples from a long-term experiment where the plots had received either no P, or SP (1856–1901), or FYM (1876–1901) with no P added to any of these plots after 1901 (Johnston and Poulton, 1977). To 400 g of soil in each pot, 10 mg of ^{32}P -labelled SP was added and mixed uniformly with the soil. Ryegrass was grown and harvested three times in a period of 87 days. Between 18 and 21 percent of the added P was recovered during this time. In a second, similar pot experiment, the recovery of ^{32}P -labelled SP was measured using soils taken from a field experiment where P had been applied for some years as either SP or PR. The recovery of added P ranged from 21 to 24 percent for SP-treated soils, and was somewhat less (18 to 19 percent) where PR had been applied (Mattingly, 1957).

Subsequently, Mattingly and Widdowson (1958) conducted a series of nine field experiments between 1952 and 1954 to estimate P recovery from placed, ^{32}P -labelled SP applied to root crops and cereals grown on contrasting soils. In 1952, the recovery of the placed SP was 7, 18 and 36 percent, by potatoes, swedes and fodder beet, respectively. In 1953 and 1954, only fodder beet was grown, and the recovery of the placed SP was 38 percent in 1953 (similar to that in 1952) but

only 6 percent in 1954, when yields were smaller. Sequential samples of the fodder beet taken during the growing season showed that the proportion of the total P in the crop that was derived from the placed, labelled SP declined during growth.

Experiments with spring barley in 1953 and 1954 on two soils, with pH_{water} values of 7.4 and 5.3, gave an average P recovery of 15 percent. Another series of field experiments with spring barley in 1953 and 1954 compared broadcast and placed ^{32}P -labelled SP (Mattingly and Widdowson, 1959). At harvest, the recovery of the placed SP varied less (ranging from 10 to 15 percent) and was larger than that (range 5–12 percent) from the broadcast application in spring.

There was little variation between estimates of percentage P recovery in greenhouse experiments, where only ryegrass was grown, but results from field experiments varied considerably, both between crops and between years for the same crop. For the field experiments, the variation between seasons was related to soil conditions and yield. Based on the results from all the field experiments, the recovery of ^{32}P -labelled SP ranged from 5 to 25 percent.

In contrast, Larsen (1952) reported much larger recoveries (about 85 percent) of the P from MCP added to soils in pots growing ryegrass in a greenhouse. More recently, Sisworo *et al.* (1998) used ^{32}P labelling to compare different PRs with either TSP or SP-36 in field experiments with rice grown both in the lowlands and uplands in Indonesia. Yields of lowland rice were very similar with both TSP and PR at each level of P tested. At 32 days after planting, 66–75 percent of the P in crop was derived from the added P. Yields of upland rice were larger with SP-36 than with any of the PRs tested. With SP-36, 40 percent of the P in the crop was derived from the added P. The smaller yields of upland rice with PR were associated with 25–32 percent less P in the crop compared with the percentage of P in the crop grown with SP-36.

Difference method

For many years, the difference method has been used widely to estimate the recovery of fertilizer P added to soil. Russell and Watson (1940) and Crowther *et al.* (1951) provide reviews of early work. If the calculation (above) is based on yields, the result is frequently considered as the agronomic efficiency of the applied P. If the calculation is based on P uptake, the result is considered to be the apparent recovery or efficiency. Many factors can affect the result, some of which have been discussed above. The percentage recovery of applied P determined in this way depends on the yield and P uptake by the crop grown on the soil to which no P was applied, and this, in turn, depends on the amount of plant-available P in the control soil.

In greenhouse experiments, growing conditions can be controlled well, and because roots tend to grow throughout the soil mass, optimal conditions exist for P uptake if the added P is mixed uniformly with the soil. In a recent greenhouse experiment, Johnston and Richards (2003) measured the recovery of P by ryegrass grown on ten soils with available soil P (Olsen P) ranging from very low to high (from 4 to 40 mg P per litre) and pH_{water} values ranging from 4.9 to 8.1. The P was

added as MCP at four rates: 44, 66, 88, and 110 mg P per pot, each pot containing 1 kg of soil.

The recovery of added P was measured during one growing season. Calculated by the difference method for soils with very low to medium P status (4–20 mg kg⁻¹ Olsen P), recovery (range 38–44 percent) was largely independent of the amount of P added (Table 4). Averaged over the four amounts of P tested, recovery was 41 and 43 percent for the low and the medium soil P groups, respectively. This was despite the fact that there was a large difference in the total P uptake from the control soils of the low and medium soil P groups: 14.0 and 35.8 mg P per pot, respectively. Even on soils with 28 and 40 mg kg⁻¹ Olsen P, the recovery of added P was, on average, 34 percent.

Several field experiments were analysed by the difference method. The effect of N on yield, P uptake, and P-use efficiency over time is clear in the Broadbalk experiment at Rothamsted. There, the same annual amounts of N (96 kg ha⁻¹), P (33 kg, then 35 kg ha⁻¹ from 1974) and K (90 kg ha⁻¹) have been applied to plots growing winter wheat since 1852. In the absence of N, the recovery of the added

TABLE 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

Olsen P (mg kg ⁻¹)	Total P uptake on control (mg pot ⁻¹)	P added (mg P pot ⁻¹) as MCP				Mean
		44	66	88	110	
		Recovery of added P (%)				
4–11	14.0	44	42	40	38	41
16–21	35.8	44	43	44	41	43
28–40	61.7	34	35	34	33	34

Source: Adapted from Johnston and Richards (2003).

TABLE 5
Change in P recovery over time determined by the difference method, Broadbalk, Rothamsted

Period		Annual treatment*				
		Without N		With N		
		None	PK		P	PK
1852–71	P in crop** (kg ha ⁻¹)	4.9	6.6	6.5	9.2	11.3
	% recovery		5		8	14
1966–67	P in crop (kg ha ⁻¹)	4.5	5.7	4.8	11.0	12.0
	% recovery		4		19	22
1970–75	P in crop (Kg ha ⁻¹)	6.2	6.8	9.0	13.1	17.3
	% recovery		2		12	24
1985–2000	P in crop (kg ha ⁻¹)	3.7	4.7	5.7	12.7	17.4
	% recovery		3		20	33

* Annual treatment (kg ha⁻¹): N, 96; P, 33 (35 since 1974); K, 90.

** Total P in grain plus straw.

P was less than 5 percent and has not changed over 150 years (Table 5). With the increasing yield potential of the cultivars grown and where the crop always received 96 kg N ha⁻¹, P-use efficiency has increased over time.

The effect of plant-available soil P on the recovery of added P by three arable crops was examined in the Agdell experiment at Rothamsted. There, two levels of SOM and a range of Olsen P levels were established over a 12 year period before spring barley, potatoes, and sugar beet were each grown for two years in the three-year period 1970–72. The data in Table 6 are from soils with 2.4 percent SOM and are averaged over two years. On the soil with 6 mg kg⁻¹ Olsen P, the recovery of added P varied with the crop grown. However, on the soil with adequate Olsen P there was no response to added P, except for a small response by spring barley.

Balance method

The balance method does not make any comparison between crop yield and P uptake on soils with and without added P. It simply considers yield and P uptake relative to the amount of P applied. The reasons for adopting this method have been discussed above. As an example, P recoveries by the balance method can be calculated from the data in Table 5; the results are shown in Table 7. Percent P recoveries calculated by the balance method are larger than those calculated by the difference method. The data in Table 7 show that where N and K supply is adequate, percent recovery has increased as the yield potential of the wheat crop has increased. The data in Table 7 suggest that in recent years about 50 percent of the added P can be accounted for in that experiment. Further examples of the balance method are given below.

TABLE 6
Effect of level of plant-available soil P on the recovery of P applied to three arable crops, Agdell, Rothamsted

	Olsen P (mg kg ⁻¹) at the start of the experiment			
	6		59	
	P applied*			
	no P	P	no P	P
Spring barley				
P in crop** (kg ha ⁻¹)	8.3	12.6	17.5	19.1
% recovery		16		6
Potatoes				
P in crop (kg ha ⁻¹)	9.4	16.2	16.8	17.0
% recovery		8		0
Sugar beet				
P in crop (kg ha ⁻¹)	8.1	22.9	36.0	35.1
% recovery		27		0

*P applied to each crop, kg ha⁻¹: barley, 27; sugar beet, 54; potatoes, 82.

** P uptake: barley grain + straw; potatoes, tubers; sugar beet, tops + roots.

Note: Basal applications (kg ha⁻¹): N: barley, 95; potatoes, 250; sugar beet, 190; K: barley, 50; potatoes, 250; sugar beet, 250.

The difference and balance methods compared

A comparison of the data in Tables 5 and 7 shows that the percent recovery of P added in fertilizers is larger when calculated by the balance method, and there are valid reasons for calculating recovery in this way. Table 8 provides a more comprehensive example. Rotations of three arable crops (sugar beet–spring barley–potatoes–spring barley) were started in 1969 and in 1970 on soils with a range of Olsen P values. Three amounts of SSP (27.5, 55 and 82.5 kg P ha⁻¹) were tested at each level of Olsen P but were only applied to the potatoes and sugar beet. Thus, in four years, a total of 55, 110 and 165 kg ha⁻¹ P were applied. The P uptake in the harvested crops was measured each year and the total P uptake in four years was calculated and averaged over the two rotations. Table 8 presents data for only two levels of soil P (4 and 33 mg kg⁻¹ Olsen P). On the soil with only 4 mg kg⁻¹ Olsen P, the recovery estimated by the difference method ranged from 43 to 24 percent, declining with the amount of P applied. Yields and, hence, P uptake were much larger on the soil with 33 mg kg⁻¹ Olsen P and recovery was much less (3–4 percent). Estimated by the balance method, recovery of the added P ranged from 85 to 39 percent on the soil with least Olsen P, again declining with the amount of P applied. On the soil well supplied with Olsen P, recovery varied from 140 to 50 percent. The value of 140 percent arises because there were excellent yields on this soil without adding any P and adding 27.5 kg ha⁻¹ P to the potatoes and sugar beet increased yield and P uptake by only a small amount. Where recovery determined by the balance method exceeds 100 percent, this implies that the added P has not replaced all the P removed in the harvested crop and that P reserves are being depleted.

TABLE 7
Change in P recovery over time determined by the balance method, Broadbalk, Rothamsted

Period		Annual treatment*		
		Without N	With N	
		PK	P	PK
1852–71	P in crop **	6.6	9.2	11.3
	% recovery	20	28	34
1966–67	P in crop	5.7	11.0	12.0
	% recovery	17	33	36
1970–75	P in crop	6.8	13.1	17.3
	% recovery	21	40	52
1985–2000	P in crop	4.7	12.7	17.4
	% recovery	13	36	50

* Annual treatment (kg ha⁻¹): N, 96; P, 33 (35 since 1974); K, 90.

** Total P in grain plus straw, kg ha⁻¹.

TABLE 8
Percentage recovery of three amounts of applied P at two levels of Olsen P, sandy clay loam soil, Saxmundham

P applied* (kg ha ⁻¹)	Olsen P (mg kg ⁻¹)					
	4	33	4	33	4	33
	P uptake in 4 years (kg P ha ⁻¹)		% recovery by the difference method		% recovery by the balance method	
0	23.3	75.2				
55	46.9	77.0	43	3	85	140
110	57.2	79.4	31	4	52	72
165	63.8	82.2	24	4	39	50

Notes:

Data are the mean of two 4-year rotations, 1969–1972 and 1970–73.

Rotation: sugar beet, barley, potatoes, barley.

Total P applied in 4 years was 55, 110 and 165 kg P ha⁻¹.

* P tested at 27.5, 55 and 82.5 kg P ha⁻¹ but applied only to potatoes and sugar beet.

EFFICIENCY DETERMINED IN RELATION TO YIELD PER KILOGRAM OF PHOSPHORUS APPLIED OR TAKEN UP BY THE CROP

The efficiency with which the crop uses P can also be expressed in terms of the increase in yield per unit of P applied, and this is often known as “partial factor productivity”. The data from the greenhouse experiment given in Table 4 can be used to illustrate this method of calculating efficiency (Table 9). One feature arising from this method of presentation is that, at each of the three levels of Olsen P, although yield increased with the amount of added P, the efficiency of P use decreased, whether expressed as milligrams of dry matter (DM) per milligram of P applied or as milligrams of DM per milligram of P uptake. Thus, although yield increased with the amount of applied P, the applied P was used less efficiently. The yield and the milligrams of DM per milligram of P applied both increased with increasing Olsen P, but the milligrams of DM per milligram of P uptake decreased with increasing Olsen P (Table 9).

Another feature of the results is the relationship between yield, Olsen P, and P-use efficiency. For example, the total yield of ryegrass per pot (23.5 and 24.6 mg) was similar for the second rate of P addition (65.5 mg P pot⁻¹) at the medium level of Olsen P (16–20 mg kg⁻¹) and for the largest rate of P addition (109 mg P pot⁻¹) at the lowest level of Olsen P (4–11 mg kg⁻¹). However, in terms of efficiency, expressed as milligrams of DM per milligram of P applied, the P was used more efficiently at the medium level of Olsen P, 612 compared with 225 mg DM. A similar comparison can be made for the smallest amount of P applied at the highest level of Olsen P and the largest amount of P added at the medium level of Olsen P (Table 9). Again, P was used more efficiently when the smallest amount of P was applied to the soil with the largest Olsen P value. Both sets of results suggest that there is an advantage to be gained from maintaining soils at an adequate level of readily-available soil P to achieve maximum efficiency of applied fertilizer P.

TABLE 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

Olsen P (mg kg ⁻¹)	0	44	P applied (mg P pot ⁻¹)		
			66	88	110
			Ryegrass yield (mg pot ⁻¹)		
4 to 11	9.32	19.17	21.62	23.27	24.62
16 to 20	19.81	23.51	24.21	25.26	25.63
28 to 40	26.02	26.70	27.26	27.69	28.35
			mg DM per mg P applied		
4 to 11		440	330	266	225
16 to 20		539	370	289	235
28 to 40		612	419	317	260
			mg DM per mg P uptake		
4 to 11		579	524	480	443
16 to 20		428	380	341	321
28 to 40		350	322	305	289

SUMMARY OF METHODS FOR ESTIMATING THE RECOVERY OF PHOSPHORUS FERTILIZERS

The various methods of estimating P-use recovery or efficiency can be best summarized by data from the Broadbalk Winter Wheat experiment at Rothamsted for the period 1985–2000. Table 10 presents the effects of Olsen P and added N on the average yield of wheat grown continuously and in the rotation used in the 16 year period.

When determined by the difference method, the recovery of applied P was less for wheat grown in rotation than for wheat grown continuously. The reason is that yields are larger when wheat is grown in rotation because the effects of soil-borne pathogens on root growth and uptake of applied nutrients are minimized in the rotation. However, when calculated by the balance method, wheat grown in rotation recovered more P than did continuous wheat. When calculated by both the difference and the balance method, recovery of P added in FYM is smaller than that of P added in P fertilizer when sufficient fertilizer N is given with the fertilizer P.

When efficiency of P use was calculated as kilograms of grain per kilogram of P uptake, the largest values were for the crops given N, but no P, i.e. the crop was using soil P very efficiently but not effectively, because without N, yields were very small and not financially viable. Where the same amount of fertilizer P was applied each year, the range in terms of kilograms of grain (306–334) per kilogram of P uptake was small, which suggests a fairly constant concentration of P in both grain and straw.

These data indicate that different methods of calculating P recovery or efficiency can give very different results. In addition, the recovery of added P

depends not only on the crop grown, but also on all those factors, such as other inputs, soil conditions, and weather during the growing season, that affect the final yield and, thus, the amount of P taken up by the crop. These factors need to be borne in mind when evaluating the data and the information generated in the case studies included in Annex 1.

SOIL ANALYSIS

Another approach to estimating the recovery or efficiency of P added in fertilizers is to use soil analysis to assess whether P residues have remained in soil P pools from which they can be recovered by crops.

TABLE 10
Effect of Olsen P and N on the yield and efficiency/recovery of P by winter wheat, Broadbalk, Rothamsted, 1985–2000

Continuous wheat	Treatment						
	Nil	N ₂ K	N ₂ PK	N ₄ PK	N ₆ PK	FYM	FYM + N ₂
Olsen P (mg kg ⁻¹) in 1992	7	4	115	76	73	85	74
Grain yield (tonnes ha ⁻¹)	1.17	2.46	5.32	6.58	7.29	6.04	8.07
P in grain+straw (kg P ha ⁻¹)	3.7	5.0	17.4	20.6	22.8	22.9	28.6
% recovery							
Difference method			35	45	51	39	51
Balance method			50	59	65	50	62
Efficiency of P use							
kg grain per kg P uptake	316	492	306	319	320	264	282
kg grain per kg P applied			152	188	208	131	175
Rotational wheat	Nil	N ₂	N ₂ PK	N ₄ PK	N ₆ PK	FYM	FYM + N ₂
Olsen P (mg kg ⁻¹) in 1992	9	6	86	80	77	111	93
Grain yield (tonnes ha ⁻¹)	2.25	5.53	7.26	8.76	8.67	7.78	9.36
P in grain+straw (kg P ha ⁻¹)	6.7	13.2	21.9	26.8	27.5	27.0	33.7
% recovery							
Difference method			25	39	41	30	44
Balance method			63	77	79	58	73
Efficiency of P use							
kg grain per kg P uptake	336	421	334	327	316	289	278
kg grain per kg P applied			207	250	248	169	203

Notes:

Cultivars grown: Brimstone, 1985–1990; Apollo, 1991–1995; Hereward, 1996–2000.

Treatment per hectare annually: N₂, N₄, N₆: 96, 192, 288 kg N; P, 35 kg; K, 90 kg. FYM, 35 tonnes ha⁻¹ supplying 46 kg P and 225 total N.

For rotational wheat treatment N₂ had to be used instead of N₂K.

Assessing the increase in readily plant-available soil phosphorus

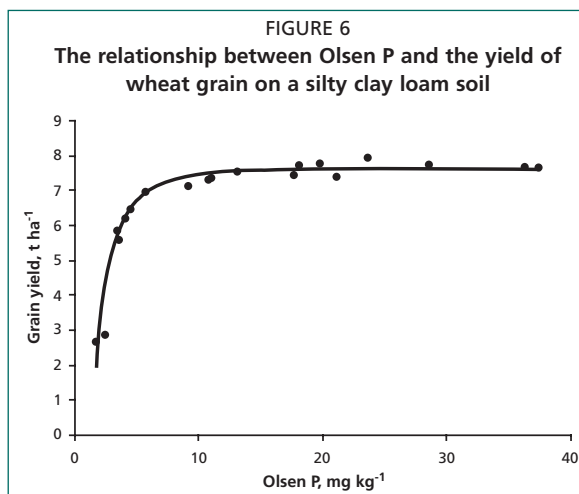
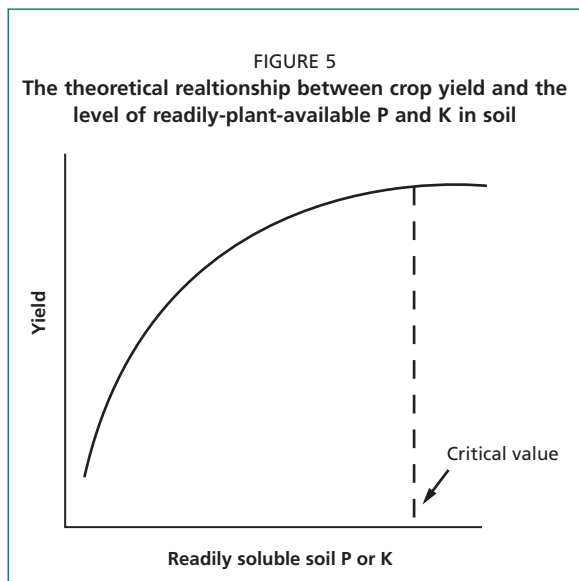
On soils where P residues can accumulate in readily plant-available forms (Chapter 3) the concentration of P in the available pool can be measured by appropriate methods of soil analysis such as Olsen, Morgan, Bray, Mehlich and CAL (Kamprath and Watson, 1980). The concentration of P, i.e. in milligrams per kilogram of soil, measured using these reagents will increase as the amount of total P in a given soil increases. However, relative to the increase in total P, the increase in the P extracted by the reagents is usually small (Johnston, Poulton and Syers, 2001). In Rothamsted experiments, the increase in Olsen P is only about 13 percent of the increase in total P. In order to determine the amount of P, i.e. in kilograms per hectare, in the readily-available pool, the weight of soil per unit area to the depth of sampling must be known with accuracy.

Figure 3 indicates reversible transfer of P between the readily-available and less readily-available pools of soil P, and thus the P in the latter pool does become available to plants. There is ample evidence for this (Johnston, 2001). The amount of P in the less readily-available pool cannot be determined by routine soil analysis methods. Therefore, little is known about the relative amounts of P in these two pools for a range of soils. Unless the quantity of P in the soil P reserves is known together with its rate of release, it is not possible to predict how long the reserves will last. Chapter 3 described an experiment in which the decline in Olsen P was measured over a 16 year period of arable cropping. Because the decline curves for eight soils could be brought into coincidence, it was possible to estimate from the combined curve that it would take about 50 years for Olsen P to decline from 60 to 5 mg kg⁻¹ with a half-life of 9 years.

Optimizing the use of soil phosphorus reserves

On soils where plant-available P can accumulate, the response of crops to increasing levels of these P reserves will follow the law of diminishing returns, i.e. as readily-available P reserves increase, the yield will increase rapidly at first and then more slowly to reach an asymptote (Figure 5).

The level of readily-available soil P (assessed by a well-tried and accepted method of analysis, at least for weakly acid, neutral and calcareous soils) at which the yield asymptote is approached can be considered to be the critical value for that soil type and farming system. The critical value will vary with these two factors, and at the critical value, readily plant-available soil P is used with maximum efficiency and maximum effectiveness. Below the critical value, there is a serious risk of loss of yield. Above the critical value, applying P is inefficient because there is no increase in yield, and there is also an unnecessary cost to the farmer. Where such P-enriched soils are transferred to surface waterbodies by erosion, there is an increased risk of eutrophication. At the critical level, P is used most effectively when the amount applied replaces that removed in the harvested crop (maintenance or replacement applications). To check whether this approach is maintaining the critical level, the soil can be sampled every 4–5 years. This approach is applicable



where comprehensive information for soils and farming systems exists (Johnston and Dawson, 2005).

Figures 6 and 7 show examples of the relationship between Olsen P and the yields of winter wheat and grass (DM) grown on a silty clay loam soil. Figure 4 shows other examples of this relationship. For each of the three crops shown in Figure 4, the Olsen P value at which the yield approached the asymptote was similar irrespective of the large annual differences in yield, which in this case were caused by weather and N supply. Although the critical value was essentially independent of the yield, more P will have to be applied to make good the larger uptake of P in the larger yield, i.e. the use of applied P will be efficient because only the P removed will be replaced. The data in Table 1 show that the level of SOM had a large effect on the critical Olsen P value for spring barley, potatoes and sugar beet grown on one site where the lower level of SOM was far below the optimum. This effect of SOM could be explained by its positive effect on soil structure in the field and, in consequence, better root growth. In this situation, it

would be better to improve soil structure, perhaps by increasing SOM, rather than applying excessive amounts of P to achieve very high levels of available soil P.

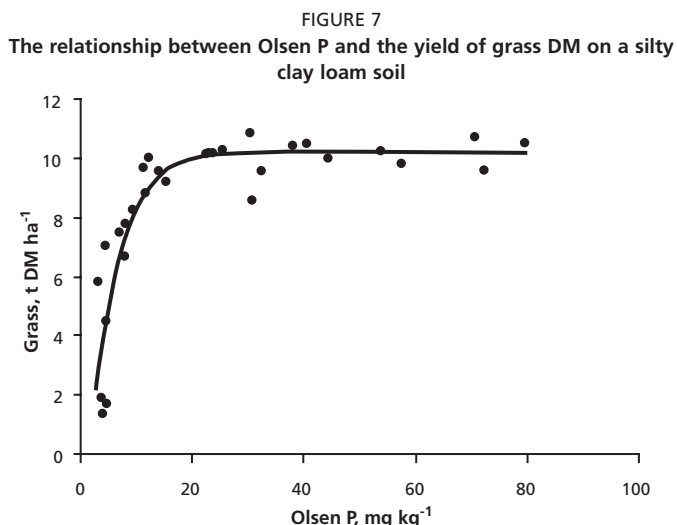
Sequential analysis of soil phosphorus

Chapter 3 has described a method for categorizing soil P according to its ease of extraction and availability for crop uptake, using sequential extraction of the P in soil (Figure 3). Another approach to describing soil P has sought to identify different chemical forms of P in soil. This has involved sequential extraction of the soil with chemical reagents that have an increasing ability to remove P from the soil. For this purpose, various methods have been described by, among others, Chang and Jackson (1958), Hedley, Stewart and Chauhan (1982), Perrot, Maher

and Thorold (1989), and Tiessen and Moir (1993). It was initially thought that sequential extraction would give some insight into the chemical association of the P removed by each extractant. However, with improved understanding, it seems preferable to consider a continuum of P adsorbed or absorbed by mineral components in the

soil, as well as P in more or less discrete chemical forms. Consequently, no specific P compounds can be related to each extractant. Although sequential extraction of a single soil sample gives data that are little more than a “snapshot in time”, Blake *et al.* (2003) have shown how the usefulness of such data might be extended. In experiments with contrasting P treatments, it is possible to see how the amount of P extracted by each reagent has been affected by a treatment. Where there are archived soil samples, it is sometimes possible to assess how P extracted by each reagent has changed with treatment and time, and to relate these changes to P balances and plant availability of the P in each fraction. This approach to using sequential extraction of soil P is illustrated here using an example from a long-term experiment at Rothamsted. Other examples are given in the Peru and India case studies in Annex 1. Knowledge about the amount of P in those soil fractions that are known not to be immediately plant available, identified as less-labile P pools in some reports, could lead to a better understanding of soil P dynamics. This could lead to improved management of P fertilizer use and, hence, higher P-use efficiency.

There is ample evidence that P extracted by an anion-exchange resin or by 0.5 M NaHCO₃ is usually well related to the amount of P that is available for crop uptake. These two reagents are used as the first and second extractants, respectively, in several methods of sequential extraction. It is unlikely that the P extracted by 0.5 M NaHCO₃ following equilibration of the soil with resin will be the same in quantity or form as the P extracted by the Olsen method for routine soil analysis. Repeated extraction of a soil with 0.5 M NaHCO₃ following a first extraction, as in the Olsen method, continues to extract P, but in decreasing amounts, for about ten extractions. Hence, extraction with bicarbonate following equilibration with resin would be expected to remove more P from the soil. Here



the amount of P extracted by 0.5 M NaHCO₃ in the sequential extraction method will be identified as NaHCO₃ P (or bicarbonate P) to distinguish it from the Olsen P in routine soil analysis. Rarely does the sum of the amount of P extracted by resin and bicarbonate relate directly to the P balance. This is because much of the residual P moves rapidly to the less-readily-available pool (Figure 3); it is the continuing availability of the P in this pool of P that is of particular interest.

Using archived and current soil samples and estimates of P balances in long-term experiments managed by Rothamsted Research on contrasting soil types at Rothamsted, Woburn, and Saxmundham, it has been possible to evaluate sequential extraction of soil P. Blake *et al.* (2003) give details of the soil, experimental treatments, P balances for three long-term experiments, and the sequential extraction method used. Here, data for the Exhaustion Land experiment at Rothamsted (case study on arable cropping in Annex 1) are summarized. Started in 1856, there were three P treatments: none, SP (1856–1901), and FYM (1876–1901). Since 1901, no P has been applied. The top 23 cm of soil has always been sampled, and there are samples for 1856, 1903 and 1993. The two-year difference between the last application of P in 1901 and the soil samples in 1903 has no effect on the interpretation of the data to derive P balances because of the long time scales of P accumulation and depletion.

The extractants used were, in order: (i) an anion-exchange resin; (ii) 0.5 M NaHCO₃; (iii) 0.1 M NaOH; (iv) 1 M NaOH; (v) 0.5 M H₂SO₄; (vi) hot concentrated HCl; and (vii) analysis of the residue to determine residual organic P (Po) and recalcitrant residual inorganic P (Pi). The P removed by extractants (ii), (iii) and (iv) was determined analytically as both Po and Pi. However, for simplicity, only the sum of Po and Pi is given here, and the discussion is restricted to the P extracted by the first five reagents. Before 1901, the P balance was positive where both fertilizer and FYM were applied; P accumulated in the soil and there were increases in all the first five soil P fractions. During the period of P depletion (1901–1993 on all plots), there were negative changes in all five P fractions (Table 11). These positive and negative changes account for almost 90 percent of the increase or decrease in total soil P determined separately for each soil in each period. Inorganic P changed much more than Po in these soils growing arable crops. The change in resin P contributed most (25 percent) to the change in total P.

In another experiment, it was seen that added P distributed itself between the different soil P fractions quite quickly (Blake *et al.*, 2003). On a sandy clay loam soil, 230 and 490 kg P ha⁻¹ were added in FYM and SSP, respectively, between 1965 and 1967. By spring 1969, the sum of the Pi extracted by resin and 0.5 M NaHCO₃ was only 56 and 58 percent, respectively, of the total increase in the Pi in the first five fractions. The sum of the change in P in all five fractions (expressed as kilograms per hectare) did not account for all the P balance. This was probably because the authors were calculating differences between analytical values, and any small error in the determination of P in each fraction contributes to the overall error.

The data from both these experiments indicate that there were both increases and decreases in all five fractions of soil P related to the known accumulation and depletion of soil P, i.e. there was reversible transfer of P between these fractions. Thus, the P accumulated in more strongly-held forms was subsequently released and taken up by the crops grown (Johnston and Poulton, 1977).

USING OMISSION PLOTS TO ASSESS THE NEED FOR PHOSPHORUS

Applying fertilizer P when the soil supply is sufficient to meet the requirement of a crop is an inefficient use of P. To apply this concept to large areas of farmland, for which little is known about past fertilizer additions and soil fertility status, an “omission plot” technique has been developed (Dobermann *et al.*, 2003). The technique entails establishing a series of plots in farmers’ fields, and applying to one of them all major nutrients as well as those micronutrients that might be deficient. On each of the remaining plots, one of the nutrients given to the fully fertilized plot is omitted. Comparing the yields on these plots with those on the fully fertilized plot gives an estimate of the indigenous supply from the soil of that nutrient for that crop and year. By combining this site-specific crop-based data with modelling the expected yield response as a function of nutrient interactions and climatic yield potential (Dobermann *et al.*, 2002), a site-specific nutrient management (SSNM) approach has been developed that can be used on similar soils within a region. A consortium consisting of the Swiss Development Cooperation (SDC), IFA, International Potash Institute (IPI) and International Plant Nutrition Institute (IPNI) co-sponsored a multinational project to evaluate SSNM at numerous locations in many rice-growing areas in Asia (Wang *et al.*, 2001; Dobermann *et al.*, 2002; 2003). This project has had considerable success in indicating the indigenous nutrient supply of soil at the different sites and the need

TABLE 11
Relationship between P balance at the end of each treatment period and the change in soil P fractions, Exhaustion Land, Rothamsted

Plot, treatment & period	P balance	Resin	Change in first five P fractions, kg P ha ⁻¹				Total change
			0.5 M NaHCO ₃	0.1 M NaOH	1 M NaOH	0.5 M H ₂ SO ₄	
	(kg ha ⁻¹)					(kg P ha ⁻¹)	
No P							
1903–1993	-300	-49	-20	-195	-82	-19	-365
FYM applied							
1876–1901	1 035	193	129	133	107	335	917
Not applied							
1903–1993	-752	-259	-123	-159	-112	-164	-817
P fertilizer applied							
1856–1901	1 222	158	126	79	7	270	640
Not applied							
1903–1993	-644	-234	-138	-114	45	-253	-694

Source: Adapted from Blake *et al.* (2003).

to apply P fertilizer when the soil supply was too small. When used for N, the timing and amount of N to apply can be fine-tuned to the needs of a crop based on leaf chlorophyll content (Peng *et al.*, 1996). For P, the omission plot only indicates whether or not to apply P. To determine the efficiency with which the applied P has been used, the grain and straw should be sampled and analysed.

SUMMARY

A variety of methods have been used to measure P recovery and to estimate the efficiency of use of soil and fertilizer P. These methods often give widely different results depending on the basis of the calculation. Of the methods used, the direct and balance methods have been emphasized. Of the two, the balance method is preferred because this includes allowance for the plant-available soil P derived from previous fertilizer or organic manure applications; that is, it takes into account residual P. Results obtained using the balance method are invariably higher than those using the direct method. However, as the former takes into account residual P, it is considered to be both more realistic and more useful.

Chapter 5

Improving the efficiency of soil and fertilizer phosphorus use in agriculture

Of the major plant nutrients, world resources of P are the smallest and, thus, on a global scale, P should be used as efficiently as possible in order to conserve the resource base and to maintain and increase, where necessary, agricultural productivity. This report has indicated that the efficiency of P fertilizer use in a range of agricultural systems is often much higher than thought previously, depending on how the recovery of P is calculated and the time scale over which it is measured.

There is a need to increase the use of P fertilizers in most developing countries in order to ensure food security for their growing populations. Soils containing insufficient amounts of plant-available P not only produce economically unacceptable yields, but other inputs, particularly N, are also used less effectively. Thus, there is an urgent need to seek strategies by which P fertilizers can be used more effectively in those farming systems where P is currently deficient and where its use is economically feasible. Production systems where this is the case include some on acid soils, on grazed pasture, and on land susceptible to soil erosion.

In many developed countries, there has been a decline in P fertilizer use, partly for financial reasons, and partly because more P is being recycled through organic manures (e.g. animal manure, biosolids and compost). Where plant-available P levels are well above the appropriate critical value for the soil and farming system under consideration, there is also a need to use fertilizer P more efficiently. In such situations, the application of P may be interrupted or reduced to amounts less than crop uptake until elevated levels decline. However, this mining of soil P reserves should not continue much below the critical value if financially viable yields are to be obtained.

Possible options for improving the efficiency of soil and fertilizer P use include: modifying surface soil properties to increase P availability; managing surface soil to minimize losses of P in surface runoff; managing P sources (both fertilizers and organic manures); and investment to optimize soil P status. These options are discussed briefly below. Plant modification, particularly of the root system and function, has received decades of research attention, but with limited success to date. Cultivars that produce root systems showing very efficient P uptake are being tested in low-P-status soils in South Africa and South America (Trolove *et al.*, 2003).

Although each of the following options individually might make only a small contribution to improving P-use efficiency, the combined benefit may be sufficiently large and worthwhile, at least in some production systems, if more than one option can be used. However, although the efficiency of soil and fertilizer P can potentially be increased using some of these strategies in some production systems, the prospects of obtaining substantial increases are unlikely where efficiency is already high. This report shows that this is the case in several situations, and that, in such cases, it is essential to maintain a high P-use efficiency. The rather limited success obtained thus far with some of the approaches mentioned below may simply be related to an already high P-use efficiency. Finally, the probability that any of the above strategies for increasing the efficiency of P use will be adopted (or even pursued) will be determined largely by costs and benefits.

MODIFYING SURFACE SOIL PROPERTIES

Soil fertility and P-use efficiency depend, in part, on the complex interactions of the biological, chemical and physical properties of soils, and the processes that take place in them. Some of these properties can affect root growth and development, restricting the uptake of P. For example, crop rotation is important to minimize the soil-borne fungal pathogens and nematodes that attack roots and limit their growth and nutrient uptake. Important physical limitations to root growth and development include the presence of dense subsurface layers (e.g. plough pans) and surface-soil compaction. These may be avoided by timely cultivations or by zero-tillage and maintaining a permanent crop or crop-residue cover, and by minimizing traffic over the soil surface and encroaching by livestock when the soil is wet, as occurs on heavy-textured soils in humid temperate regions.

Chemical limitations to the efficient use of P fertilizers include soil acidity, which can be corrected by liming. To overcome Al toxicity (which reduces soil P availability), liming acid tropical soils to pH 5.5 (or better still to increase base saturation to around 50 percent) is usually sufficient.

The distribution of P between the various soil P pools (Chapter 3) is to a significant extent an inherent characteristic of the soil, related to both its chemical and its physical properties. Major changes to the distribution of P between the pools can be difficult to achieve economically, even where it is possible to make these changes.

The retention of P in soil in forms that are not immediately available to plants is, essentially, an inherent soil characteristic, and changing these retention characteristics may be difficult to achieve. Many studies have investigated the effects of pH modification (usually by lime application to acid soils) on P retention and extractability, but consistent improvements in the availability of soil P have not been obtained (Haynes, 1982; Sumner and Farina, 1986; Mansell *et al.*, 1984; Holford, Scheirtzer and Crocker, 1994; Curtin and Syers, 2001). However, minor changes may be achievable. For example, evidence from long-term experiments at Rothamsted shows that the more organic matter there is in soil, the more the amount of very readily-available plant P, i.e. P that is extracted by 0.01 M CaCl₂, compared with soil with less SOM (Johnston and Poulton, 1992).

Another option for increasing the availability of P in very P-deficient soils is the application and incorporation of a substance competing with the phosphate ion for adsorption sites within the soil. Such materials would have to be available at a much lower price than phosphate fertilizer. Silica or silicate is such a competitor and may be available at low cost, e.g. in the form of rice-husk ash, assuming sufficient quantities are available. Uehara, Ikawa and Hue (2001) found that re-silication of strongly-weathered, hydrous oxide-rich soils (Ferralsols) with calcium silicate improved P availability, and also restored cation-retention capacity and provided a source of silicon for plants. However, in order to be effective, the silicon source must be water-soluble, which further increases the cost. Moreover, not all P-deficient soils react to silica or a silicate in the same way, which further limits the widespread use of silicon “fertilization”.

MANAGING SURFACE SOIL AND ITS PHOSPHORUS CONTENT

Several aspects of surface-soil management are important to the efficient use of fertilizer P. Root growth and the extent to which roots exploit the soil to take up nutrients depend to a large extent on the structure and structural stability of a soil. This is particularly the case for P because, in contrast to N, phosphate ions move to only a limited extent in most soils (Barber, 1984). Structural stability is related to particle-size distribution and to the calcium carbonate and organic matter contents of the soil. Chapter 2 gives an example of the importance of soil structure in relation to the level of Olsen P needed to achieve maximum yield.

Replacing the P lost from soil by water or wind erosion is an inefficient use of P because the lost P has to be replaced in order to maintain productivity. Minimizing surface runoff and the associated P losses, particularly on sloping land, is important from a water-quality standpoint. Even small amounts of P can be a cause of the adverse effects of eutrophication of surface waters. These amounts are often considered insignificant from an agronomic standpoint, but it is still useful to minimize them. Eroded soil and its associated P is one pathway by which P is transported from soil to surface water. Soil erosion can be minimized by adopting well-tested technologies, such as cultivation and planting along the contour, and maintaining a soil cover of actively-growing vegetation or plant residues. Simple procedures to minimize losses of P in subsurface runoff include not applying P fertilizers and organic manures to cracking soils while the fissures remain open, and not applying them to soils that are dry and hard or saturated with water.

A further approach to minimizing soil erosion is to replace ploughing with zero-tillage or minimum tillage. The impact of no-till systems on the availability of soil and fertilizer P has been studied extensively in the United States of America and in Canada. Although it was anticipated that the surface soil would become enriched in P in the absence of, or with shallow, cultivation, it seems that fears regarding the possible negative impact of P stratification on the availability of P to plants have been overestimated. The extent to which an improvement in the structure of the surface soil under reduced tillage offsets any negative effects of stratification on available-P distribution warrants investigation.

The intensification of animal production, especially for dairy cows, pigs and poultry, has resulted in large numbers of animals producing more manure than can be used effectively on the land associated with the production unit. Much of the P in such manures is the inorganic P (usually DCP) added to the animal feed. There are several opportunities to improve the efficiency of P use in such animal-farming systems. One method is to improve the digestibility of P in animal feeds by adding the enzyme phytase. Feeds with added phytase need less, or no, inorganic P added as a feed supplement. This will result in a reduction in P being excreted (Steén, 2006). In grazed pasture, improved recycling of P may be achieved through grazing management that achieves a more uniform distribution of animal excreta and, hence, of P returned to the pasture (Gillingham, Syers and Gregg, 1980). Similarly, where manure is collected from housed animals, the manure could be spread more uniformly on arable land and grassland.

Making more effective use of organic manures and biosolids might allow a decrease in P fertilizer use but not an improvement in the efficiency of P fertilizer use. Some of the environmental issues associated with the application of manure may be controlled by limiting the amount of P that can be applied, but it will be necessary to have appropriate methods of soil analysis in order to monitor the level of plant-available P in manure-treated soils. There is evidence from the British Survey of Fertiliser Practice that farmers in the United Kingdom rarely make allowance for the amount of P added in manure when deciding how much P fertilizer to apply (Johnston and Dawson, 2005). Manure and biosolids should be considered as sources of P and other nutrients rather than as wastes for disposal. Any concern of farmers about the short-term availability of P in these organic materials can be minimized if farmers are persuaded to monitor whether the P added maintains the critical value of soil P.

For farming systems supported by an appropriate infrastructure, identifying the critical level of plant-available P for a soil is arguably one of the most effective ways to increase the efficiency of fertilizer P use (Figures 4 and 6). Current evidence suggests that the critical value is independent of the yield achieved in any one year, but when yields are large more P is required to replace the P removed and maintain the critical value. Once this is established, maintaining soils at or very close to the critical value for the soil type and farming system is largely a matter of replacing the P removed in the harvested crop. To check that this is the case, the soil should be analysed for available P every 4 or 5 years. Phosphorus is used very inefficiently when soils are maintained much above the critical value.

There are many parts of the world, especially in developing countries, where the infrastructure and background information required to apply the “critical value” approach for the efficient use of P inputs does not yet exist or is rather poorly developed. Moreover, in many soils, plant-available P levels are often low, sometimes very low, and there is usually a response to added P. In these situations the “critical value” concept has little immediate relevance, and it is necessary to develop appropriate approaches to provide advice on P fertilizer use. To help identify soils that have too little P to produce acceptable yields, an “omission plot” technique has been developed (Chapter 4).

MANAGING PHOSPHORUS SOURCES

Applying P to a soil where there is sufficient readily-plant-available P, such that there is no increase in yield or benefit to crop quality, is an inefficient use of fertilizer or manure and biosolids. When P is required, both the amount applied and the timing of the application is important for improving the efficiency with which the P is used. Therefore, the amount of P applied at any one time should match P uptake in the harvested crop when the soil is at or about the critical soil P level. There are many logistical problems in storing and applying animal manures and biosolids, mainly because of their bulk, but farmers should be encouraged to follow codes of good agricultural practice in using them.

A more efficient use of P fertilizers within fields can be achieved using the tools of precision agriculture. Plant-available P varies within fields for a number of reasons. For example, where P has been applied uniformly for many years but yields have varied within a field, a larger P uptake with the larger yield results in a smaller amount of plant-available P in the soil. Providing that the level of available P in the high-yielding areas is maintained at the critical level, smaller amounts of P can be applied to those areas where yield is consistently less. Using variable P application rates requires relating yield maps to soil analysis data and using computer-controlled fertilizer spreaders guided by the Global Positioning System (GPS) to apply the appropriate amount of fertilizer to different areas within the field.

Any possible effect of the amount of water-soluble phosphate in a fertilizer on the efficiency of P use is not easy to determine. It has been suggested that it could be beneficial to use P fertilizers with less water-soluble P, i.e. a P fertilizer with a lower percentage water solubility than is currently required by, for example, the European Community regulations for percent water-solubility of the phosphate in SSP and TSP. However, achieving this for SSP and TSP by only partially acidulating the PR and leaving an un-reacted rock residue would produce a fertilizer that is unsuitable for use on neutral and calcareous soils. This is because the availability to plants of the P in the un-reacted rock would be very small and using such materials would be using P inefficiently.

Phosphate rock could be used as a source of P for crop production, but its effectiveness depends on its reactivity in the soil. There is abundant evidence that PR is not effective on neutral and calcareous soils; its use is limited to acid soils where it can be very effective (Johnston and Syers, 1998). In addition, Sharpley, Syers and Gregg (1978) have shown that the losses of particulate P in surface runoff can be substantial when a P source with low water-solubility (DCP) is added to grazed pasture on sloping land.

There may be a place for slow-release P fertilizers, e.g. PR on acid soils. One new slow-release product containing water-soluble P is currently being marketed. It consists of di-ammonium phosphate (DAP), mono-ammonium phosphate (MAP), or TSP coated with a high-charge-density polymer, which is claimed to reduce P fixation, resulting in a larger and longer-term plant availability of P. The main use for slow-release P fertilizers would be in situations where P is at risk of

loss by leaching. This would be the case on coarse-textured soils in high-rainfall areas, as illustrated in the Peru and India case studies in Annex 1.

The recovery of nutrients in fertilizers is usually increased when the material is placed near the seed, e.g. by band placement. Benefits from placing added water-soluble P fertilizers depend on the speed of the adsorption and absorption reactions that occur soon after the application of the fertilizer. Generally, placing P fertilizer in a band leaves more of the P readily available after the initial P–soil reactions take place. Placing fertilizer with the seed or in a band close to it improves the recovery of fertilizer P significantly, especially in the year of application (Barrow, 1980; McKenzie and Roberts, 1990).

The introduction of mycorrhizae and P-solubilizing bacteria into soils has been suggested for improving the availability of soil P, but initial enthusiasm for these has waned. Mycorrhizae are important for many plant species when grown in P-deficient soils, but they are much less effective where soil P status is adequate. There has been little success with soil introduction of improved species of mycorrhizae, selected for improved P transfer to the host plant, because of competition from the indigenous population.

INVESTMENT TO OPTIMIZE SOIL PHOSPHORUS STATUS AND AVAILABILITY

Chapter 3 has shown how the yield of crops can be related to the amount of readily-available P and a “critical value” estimated at which the optimal economic yield is achieved. Below the critical value, yield is lost. Above the critical value, there is no justification for applying more P and such applications use P inefficiently. Figure 3 shows how, on the one hand, readily plant-available P is related to P in the soil solution, from which P is taken up by plant roots, and, on the other, to a reserve of less-readily plant-available P. There is now much evidence to indicate that there is reversible transfer of P between these three pools of soil P, and that this transfer can be quite rapid. Phosphorus is accumulated in the readily-available and less-readily-available pools of P from additions of P in fertilizers and organic materials. A key question then relates to the practical and economic constraints to increasing soil P status to the appropriate critical value and maintaining it at or close to that value.

Many different methods have been used to estimate the amount of P in the readily-available pool, and because they each extract a different amount of P, there is no specific quantity of P in this pool. However, the different methods used are quite robust because the amount of P extracted by the reagent used often correlates well with the response of crops to the application of P fertilizer. There is little information on the quantity of P in the less-readily-plant-available soil P pool or on the relation between the amounts of P in both these pools. Sequential extraction of soil P (Chapter 4) shows that the quantity of P in all soil P fractions extracted by the different reagents used usually increases as P accumulates in the soil and decreases as soil P reserves are depleted. However, no clear relationship has yet been shown between the amounts of P extracted by each reagent. The

method is also time-consuming and does not lend itself to routine soil analysis. Therefore, assessing the practical and economic constraints to increasing the soil P status to the critical value will depend on the method of analysis used and the effects of soil type and farming system on the critical value. In addition, the rates of transfer between the pools of P in Figure 3 are not well understood and require further investigation.

In those countries with a long history of P application, and these are usually developed countries, many soils are at or near the critical value. For example, in the United Kingdom, the upper limit for the critical value for most arable crops and grassland is 25 mg kg⁻¹ Olsen P in soil. The Representative Soil Sampling Scheme, which monitors nutrient levels in soils from a representative sample of farms in the United Kingdom, shows that in 1993–95 some 30 percent of soils growing arable crops contained between 15 and 25 mg kg⁻¹ Olsen P, while some 52 percent had more than this value. The current recommendation is to maintain the 15–25 mg kg⁻¹ level of Olsen P by replacing each year the amount of P removed from the field in the harvested crop. To check that this approach is satisfactory, it is further recommended that the soil be sampled every 4 or 5 years to determine whether that Olsen P is being maintained at or close to the desired level. If soils are well below the critical value, it is recommended that in addition to replacing the amount of P removed in the harvested crop, an additional amount of P, usually an extra 20 kg P ha⁻¹, be applied annually until soil P status is satisfactory. Current observations suggest that, at least under conditions in the United Kingdom, where much more than this extra amount of water-soluble P is applied at one time, then there is an unacceptable environmental risk of P loss from soil to water. At current prices, the payback time would also be too long. The approach to building up a low soil P status soil slowly to a satisfactory level is usually economic under farming conditions in the United Kingdom, and it has the very important added advantage that the applied P is used very efficiently when assessed by the balance method (Chapter 4).

In developing countries, much less information is available on the appropriate critical value for soil P for most soils and farming systems. However, given the fact that many of these soils are P-deficient and that a P response to fertilizer addition is usually obtained, advisory efforts should focus on demonstrating to farmers that P application is worthwhile. Such efforts to raise the soil P status can be considered as an investment that will ensure the production of optimal economic yields and a higher use efficiency of added P, but the cost of doing this must be considered.

Work in Indonesia (von Uexkull and Mutert, 1995) on the rehabilitation of anthropic savannah suggests that a high initial P application may result in stable or even increasing yields during subsequent cropping seasons, giving increasing economic returns from a one-time application. However, the economics of such a strategy require a more detailed agronomic and economic evaluation. It is also essential to assess the environmental impact from using such a large single application.

Some of the papers in Johnston and Syers (1998) provide useful examples of ways to improve the yield potential of P-deficient soils in Africa, Asia, Brazil, India and Indonesia. Comparisons between reactive phosphate rock (RPR) and water-soluble forms of P, such as TSP and SP36, invariably show that RPR is as effective as water-soluble forms of P, especially on acid soils. On the latter, it was usually necessary to apply sufficient lime to increase base saturation to about 50 percent and reduce exchangeable Al, especially where water-soluble P forms are used.

A further approach to increasing yields on P-deficient soils would be to place the applied P close to the seed. Traditional methods of adding small amounts of P in the planting holes of hand-planted crops are well documented. Where seeds are planted by drill, placing fertilizer near the seed requires the purchase and maintenance of more expensive equipment than is usually available on farms in developing countries. Often, smaller amounts of placed P can give the same yield as a larger broadcast application (van der Eijk, Janssen and Oenema, 2006). If more of the smaller application of the placed P is taken up by the crop, less will remain in the soil, and, consequently, reserves of plant-available P in soil will accumulate only slowly. However, in terms of P-use efficiency, there may be a trade-off in the comparison of broadcast and placed P. A proportionately larger P uptake from a smaller placed application of P may indicate the same P-use efficiency as when a larger broadcast application of P is applied to a soil in which the P level is at the critical value.

There is scope for a comprehensive review of the available literature and a subsequent research effort on the agronomic and economic effectiveness of the different approaches to increasing crop yields through inputs of P with different strategies on different soils in a range of farming systems in developing countries. Such studies should consider both the agronomic and economic criteria for the strategy of P application.

Chapter 6

Conclusions

There is strong evidence that P added to soils in fertilizers and manures is sorbed reversibly and that it is not irreversibly fixed in soil. This even applies to very acid soils in Brazil and Peru.

Plant roots can take up P accumulated in soil as residues from applications of fertilizers and manures, i.e. animal manures, composts and biosolids, over a period of many years. Thus, P-use efficiency must be measured over an adequate period, i.e. at least a decade.

To measure P-use efficiency, the difference method is inappropriate because it does not consider the residual effect of added P. The balance method provides a more realistic estimate of P-use efficiency, which can be as high as 90 percent in some situations.

Most of the inorganic P added to soils in fertilizers and manures is usually adsorbed initially, but it may become absorbed by diffusive penetration of phosphate ions into soil components. It is considered that this added P is held with a continuum of bonding energies on the surfaces of, or within, soil components, and that this gives rise to the differing extractability of soil P and its differing availability to plants.

The observation that chemical reagents of increasing strength can extract phosphate sequentially from soil provides strong support for the concept that P is held in soil with different bonding energies. Thus, conceptually and for simplicity in terms of characterization, P can be considered to exist in different pools related to the ease of extraction. Experimental evidence, obtained using soils from a range of farming systems, indicates that there is reversible transfer of P between the different pools, and this is supported by the uptake of residual P by plants over many years.

There is a strong relationship between the amount of P in the most readily-extractable P pool in soils and the P that has the greatest availability for plant uptake. “Critical” values for the most readily-available pool have been established for a number of crops grown in different farming systems on a range of soil types.

In order to build up soil P to the critical value, it may be necessary to accept a lower recovery of added P for a number of years. Once the critical level is achieved in many arable cropping systems, the amount of P required to maintain it is often similar to that removed in the crop (i.e. there is a very high P-use efficiency).

Residual P contributes to the readily plant-available pool, but the rate of release may not be sufficient to maintain the critical value required to meet the P requirements of high-yielding cultivars. In such situations, P must be added in order to maintain the critical value to obtain optimal yields.

Accumulating and then maintaining plant-available soil P near the critical value has both financial and environmental implications. In the developed situation, the farmer should apply sufficient P to first achieve and then maintain the critical value. Maintaining soils at or close to the critical value for that soil ensures economically optimal yields and the most efficient use of P and other nutrient inputs, particularly N. It also diminishes the risk of unacceptable P transfers to surface waters. In developing situations, the critical level concept is less useful because most soils have low available-P levels and usually respond to P fertilizer additions.

Strategies for improving the efficiency of use of soil and fertilizer P are available. They include: modifying surface soil properties; managing surface soil and its P content; managing P sources; and optimizing P use through the use of economically appropriate rates and timing. However, because P-use efficiency is often already high in many situations, further substantial increases will not be easy to achieve. The extent to which any of the above strategies are pursued will depend on the relative costs and benefits involved.

The major conclusion arising from this report is that, on many soils, added P is not irreversibly fixed in forms that are unavailable to plants. Consequently, the efficiency of use of P added in fertilizers is often high (up to 90 percent) when considered over an adequate time scale and when evaluated using the balance method. The long-term recovery of P added in fertilizers and manures should be considered as part of the efficiency of P use from these sources, and this has not been recognized adequately in the past.

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Annex 1

Case studies

INTRODUCTION

The following case studies from a range of agro-ecological zones present and compare P recovery and P-use efficiency in the agricultural systems practised in these different zones.

Data from experiments in all these case studies show that P recovery as determined by the difference method is frequently much larger than 25 percent, a value often thought to be the upper limit for most field-grown crops. However, the more appropriate balance method reveals that P recovery often ranges from 50 to 90 percent. More importantly, the results in a small number of the experiments in these case studies show that crops can continue to recover P from residues of previously-applied P fertilizers over long periods. These results indicate that P is not irreversibly fixed in soil in forms that are unavailable to plants.

Initial discussion between the five joint sponsors (FAO; The Fertilizer Institute [TFI]; the International Fertilizer Industry Association [IFA]; the International Plant Nutrition Institute [IPNI]; and the World Phosphate Institute [IMPHOS]) produced a list of ten possible candidates for case studies. However, it has proved difficult to find information for some of these agricultural systems. Only in very few has it been possible to obtain data for experiments in which, after a number of years of applying P, applications ceased and residual effects were measured. In some cases, information for the countries initially suggested was not available, but where appropriate data were found for similar environmental conditions in other countries, these have been used. In addition, examples from two countries that were not on the original list have been provided. One of these case studies is from China, and in this case the data are not presented by agro- ecological zones but as a data set for China as a whole. The other additional case study presents some sets of data from experiments in the United States of America.

SEMI-ARID ARABLE CROPS AND PASTURE IN THE CERRADO REGION OF BRAZIL

The large increase in agricultural production in the Cerrado Region of Brazil is a success story of modern agriculture. In this region of about 200 million ha, substantial areas of previously unproductive land have been brought into production to the extent that in 2001/02 the region was already accounting for 44 percent of the maize and 52 percent of the soybean production of the whole country (de Sousa and Lobato, 2003). Pasture for beef production has also become

a major cropping system, and some 55 percent of all beef produced in Brazil in 2001/02 originated in the Cerrado Region.

During the early stages of agricultural development in the Cerrado Region, it was recognized that the major limiting factors to crop production were acute soil acidity and the very low P status of the soils (Goedert and Lobato, 1984). This led to a major research effort to find cost-effective ways of correcting soil acidity and P deficiency (Goedert, 1983). This research included investigation of the extent to which acidity had to be corrected and evaluation of the most appropriate form of P fertilizer, its rate and frequency of application, as well as the method of placement, and residual effects of the added P fertilizer. Most of these investigations were conducted by the Cerrado Center, near Brasilia, on a Ferralsol (Latossolo Vermelho Amarelo) (W.J. Goedert, personal communication, 2006). The results of these experiments have been published in several papers (e.g. Goedert and Lobato, 1980, 1984; Goedert *et al.*, 1986a, 1986b). The Cerrado P work has recently been reviewed and summarized by de Sousa and Lobato (2003).

Having recognized that P was deficient, one of the driving forces for the Cerrado P research programme was to determine the most technically effective and economically efficient way of correcting P deficiency and soil acidity. Brazil has several phosphate rock (PR) sources, and the prospect of using these materials on acid soils was an attractive one. However, Goedert and Lobato (1984) and Goedert *et al.* (1986a) soon showed that the native PR sources usually had a low solubility and a low agronomic efficiency relative to triple superphosphate (TSP). In the short term (over four years), the efficiency of local PRs was about half that of TSP.

Many experimental results have been reported for P responses and the efficiency of P use, including the residual effects of P added to Cerrado soils under different cropping systems. Invariably, the results depend on the crop grown, and the rate and method of applying P and correcting soil acidity; generally, the efficiency of P use is improved by correcting acidity to a base saturation of about 50 percent. When the clay Ferralsol was first brought into cultivation, the recovery of P from a single application of 105 kg P ha⁻¹ ranged from 36 to 39 percent for TSP and Gafsa PR, respectively, during the first five years of cropping with soybean (de Sousa and Lobato, 2003).

Table A1.1 shows the recovery of added P by maize grown continuously for 13 years. Four rates of P were incorporated into the surface soil in the first year and the total offtake of P over the subsequent 13 years was measured. Recovery of the added P decreased as the amount of fertilizer P increased. Two treatments received smaller amounts of P, 35 and 70 kg P ha⁻¹ on four occasions during the 13 years to give the same total amount of P as the treatments that received a total of 140 and 280 kg P ha⁻¹ at the start of the experiment. Dividing the P in this way gave only a very small increase in total grain yield and percent recovery of the applied P.

A more complex experiment compared two cropping systems over a 17-year period following the incorporation of four amounts of P as SSP into the surface soil at the start of the experiment (Table A1.2). Where only arable crops were grown, percent recovery of the added P was independent of the amount added and ranged from 34 to 38 percent. In the other cropping system, four years of soybean were followed by nine years of *Brachiaria humidicola* (a deep rooted, high yielding tropical grass), which in turn was followed by two cycles of maize and soybean grown in rotation. Including the nine years of pasture in the 17 years of cropping increased considerably the recovery of added P (range 69 to 52 percent). As observed in the previous experiment, percent recovery of the added P decreased as the amount applied increased. When the experiment was continued for a further five years, the recovery of P by *B. Humidicola* from the single addition of 44 kg P ha⁻¹ as SSP increased to 85 percent (D.M.G. de Sousa, personal communication, 2006).

TABLE A1.1

Total yield of grain from 13 crops of maize and P recovered in the grain following a single application of SSP to a clay Ferralsol

Method of application		Total P applied	Total grain production	P recovered
Incorporated into the surface soil	Applied to the surface soil			
	(kg ha ⁻¹ P)		(tonnes ha ⁻¹)	(%)
70	0	70	17.3	62
140	0	140	28.1	49
280	0	280	43.8	45
560	0	560	66.1	35
0	35(x4)	140	31.3	55
0	70(x4)	280	46.0	47
140	35(x4)	280	45.7	47

Source: Adapted from de Sousa and Lobato (2003).

TABLE A1.2

Recovery of P over a 17-year period with two contrasting cropping systems following one application of SSP at the first cultivation

P applied	P recovered by	
	Annual arable crops ¹	Annual arable crops and pasture ²
(kg ha ⁻¹ P)		(%)
44	38	69
88	37	67
176	34	57
352	37	52

¹ Soybean for 10 years followed by maize for 1 year, followed by 3 two-year cycles of maize and soybean grown in rotation.

² Soybean for 4 years followed by *Brachiaria humidicola* for 9 years, followed by 2 two-year cycles of maize and soybean grown in rotation.

Source: Adapted from de Sousa *et al.* (1997).

These results show that good recoveries of added P are achievable on what was considered to be a P-deficient virgin soil with a large “P-fixation” capacity, provided that soil acidity is decreased by liming to 50–60 percent of base saturation, which increases soil pH to between 6.0 and 6.5 and reduces exchangeable aluminium to essentially zero. The results show that the clay Ferralsols (Latosols) of the Cerrado Region of Brazil do not fix large amounts of added P in forms that are unavailable for crop uptake over time, as was previously thought.

SEMI-ARID WHEAT PRODUCTION IN WESTERN CANADA

Almost 80 percent of Canada’s arable land is in the Prairie Provinces of Alberta, Saskatchewan and Manitoba in the west of the country. The Prairies represent a semi-arid agro-ecosystem with long, cold winters, hot summers, and a short growing season, usually 100–120 days. Dryland cereal production (mainly hard, red spring wheat) is the predominant crop in the Prairies, which produce over 90 percent of Canadian wheat, but oilseeds and pulses are becoming important components of crop rotations. In the more arid parts of the Prairies (e.g. southwestern Saskatchewan and parts of southern Alberta), a significant fraction of the land is summer fallowed, i.e. the land is left bare over an entire growing season in order to conserve moisture. In the more humid areas, mixed farming with grain and livestock production is common.

Native prairie grasslands were first cultivated in the early 1900s. For several decades, the large amounts of P in the soil sustained crop production. Much of this P was probably derived from the mineralization of organic P, as suggested by the much lower organic P contents in cultivated soils compared with native grasslands (Tiessen, Stewart and Moir, 1983).

Little commercial fertilizer was used until 1927, when the benefits of seed-placed superphosphate for wheat production were demonstrated (Mitchell, 1932). Since then, fertilizer use has increased to the point where the P inputs now more or less balance the P offtakes in crops. In the period 1984–89, for example, crop removals were 221 250 tonnes P compared with fertilizer inputs of 183 720 tonnes P (Doyle and Cowell, 1993).

Much laboratory and field research has been conducted on the behaviour of soil and fertilizer P in prairie soils (Sadler and Stewart, 1974). Important characteristics of these soils in relation to the reactions of fertilizer P are their low hydrous-metal oxide content (and thus low P-sorption capacity), relatively high pH and, commonly, the presence of free CaCO_3 .

One of the first measurements of fertilizer P-use efficiency was in an experiment at Floral, Saskatchewan; only 10–25 percent of a ^{32}P -labelled fertilizer was recovered by the crop in the year of application (Spinks and Barber, 1947). The realization that the performance of fertilizer P could not be assessed only on the basis of the uptake by a first or second crop stimulated research to determine the agronomic value of P fertilizer residues.

Read *et al.* (1973) examined the residual value of a single, large application of superphosphate that supplied 100, 200 or 400 kg P ha^{-1} on four Chernozems

(chernozemic soils, pH 6.7–7.4) from Manitoba and Saskatchewan. Three years after applying the P, surface soil (0–15 cm) was collected from the plots, and P uptake by barley and oats grown alternately in the greenhouse was measured. The average recovery of the applied P by 19 successive crops was 87, 81 and 70 percent of the 100, 200 and 400 kg P ha⁻¹ rates, respectively. Although these results showed that a large recovery of applied P is possible by exhaustive greenhouse cropping, the recovery of applied P in field experiments on prairie soils has been much smaller. For example, cumulative P uptake over eight cropping seasons following the application of 100 kg P ha⁻¹ to two Manitoba soils was only about 35 kg P ha⁻¹ larger than that from the control soils receiving no P (Spratt *et al.*, 1980). However, extrapolation of the P uptake versus years after application relationship suggested that continued cropping would result in recovery of substantial additional quantities of the applied P. Based on evidence from field studies and detailed laboratory work, Doyle and Cowell (1993) concluded that: “most applied P will eventually be recovered by crops on the Canadian prairies”. Similarly, Sadler and Stewart (1974) concluded from a comprehensive review of the literature that: “there is sufficient evidence to show conclusively that a considerable portion of fertilizer P (approximately 75 percent) not used by the first crop immediately following application, remains in a chemical form which is available to succeeding crops, provided that the rooting distribution of the ensuing crop and critical growth factors permit it to be utilised.”

A significant advance since the Sadler and Stewart review has been the development of an improved methodology for fractionating soil P into components that differ in bio-availability (Hedley, Stewart and Chauhan, 1982). Theoretically, this sequential fractionation procedure removes progressively less plant-available P with each subsequent extraction. It also provides information on the organic P components of soil. Using the soil P fractionation procedure developed by Hedley, Stewart and Chauhan (1982) has provided new insights into the nature of residual P and its transformations with time in prairie soils (Wager, Stewart and Moir, 1986; McKenzie *et al.*, 1992). For example, several years after one large, broadcast application of P, about half of the P residue in two soils was still in plant-available forms, i.e. extractable with anion-exchange resin followed by 0.5 M NaHCO₃ (Wager, Stewart and Moir, 1986). In one of the two soils, about one-third of the P residues were in an acid-extractable form, considered to be Ca-phosphate compounds with an anticipated low bio-availability.

In a long-term experiment on a Chernozem (Dark Brown Chernozem, Typic Haploboroll) at Lethbridge, Alberta, after 14 years of adding P, all inorganic P fractions in the soil had been increased. The largest increases were in the most labile pools of inorganic P, i.e. resin-extractable, bicarbonate-extractable and NaOH-extractable fractions (McKenzie *et al.*, 1992). Only a small portion of the P residues was found in the more inert HCl-P fraction, and there was an increase in the labile organic P fractions only where both N and P had been applied.

Particularly useful information on P-use efficiency is provided by a crop rotation experiment started in 1967 at the Agriculture Canada Experimental Farm

at Swift Current in southern Saskatchewan (Selles, Campbell and Zenter, 1995). This study differs from other long-term experiments in western Canada in that crop P removals are available for the whole period of the experiment, Olsen P was monitored annually, and the nature of the accumulated fertilizer P residues was established using the sequential extraction procedure developed by Hedley, Stewart and Chauhan (1982).

Different spring wheat-based rotations and fertility treatments, typical of those used in farming in the region, were established on a Chernozem (medium-textured loam soil, Orthic Brown Chernozem, Aridic Haploboroll) with a pH value of about 6.8. The rotations compared different frequencies of summer fallow (i.e. treatments with no fallow, fallow once in three years, and fallow every other year) and included other crops (flax, rye, winter wheat, and lentils), grown in rotation. Apart from a fallow-wheat-wheat (F-W-W) rotation with no added P, all other rotations received P at rates currently recommended for the cereal crops grown in the region. Mono-ammonium phosphate (MAP) was seed-placed and rates of application were essentially constant over the course of the study. The amount of P applied for each crop was only 9.6 kg P ha⁻¹, because the yield potential of crops is small in this dry location (mean annual precipitation of about 350 mm), and was much less than amounts used in more humid areas. The only removal of P was in grain, as straw was returned to the soil in all rotations. Selles, Campbell and Zenter (1995) considered that there might have been some leaching of P below the top 15 cm, but wind erosion was well controlled during the experiment and loss of particle-bound P is likely to have been minimal.

The P balance for the first 24 years of the experiment shows that P inputs and removals varied according to the number of crops in the rotation and in all rotations, but inputs exceeded removals where no P was added (Table A1.3). A feature of this experiment was the very small yield response to added P when the yields in the two F-W-W rotations are compared. This resulted in very similar amounts of P being removed in these two rotations in the absence and presence of added P, respectively, values not dissimilar to P offtake in grain in other fallow-containing rotations. Estimating P recovery by the balance method gives an average of 56 percent. The difference method can strictly only be used for the F-W-W rotations, and efficiency estimated in this way is only 5 percent.

There was a good linear relationship ($R^2 = 0.89$; $P = 0.001$) between the amount of P removed in the grain and that applied when the no P treatment is excluded: $P \text{ removed} = 20 + 0.44 P \text{ applied}$. The regression suggests that in the absence of applied P, the soil would be expected to supply about 20 kg P ha⁻¹ rather than the 84 kg ha⁻¹ actually measured. This suggests that when crops do not receive P, they may be more efficient in acquiring soil P than those that do receive P. This could be because of: (i) more effective plant-mycorrhizal associations in P-deficient soils; (ii) greater allocation of carbohydrate from photosynthesis to grain when P is limiting; (iii) uptake of P from deeper in the soil profile when P in the surface soil is limited; and (iv) the ability of the plant to change conditions in the rhizosphere

TABLE A1.3

Phosphorus balance for crop rotations at Swift Current over 24 years, 1967-1990

Rotation (fertilizer treatment in brackets)	P applied	Total grain produced	P removed in grain	P balance	Percent efficiency estimated by the balance method
	(kg ha ⁻¹)	(tonnes ha ⁻¹)	(kg ha ⁻¹)	(kg ha ⁻¹)	(%)
F–W (N+P)	114	22,6	74	40	65
F–W–W (N+P)	152	26,3	92	60	60
F–W–W (N only)	0	24,4	84	-84	
F–Flax–W (N+P)	134	16,9	64	69	48
F–Rye–W/ F–WW–WW (N+P)	137	26,2	85	53	62
Cont W (N+P)	228	33,0	126	102	55
Cont W (P only)	228	28,9	113	113	50
W–Lent (N+P)	225	30,0	116	107	52

Note: F = fallow; W = spring wheat; WW = winter wheat; Lent = grain lentil; Cont = continuous.

Source: Adapted from Selles, Campbell and Zenter (1995).

in response to low levels of available P in the soil. Whatever the reason, the result suggests that the difference method may not be the most appropriate method for assessing the efficiency of P use in the soil–crop system.

The increases in the yields of cereals grown in these rotations were small with rates of P normally applied in this part of the Prairies. The small response to added P appears to be related to the level of Olsen P, on average, about 11 mg kg⁻¹ in the top 15 cm of soil, in all rotations (Campbell *et al.*, 1984). This value would be classified as medium for these soils (Leitch, McGill and Chauh, 1980). On the soil without added P, Olsen P in both topsoils and subsoils changed little throughout the 24 years (Selles, Campbell and Zenter, 1995). This provides further evidence of the reversible transfer of P between the different pools or the direct availability to plants of P held in pools other than that measured by the Olsen method.

Phosphorus fractions were determined in the top 15 cm soil under the continuous wheat and F–W–W rotations given N and P, and the F–W–W rotation given only N. The results show that fertilizer P residues accumulated mostly in forms that are considered to be plant-available, i.e. resin inorganic P (Pi) and bicarbonate-extractable Pi (Table A1.4). Any residue of the small amount of fertilizer P, which was applied only when a crop was to be grown, appears not to have entered the recalcitrant HCl-soluble pool. In this experiment, P fertilization did not increase organic P significantly.

The plots in the F–W–W rotation, with both N and P applications, received a total of 152 kg P ha⁻¹ over the 24 years of the experiment and the positive P balance was about 60 kg ha⁻¹ (Table A1.3). This equals the 59 kg P ha⁻¹ increase in the more labile resin-extractable and bicarbonate-extractable P fractions (Table A1.4). On

the zero-P treatment of the F–W–W rotation, there was no decline in Olsen P level during the 24 years. If the amount of P in the different soil P fractions with this treatment in 1967 were known, it would be possible to see which P fractions had been depleted to supply the P removed in the grain.

For a cropping system in which the P is at a steady state, P offtake as a percentage of P input can be taken as a measure of P-use efficiency. This approach corresponds to the Karlovsky method for determining P maintenance requirements of grazed pasture systems (Karlovsky, 1982). The maintenance requirement (P_m) to compensate for losses in crop products under steady-state conditions (i.e. stable levels of available P in the soil) is calculated as: $P_m = P \text{ offtake} / P \text{ utilization}$. It follows that P utilization (or P-use efficiency) is $P \text{ offtake} / P_m$, and that values approaching 1 (or 100 percent) indicate a large degree of efficiency. In this

TABLE A1.4

Phosphorus fractions in soil, 0-15 cm, after 24 years growing crops in three crop rotations at Swift Current

P fractions ¹	Cont W N + P	F–W–W N + P	F–W–W N only	LSD P = 0.05
	(kg P ha ⁻¹)			
Resin Pi	81	84	44	5
Microbial P	19	21	16	2
Bicarbonate Po	55	74	69	NS
Bicarbonate Pi	40	43	24	4
NaOH Po	196	210	197	NS
NaOH Pi	101	112	86	11
HCl Pi	279	289	269	NS
Σ Po fractions	270	305	282	NS
Σ Pi fractions	501	528	423	52
Total P	868	943	810	119

¹ Based on the fractionation procedure developed by Hedley, Stewart and Chauhan (1982).

Source: Adapted from Selles, Campbell and Zenter (1995).

TABLE A1.5

Trends in Olsen P at Swift Current over 24 years, 1967-1990

Rotation (fertilizer treatment in brackets)	Intercept (kg P ha ⁻¹)	Slope (kg P ha ⁻¹ year ⁻¹)	R ²
F–W (N+P)	20.5	1.00	0.76
F–W–W (N+P)	19.0	1.06	0.87
F–W–W (N only)	18.1	0.10	0.08
F–Flax–W (N+P)	18.9	1.44	0.84
F–Rye–W/F–WW–WW (N + P)	17.9	1.31	0.62
Cont W (N + P)	20.6	1.17	0.58
Cont W (P only)	15.5	1.66	0.75
W–Lent (N + P)	15.3	1.66	0.83

Note: Trends were determined by linear regression of Olsen P on time (years).

Source: Adapted from Selles, Campbell and Zenter, 1995.

experiment, the fertilizer rates used exceeded maintenance requirements, as shown by the increasing trend in Olsen P during the experiment (Table A1.5). In this situation, P-use efficiency will be underestimated if calculated as P offtake as a proportion of P addition. Even so, fertilizer-use efficiency values estimated in this way averaged 56 percent (Table A1.3). These results again suggest a high efficiency of fertilizer P utilization in the cropping systems used on the Canadian Prairies and they lend support to conclusion by Sadler and Stewart (1974) that, given sufficient time, crops recover some three-quarters of applied P.

HUMID TEMPERATE LEGUME-BASED PASTURE IN NEW ZEALAND

Pastoral farming is the dominant form of agriculture in much of New Zealand. Most New Zealand soils were low in native P, but regular additions of superphosphate (SP) since the early 1900s have greatly improved the P status of most agricultural soils. It is common in fields that have received P fertilizer for 50–60 years for total P in the topsoil to have increased by 600–1 000 mg P kg⁻¹ (Moir *et al.*, 1997).

The longest ongoing P trial in New Zealand is at Winchmore Research Station on the Canterbury Plains in the South Island (Condrón and Goh, 1989). This trial consists of three rates of SP (0, 188 and 376 kg ha⁻¹) applied each year (in July, i.e. winter) since 1952 to a border-dyke irrigated sheep pasture on a stony silt loam with a low P-retention capacity. An application of 188 kg ha⁻¹ of SP (17 kg P ha⁻¹) is regarded as the maintenance application for irrigated sheep pastures in the area. Table A1.6 shows the annual P balance for the three rates of SP.

The application of P has increased average annual pasture dry matter (DM) production. This has enabled stocking rates to be increased in line with pasture production. Where SP is applied at 188 and 376 kg ha⁻¹, annual P uptake in the herbage has increased by about 20 and 37 kg P ha⁻¹, respectively. However, most of the P in the herbage consumed by the sheep is returned to the plots in excreta. The amount of P removed in animal products is small. The only losses are in wool (0.01 kg P per animal) and the replacement of culled animals (0.05 kg per animal).

TABLE A1.6

Annual P balance for the Winchmore grazed pasture experiment, SP applied at three rates each year

	Control, SP at 0 kg ha ⁻¹	SP at 188 kg ha ⁻¹	SP at 376 kg ha ⁻¹
P added (kg ha ⁻¹)	0	17	34
DM production (tonnes ha ⁻¹)	3.7	9.1	10.7
Herbage P content (%)	0.22	0.32	0.42
P uptake by herbage (kg P ha ⁻¹)	8	29	45
Stocking rate (ewes ha ⁻¹)	8	19	22
P removal in animal products (kg ha ⁻¹)*	0.5	1.1	1.3
P balance (kg P ha ⁻¹)	-0.5	+16	+33

* Assuming P removals in wool and body tissue of 0.06 kg P/animal.

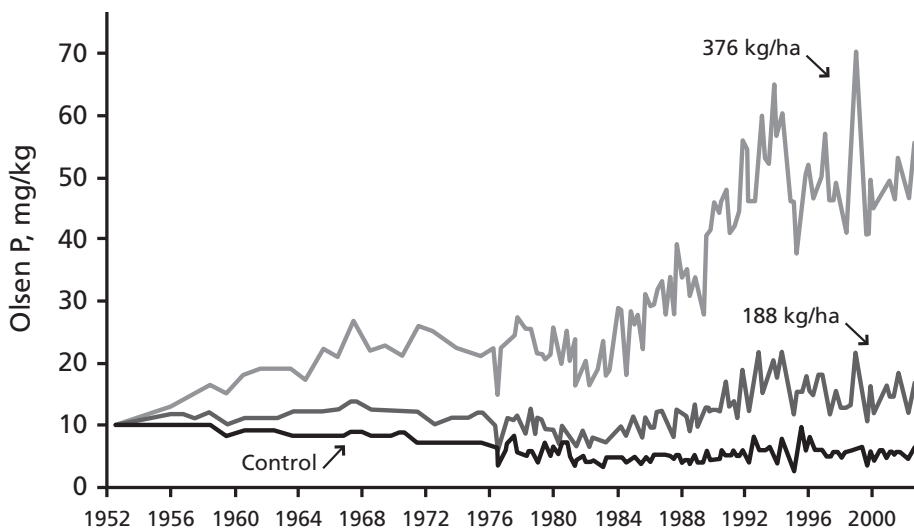
Source: Adapted from Williams and Haynes (1992).

Where SP is applied at 188 and 376 kg ha⁻¹, there is a large annual P surplus. Part of this surplus P (estimated to be 4–5 kg ha⁻¹) is transferred in dung to sheep camp areas, resulting in some inefficiency in P recycling and excessively large amounts of P in the soil in the camp areas. Although the P surpluses are large, it is only with the larger amount of SP that there has been a large increase in Olsen P (Figure A1.1).

The annual P surplus with both rates of SP has resulted in large increases in total soil P relative to the control but these increases only account for about 55 percent of the added P (Table A1.7).

Phosphorus offtake in animal products accounts for a further 6–9 percent of the applied P, leaving nearly 40 percent of the applied P still unaccounted for. Part of this missing P may have been transferred to the borders of the plots where sheep tend to “camp” and deposit a disproportionately large amount of dung. For the 0, 188 and 376 kg ha⁻¹ of applied SP, these transfers may amount to 1.5, 3.7 and 5.6 kg P ha⁻¹ annually (Nguyen and Goh, 1992). However, they are not sufficient to account for all of the missing P. Consequently, it has been concluded that significant quantities of P have been removed from the plots in surface runoff (Williams and Haynes, 1992). The plots are flood irrigated, and large losses of P

FIGURE A1.1
Trends in Olsen P (0–7.5 cm depth) in the Winchmore grazed pasture experiment, as influenced by the P balance when three amounts of SP were applied each year



may have occurred in surface runoff as dissolved P in solution and as P bound to eroded soil and dung particles with this particular irrigation system (McDowell, Monaghan and Wheeler, 2005). Because of P losses in surface runoff and transfers of P in dung to plot borders, P is not recycled efficiently in this experiment. Consequently, the amount of P required for maintenance (about 17 kg P ha⁻¹) is large in relation to the amount of P removed in animal products (about 1 kg P ha⁻¹).

However, it can be demonstrated using the approach developed by Karlovsky (1981, 1982) that P-utilization efficiency by the pasture is relatively large, about 64 percent where SP is applied at 188 kg ha⁻¹. At this rate of application, Olsen P has changed little, i.e. the situation approximates to a steady state. Annual P uptake in the herbage is 29 kg ha⁻¹ and the P inputs are 45 kg ha⁻¹. This input consists of 17 kg P ha⁻¹ in fertilizer and 28 kg ha⁻¹ in excreta and P in herbage that has not been eaten. If it is assumed that all this 28 kg ha⁻¹ contributes to pasture P supply, then P-utilization efficiency is $29/45 \times 100 = 64$ percent. In this example, P-utilization efficiency would be larger if the P supply terms were adjusted downwards to allow for less input in dung, because of its transfer to the plot borders, and P losses from the plots in surface runoff.

Leaving aside the issue of P loss from the plots in surface runoff, the Winchmore P balance is not dissimilar to that for many sheep and beef farms in New Zealand. Phosphorus removals in animal products are 1–4 kg ha⁻¹ but maintenance applications of 15–20 kg ha⁻¹ are normal, creating an annual surplus of 12–15 kg P ha⁻¹. Reducing the P surplus would require management practices that achieve a more uniform spatial distribution of excreta and, thus, the P it

TABLE A1.7

Changes in total soil P and P removal in animal products due to annual SP applications from 1952 to 1987

	Control	SP at 188 kg ha ⁻¹	SP at 376 kg ha ⁻¹
P added (kg ha ⁻¹)	0	17	34
Total P added in 35 years	0	595	1 190
Total soil P, 0–30 cm (kg ha ⁻¹)	2 205	2 533	2 869
Δ total soil P due to fertilizer application (kg ha ⁻¹)	0	328	664
Recovery of applied P in soil (%)	n/a	54	54
Δ P removal in animal products in 35 years due to fertilizer application (kg ha ⁻¹)	n/a	48	53
Fertilizer P accounted for in soil and product offtake (%)	n/a	63	60

Sources: Adapted from Nguyen and Goh (1992) and Williams and Haynes (1992).

contains. In practice, spatial variation in the return of dung is difficult to avoid in grazed pastures, and where P fertilizer is applied uniformly it will inevitably be spread over areas with and without dung enrichment. In systems where herbage is cut and carried to livestock, it is possible to provide good facilities to collect and store manure and then spread it uniformly with appropriate equipment. In such systems, more efficient recycling of P can be achieved and, in theory, it should be possible to narrow the gap between P inputs and outputs.

HUMID TEMPERATE NITROGEN-BASED GRASSLAND IN THE UNITED KINGDOM

Humid temperate grassland in the United Kingdom can be divided into two categories, permanent and temporary grassland. Permanent grassland has not been ploughed for many years, sometimes hundreds of years. Frequently, such grassland is managed extensively and is used for grazing cattle and sheep. Temporary grassland is usually classified as grassland that is sown and lasts for up to seven years before it is ploughed and re-sown or followed by arable crops. Such grassland is often sown with a single species, occasionally two species. Managed intensively and given large amounts of N fertilizer, yields can be large but are often limited by rainfall in the United Kingdom. To maintain high yields, adequate amounts of all nutrients, especially P, potassium (K), and magnesium (Mg) as well as N, are required.

Both types of grassland have been used at Rothamsted to evaluate the effects of reserves of P and K accumulated in soil from residues of fertilizers and manures.

Intensively managed temporary grassland

The experiment discussed here lasted from 1958 to 1969 and was on the site of the Agdell experiment. Started in 1848 by Lawes and Gilbert, the Agdell experiment initially had six large plots, 1 to 6, comparing two arable cropping rotations. One was the traditional Norfolk four-course rotation of turnips, spring barley, clover or beans, and winter wheat (the “clover rotation”) on plots 2, 4 and 6. In the other rotation, a one-year fallow replaced the one-year leguminous crop (the “fallow rotation”) on plots 1, 3 and 5. There were three fertilizer treatments, NPK (plots 1 and 2), PK (plots 3 and 4), and a control (plots 5 and 6). In contrast to the other classical experiments at Rothamsted (i.e. the experiments started by Lawes and Gilbert between 1843 and 1856) in which the plots received the same fertilizers and manures annually, fertilizers were applied only once every four years to the turnip crop in the Agdell experiment. This was about the frequency of manure addition to arable crops grown on farms at that time. Lawes and Gilbert (1894) gave yields and nutrient uptakes in the early years of the experiment, and Warren (1958) described the experiment up to 1957 and gave more detailed soil analytical data.

Nitrogen was applied as a mixture of ammonium salts and rape cake that supplied 160 kg ha⁻¹ total N, and this acidified the soil. Acidity was so severe by the 1940s that the yield of turnips with NPK was less than that without fertilizer.

For this reason, and because by the late 1940s the cropping and manuring were no longer relevant to current farming practice, the rotation experiment ended in 1951. Starting in 1954, soil acidity was corrected by applying different amounts of chalk to plots 1 and 2 and parts of plots 3 and 4. Subsequently more chalk was applied in 1959 and 1967. No P was applied between 1952 and 1958. The plots were fallowed (i.e. no crop was grown) in 1952; barley without N and barley and spring wheat with N were grown in 1953, 1954 and 1955, respectively. Cereal yields were small because soil acidity was not fully corrected. The crops in 1956 and 1957 were beans (*Vicia faba*) without N, and potatoes with N, respectively. The P content of both crops was strongly correlated with Olsen P in the top 15 cm of soil in 1953, and it was decided to investigate the value of the P residues from the past fertilizer applications in more detail.

In 1958, each of the original six plots was divided and one-half was sown to grass given 100 kg N ha⁻¹ for each cut (harvest), usually three or four per year depending on the amount of rainfall. During the first six years, 1958–1963, ryegrass was grown in 1958–59 followed by cocksfoot in 1960–63. Much of the cocksfoot was killed in the severe winter of 1962/63, and only one cut was taken in 1963 before the grass was killed with paraquat and the land ploughed in autumn ready for re-sowing in the following spring.

In spring 1964, it was decided to divide each of the six grass plots into eight subplots. Four were to test P with adequate K, and four were to test K with adequate P. On each of the original six plots, the four P subplots tested no new P and P added at 220, 440 and 880 kg P ha⁻¹. These large amounts of P were intended to establish three levels of Olsen P, all larger than the initial value, on each of the six main plots. Thus, the no-P subplot continued to evaluate the P reserves accumulated between 1848 and 1951 and compare the yields obtained with those given by a new application of P. On subplots with fresh P, each year the P removed in the harvested grass was replaced to maintain Olsen P.

Johnston and Penny (1972) presented the P balance (P applied minus P removed) for each of the six plots in the original experiment, and the total P and Olsen P in the top 23 cm of soil (Table 1.8). Olsen P ranged from 2–3 mg kg⁻¹ in soils that had not received P since 1848, to 6–20 mg kg⁻¹ in soils to which P had been applied. Plots 2 and 4, clover rotation plots, had less Olsen P than the corresponding fallow rotation plots because P had been removed in the legumes grown on these plots.

In the first six years, the average annual yield of grass DM was 3.6 tonnes ha⁻¹ on the plots without P since 1848 and the accumulated P residues approximately doubled yield (Table A1.8). On average, the annual P offtake from the soil without P since 1848 was 4.4 kg P ha⁻¹, while from the plots with residues the grass removed 10.3 to 15.2 kg P ha⁻¹. Over the six-year period, the recovery of the P residues estimated to be in the top 23 cm of soil ranged from 7 to 14 percent.

In the second six-year period, 1964–69, the addition of K as well as N ensured that these nutrients would not limit yield. Moreover, the addition of fresh P to three of each group of four subplots allowed the yields given by the residues to be

TABLE A1.8

Recovery of P from residues accumulated between 1848 and 1951 by intensively-managed grass, the Agdell experiment, Rothamsted, 1958–1969

	Plot number, treatment and rotation*, 1848–1951					
	1	2	3	4	5	6
	NPK	NPK	PK	PK	None	None
	f	c	f	c	f	c
P added (kg ha ⁻¹), 1848–1951	1 545	1 545	1 000	1 000	0	0
P removed (kg ha ⁻¹), 1848–1957	760	915	560	780	-325	-360
P balance (kg ha ⁻¹)	785	630	440	220	-325	-360
Total P in 0–23 cm soil in 1958	1 920	1 850	1 700	1 610	1 380	1 390
First period, 1958–1963						
Olsen P (mg kg ⁻¹), 1958	20	14	17	6	3	2
Yield grass dry matter (tonnes ha ⁻¹ year ⁻¹)	7.81	7.14	6.93	6.58	4.08	3.22
P removed by the grass (kg ha ⁻¹)						
Annual average	15.2	13.2	12.5	10.3	5	3.8
Total in 6 years	91	79	76	62	30	23
% recovery in 6 years of the P residues present in 1958 by the difference method	8	9	10	18		
Second period, 1964–69 without addition of fresh P						
Olsen P (mg kg ⁻¹) in 1967	11	7	8	4	4	4
Yield grass dry matter (tonnes ha ⁻¹ year ⁻¹)	8.04	6.64	6.10	5.10	4.18	3.09
P removed by the grass (kg ha ⁻¹)						
Annual average	17.0	11.3	11.1	8.0	6.3	3.6
Total in 6 years	102	68	66	48	38	22
% recovery in 6 years of the P residues present in 1964 by the difference method	9	8	7	14		
First and second periods, 1958–1969 without addition of fresh P						
P removed in 12 years (kg ha ⁻¹)	193	147	142	110	68	45
% recovery in 12 years of the P residues present in 1958 by the difference method	16	16	17	30		
Second period, 1964–69 with addition of fresh P						
Olsen P (mg kg ⁻¹) in 1967	11	7	8	4	4	4
Yield grass dry matter (tonnes ha ⁻¹ year ⁻¹)						
Without fresh P	8.04	6.64	6.10	5.10	4.18	3.09
With fresh P	8.96	8.67	8.38	8.27	7.81	7.88
P removed by the grass (kg ha ⁻¹)						
Without fresh P	17.0	11.3	11.1	8.0	6.3	3.6
With fresh P	27.5	23.1	24.5	20.3	18.4	19.4
Extra P removed by grass where fresh P was added	10.5	11.8	13.4	12.3	12.1	15.8
% P-use efficiency of the P added in 1964						
By the difference method	5	9	8	8		
By the balance method	12	10	11	9		

* From 1848 to 1951, the fertilizer treatments were applied to two four-course rotations that differed in the third year: in one, the plots were fallowed (f); in the other, clover was grown (c).

Source: Adapted from Johnston and Penny (1972).

compared with those where P was not limiting. By 1967, the Olsen P values in soils with residues but without fresh P were about half what they had been in 1958, but on soils without residues they had changed little. On the soils without residues, the P taken up by the grass had come from reserves that were not measured by the Olsen method. On the soils with residues, the amount of P removed in the harvested grass was larger than the decline in Olsen P in terms of kilograms per hectare. This supports the concept of reversible transfer of P between the different soil P pools. Average annual grass yields in the second period on the plots to which no fresh P was added were about the same as those on the corresponding plots in the first period. On these plots, the average annual P offtake in the second period was similar to that in the first period, 5 kg ha⁻¹ from soils without residues and 8 to 17 kg P ha⁻¹ from the soils with residues. During this second six-year period the recovery of the P residues estimated to be still in the soil in 1964 ranged from 7 to 14 percent, as in the first period.

The total amount of P recovered from the residues in the first and second six years was similar on all plots (except perhaps plot 4). This suggests that the average annual rate of release of P from the accumulated reserves was approximately constant. In turn, this suggests that there is an equilibrium between the amounts of P in each of the soil P pools. On the soil without added P since 1848, the near-constant amount of P in the grass suggests that this P was coming from P in soil minerals. The amount, about 4 kg P ha⁻¹ each year, is similar to that reported for a very similar soil type in the case study on humid temperate arable cropping (below). The total amount of P recovered from the residues in 12 years ranged from 16 to 30 percent of the total residues estimated to be in the soil in 1958. If there is a constant rate of release of P from the residues, then they should be recovered in 60 years.

In 1964, a test of adding fresh P was started in order to widen the range of Olsen P levels. This fresh P increased yields substantially where no P had been given since 1848 and gave large increases in yield on plots with residues (Table A1.8). The annual release of P from soil minerals (plots 5 and 6) and from these reserves plus P residues accumulated between 1848 and 1951 (plots 3, 4, 5 and 6) was not sufficient to meet the P requirements of well-managed grass producing large yields. This agrees with the observation in the case study on humid temperate arable cropping (below) for spring barley, namely, that P was being recovered from P residues but not at a rate that can annually meet the requirements of a crop to achieve an economically viable yield.

In this second period, the efficiency of P use for the smallest amount of P applied can be calculated by both the difference and balance methods (Table A1.8). The values ranged from 5 to 9 percent by the difference method and 9 to 12 percent by the balance method. These values are small because such a large amount of P (220 kg P ha⁻¹) was applied initially and the P removed each year in the harvested grass was replaced. The next part of this section reports much larger percent recoveries where 33 kg P ha⁻¹ was added each year to permanent grassland.

Permanent grassland

The experiment discussed here was conducted between 1965 and 1978, and was on two plots of the Park Grass experiment at Rothamsted. This experiment was started in 1856 on a grass sward that had not been ploughed for at least 100 and probably 200 years (Warren and Johnston, 1964). The initial aim was to compare the effects of the nutrients added in fertilizers and farmyard manure (FYM) on the yields of herbage harvested for hay in early June and the re-growth harvested in autumn. Where applied, fertilizer P (33 kg P ha^{-1}) and K (224 kg K ha^{-1}) were added annually in late winter, and the three amounts of N tested were applied in early spring. Initially, the surface soil had a pH_{water} of about 5.5. The two plots of interest here are plots 5/1 and 5/2 sited on the original plot 5, which had received 96 kg N ha^{-1} annually from 1856 to 1897. In 1898, plot 5 was divided and thereafter plot 5/1 received no fertilizer while plot 5/2 had P and K annually at the standard rate. In 1959, the top 23 cm soil had pH_{water} 4.61 and 4.63 on plots 5/1 and 5/2, respectively, while Olsen P was 3 and 137 mg kg^{-1} , respectively. The species composition of the sward reflected the acidity of the soil and the availability of soil P.

Recovery of P residues, 1898–1964

In the period 1898–1964, total yields (hay plus aftermath) of herbage DM were small in the absence of applied N (1.37 and $2.65 \text{ tonnes ha}^{-1}$ on plots 5/1 and 5/2, respectively). The extra yield on plot 5/2 receiving P and K annually was probably caused by the presence of legumes in the sward. A P balance sheet for 1898–1964 was prepared for both plots using the annual yields of hay and aftermath and the percent P in both hay and aftermath in 1956–59. On the plot without P, the herbage grown without N removed 120 kg P ha^{-1} between 1898 and 1964, an average annual P offtake of 1.8 kg ha^{-1} . On the soil to which P had been applied each year, 565 kg P ha^{-1} was removed in the crops, an average annual P offtake of 8.6 kg P ha^{-1} . These offtakes were less than those removed from similarly-treated soils in other long-term experiments at Rothamsted because yields were so small in the absence of applied fertilizer N. Recovery of the accumulated P residues was 20 percent by the difference method and 26 percent by the balance method.

Recovery of P residues during, 1965–1978

In 1965, it was decided to evaluate more rigorously the P reserves on plot 5/2. Plots 5/1 and 5/2 were both divided into 40 subplots, and on each there was a test of all combinations of 2 levels of N \times 4 levels of P \times 4 levels of K, leaving 8 subplots to test additional amounts of K. The amounts of N, P and K tested were: N, 224 and 448 kg ha^{-1} (this quantity was divided into six equal dressings, one for each of six harvests [cuts] taken each year); P, 0, 16.8, 33.6, and $67.2 \text{ kg P ha}^{-1}$ (applied as SP); and K, 0, 56, 112, and 224 kg K ha^{-1} (applied as potassium chloride). Both P and K were applied in late winter, and the first application of N was given in early

spring. This summary uses data for the following treatments: two amounts of N; two amounts of P (0 and 33.6 kg P ha⁻¹); and one amount of K (224 kg K ha⁻¹). The results and discussion can be divided into two sections. (i) assessment of the P residues accumulated on plot 5/2 between 1898 and 1964 but now with adequate N and K applied to the appropriate subplots; and (ii) estimation of the efficiency of use of freshly applied P (34 kg ha⁻¹) on the yield and recovery of this P on a soil deficient in plant-available P (3 mg kg⁻¹ Olsen P), and a soil well supplied with P (130 mg kg⁻¹ Olsen P).

Recovery in 1965–1978 of P residues accumulated in 1898–1964

In the period 1898–1964, no P was applied to plot 5/1 while 2 180 kg P ha⁻¹ was applied to plot 5/2, and 120 and 565 kg P ha⁻¹ were removed in the herbage from plots 5/1 and 5/2, respectively. Thus, of the P applied, a maximum of 1 735 kg P ha⁻¹ remained on plot 5/2 in autumn 1964.

Table A1.9 shows the average annual yield of DM and the P taken off in the herbage on subplots without added P. Doubling the amount of N applied increased yield, on average, by only 0.6 tonnes ha⁻¹ on subplots without P since 1856. There was insufficient Olsen P in the soil for there to be a large response to N. On plot 5/2, where there were appreciable P reserves, the smaller and larger amount of N increased yield by 60 and 90 percent, respectively. On the P-deficient soil, annual P offtake was less than 7 kg P ha⁻¹ but 3.5 times this amount was removed from plot 5/2 with P reserves. In 14 years, 14 and 19 percent of the P residue was recovered in the herbage where the smaller and larger amounts of N, respectively, were given. There was no evidence of a consistent decrease in the annual P offtake over the 14 years, suggesting that most or all of the P reserve would be recovered in time.

TABLE A1.9

Recovery of P residues accumulated between 1898 and 1964 by permanent grass in 1965–1978, Park Grass experiment, Rothamsted

Total N applied in six equal amounts	Soil without P residues	Soil with P residues	Effect of P residues on yield	
	Yield, dry matter			
(kg ha ⁻¹)	(tonnes ha ⁻¹)		(tonnes ha ⁻¹)	
224	4.79	7.68	2.89	
448	5.43	10.33	4.90	
	Total P offtake, 14 years		Effect of P residues on P offtake 14 years	Recovery of the P residues
	(kg ha ⁻¹)		(kg ha ⁻¹)	(%)
224	92	333	241	14
448	102	437	335	19

Recovery of fresh P added annually between 1965 and 1978 to soils deficient and well supplied with Olsen P

On the soil without P residues, adding 34 kg P ha⁻¹ increased yield by about 1.5 tonnes ha⁻¹ with the smaller amount of applied N but by almost 4 tonnes ha⁻¹ with the larger amount of applied N (Table A1.10). The total amounts of P taken up during 1965–1978 by the crops given the smaller amount of N were 92 and 223 kg P ha⁻¹ without and with fresh P, respectively. This represents a 27 percent recovery of the applied P by the difference method and 47 percent by the balance method. With the larger amount of N, the total amounts of P removed in 14 years were 102 and 335 kg P ha⁻¹ without and with fresh P, respectively. This represents a 49 percent recovery of the applied P by the difference method and 70 percent by the balance method. The very much better recovery with the larger amount of N indicates the need to ensure that there is no other limitation to yield other than P when estimating the recovery of applied P.

On the soil with P residues, adding 34 kg P ha⁻¹ had little effect on yield at either level of applied N although the larger amount of N increased yield by about 4 tonnes ha⁻¹ (Table A1.10). The total quantities of P taken up between 1965 and 1978 by the crops given the smaller amount of N were 333 and 326 kg ha⁻¹ without and with fresh P, respectively. Thus, by the difference method, none of the fresh P

TABLE A1.10

Recovery of P added annually at 34 kg P ha⁻¹ on soils with and without P residues, Park Grass N × P × K experiment, Rothamsted, 1965–1978

	Total N applied, in six equal amounts (kg ha ⁻¹)			
	224		448	
	P applied each year, 1965–1978 (kg P ha ⁻¹)			
	-	34	-	34
Soil without P application, 1898–1964				
Yield, DM (tonnes ha ⁻¹) per year	4.79	6.04	5.29	9.36
Total P offtake (kg ha ⁻¹), 14 years	92	223	102	335
Extra P taken up from plot with P applications 1965–1978 (kg ha ⁻¹)		131		235
% recovery of applied P				
By the difference method		27		49
By the balance method		47		70
Soil given P, 1898–1964				
Yield, DM (tonnes ha ⁻¹) per year	7.68	7.03	10.33	10.92
Total P offtake (kg ha ⁻¹), 14 years	333	326	437	520
Extra P taken up from plot with P applications 1965–1978 (kg ha ⁻¹)		-7		83
% recovery of applied P				
By the difference method				17
By the balance method		68		109

was recovered, but by the balance method the recovery was 69 percent. With the larger amount of N, the P offtakes were 437 and 520 kg P ha⁻¹ without and with fresh P, respectively. This represents a 17 percent recovery of the applied P by the difference method and 109 percent by the balance method. This is an example of the need to consider whether applied P has increased yield. Where, as in this case, P does not increase yield, this indicates that the soil contains sufficient readily plant-available P. Adding P in such a situation is an inefficient use of P. Where more than adequate plant-available P already exists in soil, P should not be added until there is a yield response or until the Olsen P has declined to about the critical level. In this case, replacing the P removed in the harvested crop is the best practice to maintain an appropriate level of plant-available P, as measured by the Olsen or another acceptable method of soil analysis.

HUMID TEMPERATE ARABLE CROPPING IN THE UNITED KINGDOM

This case study is from Rothamsted. The surface soil, pH_{water} of about 7, is a silty clay loam, classified as Chromic Luvisol. The 30-year mean annual rainfall is about 700 mm, and the experiment discussed here is on a level site.

From 1852 to 1901, the site of what is now known as the Exhaustion Land was used for a succession of three experiments on arable crops. The first, which lasted four years, tested the Lois Weedon system of soil cultivation for winter wheat and no N, P or K was applied (Lawes and Gilbert, 1856). This was followed from 1856 to 1874 by an experiment on winter wheat grown continuously that tested N, P and K applied as fertilizers. In the following 26 years (1876–1901), potatoes were grown each year and, in addition to continuing the fertilizer treatments, an FYM treatment was added to make a total of ten plots (Johnston and Poulton, 1977). After 1901, no more P or K fertilizers or FYM were applied until 1986. In 1986, plots 1, 3, 5, 7 and 9 were divided into four subplots, each of which received sufficient K to ensure that K would not limit yield. One of the four subplots continues to receive no P, the other three have received increasing amounts of fertilizer P in order to establish a range of Olsen P values in the top 23 cm of soil. The subplot that has continued to receive no P from 1986 has, for 100 years, measured the recovery of the residues of the P fertilizer applied as SSP between 1856 and 1901. In addition, since 1987, the effect of these P residues on cereal yields has been compared with that of freshly-applied P.

In the first ten years of the wheat experiment that started in 1856, plots given NPK gave average annual yields of 2.52 tonnes ha⁻¹ grain; this is about the national average yield for the period. Yields were about half of this on plots given PK or N only. In the second ten years, the yields on all plots declined appreciably, possibly because of the difficulty of controlling weeds adequately (Johnston and Poulton, 1977). In the first six years of the potato experiment, tuber yields with NPK (19.2 tonnes ha⁻¹) were above the national average of 15.4 tonnes ha⁻¹ (Gilbert, 1888) but were less in the next 10 years, perhaps because of potato cyst nematode affecting potatoes grown continuously. Without N, PK gave smaller yields of potatoes in each period (Johnston and Poulton, 1977).

Since the end of the potato experiment in 1901, the site has been cropped mainly with cereals. Spring barley was grown without N from 1902 to 1940 and then with N, the amount adjusted according to the yield potential of the variety, until 1991. Since 1992, winter wheat with N has been grown. In the period 1970–74, the soils containing residual P accumulated from P fertilizer applications applied between 120 and 70 years earlier, gave yields of spring barley grain approximately equal to the national average yield for this crop in the United Kingdom. There had been no observable irreversible fixation of P applied as SP to this soil.

Having demonstrated that the soils of Rothamsted farm were P-deficient, Lawes and Gilbert always tested a large amount of P in their experiments (about 34 kg P ha⁻¹ applied annually as SSP). Johnston and Poulton (1977) calculated that a total of 1 410 kg P ha⁻¹ was applied in 42 applications of SP to the P-treated plots between 1856 and 1901. They also calculated the offtake of P in the wheat grain and straw and potato tubers harvested in the same period, and in the spring barley grown from 1902 to 1974, using actual crop analyses where these existed or estimates based on appropriate analytical data. After 1976, some of the barley crops and all of the wheat crops were analysed for P. Using the analytical data or estimates based on them, the P offtake for this last period was calculated. The data presented in Table A1.11 are for the P offtakes in different periods between 1856 and 2001 for plot 5, always without P, and for plot 7 with P applied as fertilizer from 1856 to 1901 and none since.

The annual P offtake in potato tubers between 1876 and 1901, both with and without P, was smaller than in cereal grain plus straw, except for the spring barley grown between 1902 and 1940 when no N was applied and yields were small. From 1941 to 2001, both spring barley and winter wheat were given the near-optimal amount of N for the variety. On average, the annual P offtake on the soil with P residues was 9.2 kg ha⁻¹, but only 4.4 kg P ha⁻¹ on the soil without P since 1856. Thus, P residues are still being recovered at a remarkably constant average annual rate, which is probably related to the bonding energy with which P is held in the different soil P pools. The constant rate of release from the soil without P suggests that this is the rate of release of P held within soil matrices (absorbed P).

The cumulative recovery by arable crops of the P applied between 1856 and 1901 can be calculated from the data in Table A1.11 by both the balance and the difference method. Table A1.12 shows that in the first period (1856–1901), when the annual P application was large relative to the yield, the percentage recovery by the balance method was 23 percent (14 percent by the difference method). Over the whole period of the experiment (1856–2001, the recovery of the added P by the balance method has been 79 percent, compared with 41 percent by the difference method. Using the balance method of calculation and assuming that the average annual P offtake continues at about 9 kg ha⁻¹, the remainder of the 1 410 kg ha⁻¹ of applied P between 1856 and 1901 should be recovered in the next 30–35 years.

The data in Table A1.12 can also be used in a slightly different way. At the end of the two cropping periods, 1856–1901 and 1902–1948, the amount of residual P remaining in the soil can be calculated and the recovery of this P estimated

(Table A1.13). By 1901, 1 081 kg P ha⁻¹ remained in the soil (1 410 minus 329, Table A1.11) but the P offtake was small (307 kg ha⁻¹) when yields were small because no N was applied. In consequence, only 28 percent of the remaining soil P residue was recovered. By 1949, the P residue had declined to 774 kg ha⁻¹ (1 081 minus 307, Table A1.11) and the P removed in the next 53 years (479 kg ha⁻¹) represented a recovery of 62 percent. The level of the yield, which can be affected by several factors, has a major influence on percent recovery of P from soil.

The P balance can be related to the changes in Olsen P during the period of this experiment (Table A1.14). Between 1856 and 1901, when the P balance was positive on plot 7, the increase in Olsen P accounted for only about 17 percent of the balance, i.e. much P had transferred to soil P pools where the P was not extracted by the Olsen reagent. From 1902, no P was applied and the P balance was negative. However, the decrease in Olsen P did not account for all the P taken off in the harvested crop. Thus, P in pools not extracted by the Olsen reagent was released for crop uptake. The percentage of the P balance that could be accounted for by the decrease in Olsen P was larger in the first period (1902–1974) than in the second period (1976–2001). However, the annual P offtake in the second period was larger than in the first. This suggests that the equilibrium between the readily-available and less readily-available pools of soil P is constantly changing, depending on P inputs and offtakes. On the soil to which no P had been applied since 1852, the change in Olsen P accounted for very little of the negative P balance. Consequently, most of the P taken up by the crop had come from pools other than the very small pool of soil P extracted using the Olsen method.

The data presented here show that P applied as SP between 1856 and 1901 is still being recovered 100 years later, i.e. P residues have not been irreversibly fixed in the soil. However, the rate of release of P from the residues on plot 7 is not sufficient to achieve the optimal yield of the varieties of spring barley and winter wheat currently available, as seen by comparing the yields on the four subplots

TABLE A1.11

P offtake 1856–2001 by arable crops growing on plots that had received no P or a total of 1 410 kg ha⁻¹ from 1856 to 1901 and none since, Exhaustion Land, Rothamsted

Period and number of years	Cropping ¹	Plot 7 (NPK) ² P offtake		Plot 5 (N) ² P offtake		Difference in annual P offtake
		Total	Per year	Total	Per year	
				(kg ha ⁻¹)		
1856–1875 20	Wheat	160	8.00	93	4.65	3.35
1876–1901 26	Potatoes	169	6.50	45	1.73	4.77
1902–1940 39	Barley	235	6.02	131	3.36	2.66
1941–1948 8	Barley	72	9.00	39	4.90	4.10
1949–1974 26	Barley	248	9.54	116	4.46	5.08
1976–1991 16	Barley	135	8.44	65	4.06	4.38
1992–2001 10	Wheat	96	9.63	42	4.18	5.45

¹ P in winter wheat and spring barley grain plus straw and in potato tubers.

² Except 1902–1940 when no N was applied.

TABLE A1.12

Cumulative recovery by arable crops of P applied between 1856 and 1901, Exhaustion Land, Rothamsted

Period	P offtake (kg ha ⁻¹)	Recovery	
		Balance method	Difference method
1856–1901	329	23	14
1856–1948	636	45	23
1856–2001	1 115	79	41

TABLE A1.13

Percentage recovery by the balance method of the residue of P applied between 1856 and 1901 that remained in the soil in 1901 and 1948, Exhaustion Land, Rothamsted

Period	P residue (kg ha ⁻¹)	P offtake	Recovery (%)
1902–1948	1 081	307	28
1949–2001	774	479	62

to which P has been applied since 1986. Between 1986 and 1991 (excluding 1989, when yields were very small), the P residues alone gave only 3.62 tonnes ha⁻¹ spring barley grain. Applying fresh P increased the yield to 5.29 tonnes ha⁻¹ when Olsen P had been increased above a critical value of about 10 mg kg⁻¹. Similarly, in 1992–2001, the P residues alone gave winter wheat yields of 4.58 tonnes ha⁻¹. However, where Olsen P had been increased above 10 mg kg⁻¹ by applying P since 1986, the yield rose to 6.88 tonnes ha⁻¹.

HUMID TROPICS, MIXED CROPPING IN PERU

Beck and Sanchez (1994) reported on changes in P in the plough layer after 13 years of continuous arable cropping with added fertilizer P on a coarse sandy soil at Yurimaguas, Peru. The pH of the top 70 cm of uncultivated soil was less than 4.0, but on the fertilized plots, soil pH was maintained between 5.0 and 5.6 by periodic liming. Although the soil at Yurimaguas is sandy, like that in Ludhiana in the India case study (below), the pH of the soil at the latter was 8.7, which contrasts sharply with that at Yurimaguas. Thus, similarities and contrasts between the results at the two sites are of considerable interest.

The field experiment at the Yurimaguas Experiment Station in the upper Amazon basin in Peru was established in 1972 following the slash and burn of a 17-year-old secondary forest. The mean annual rainfall is 2 100 mm. The soil is deep and well drained with a sandy topsoil (0–40 cm deep) and increasing amounts of fine siliceous material at depth. The P-sorption capacity of the soil was described as being low. The climate is such that three crops can be grown each year; initially, these were upland rice, maize and soybean in rotation but rice was not grown after 1983. A cover crop of mucuna, to control weeds, was planted in April 1988, and this was incorporated into the soil in November, 1989.

TABLE A1.14

Relationship between Olsen P in the top 23 cm of soil and the P balance at different times, Exhaustion Land, Rothamsted

Period*	Plot 7 (NPK)				Plot 5 (N only)			
	P balance		Change in Olsen P		P balance		Change in Olsen P	
	(kg ha ⁻¹)	(mg kg ⁻¹)	(kg ha ⁻¹)	(% of P balance)	(kg ha ⁻¹)	(mg kg ⁻¹)	(kg ha ⁻¹)	(% of P balance)
1856–1903	1 081	60	182	17	-138	-3	-9	6
1903–1974	-555	-62	-188	34	-286	-4	-12	4
1974–2001	-231	-4	-12	5	-107	-1	-3	3

Note: Weight of air-dry soil to 23 cm is 3030 tonnes ha⁻¹ (Johnston and Poulton, 1977).

* Soils sampled in 1903 two years after the potato experiment ended.

The total amount of P that was applied as SP was 1 248 kg ha⁻¹, equivalent to an average 80 kg ha⁻¹ each year. In year 12 (1984), 80 kg P ha⁻¹ was applied inadvertently to the control plot. It was estimated that initially 23 kg P ha⁻¹ was added in the ash after burning the forest biomass. Fertilizer, and lime when required, were broadcast and initially incorporated to 10–15 cm with a rototiller. In 1985, tillage depth increased to 20 cm as more powerful equipment became available. For the first ten years (26 crops), all crop residues and weed biomass were removed from the plots. Then from the 27th to the 38th crop (in 1989), all crop residues were incorporated. On the non-fertilized control biomass, incorporation was negligible because nutrient deficiencies minimized crop growth.

The soil samples that were available for analysis included those taken one week before clearing the forest by slash and burn; 25 days after burning; and after harvesting a crop and before fertilizer was applied. While the soil was cultivated to 15 cm, soil samples were taken from the 0–15 and 15–30-cm depths. Following the introduction of deeper cultivation, soil samples were taken from the 0–20 and 20–40-cm horizons. To allow for the deeper ploughing, Beck and Sanchez (1996) calculated the P concentrations in the 0–15 and 15–40-cm soil depths. Soil P was extracted sequentially using the method developed by Hedley, Stewart and Chauhan (1982). After the extraction with 0.1 M NaOH, the soil was extracted again with 0.1 M NaOH but the soil suspension was sonicated at 75 W to disperse very small soil aggregates. This is considered to expose P on the inner faces of these very small aggregates to extraction with 0.1 M NaOH. The same method was used in the India case study (below). A complete P balance for both the 0–15 and 15–40-cm soil horizons was prepared for the fertilized and non-fertilized plots to evaluate the extent of P movement downwards and the distribution of P among the various soil P pools extracted by the different extractants. Phosphorus concentrations in soil were converted to amounts (kilograms per hectare) using measured soil bulk density values of 1.40 g cm⁻³ (0–15 cm) and 1.45 g cm⁻³ (15–40 cm).

Phosphorus balance and P recovery estimated by the difference and balance methods

Table A1.15 gives the P balance for both the fertilized and non-fertilized treatments for the 31 crops grown in 13 years. It also includes the net change in the measured total P in the soil and the P that is not accounted for. Calculated by the difference method, the P recovery is 41 percent when the 80 kg P ha⁻¹ applied inadvertently to the control plot in 1984 is not included as an input because it had very little effect on yield. When calculated by the balance method, P-use efficiency is 43 percent. The results by either method are similar, in part because so little P was removed from the unfertilized control. The result also implies an efficient use of P on this soil with a low P-sorption capacity. A similar large P-use efficiency determined by the difference method was reported in the India case study (below), suggesting very little difference between the efficiency with which fertilizer P was used on these two sandy soils with such a large difference in soil pH.

The P balance in Table A.15 shows that 196 kg P ha⁻¹ of the total P applied was not accounted for; i.e. about 15 percent of the P added when the change in soil P to 40 cm was included in the calculation; a similar percentage could not be accounted for in the India case study (below). On this very sandy soil and with a large annual rainfall, P in soil may well be subject to leaching. Beck and Sanchez (1996) noted that in 1972 there was 377 kg ha⁻¹ total P in the 15–40 cm soil layer. Of this total, 48 kg was Pi (< 2 kg was resin Pi), 174 kg organic P (Po), and 155 kg was residual P. After 13 years of continuous cropping without P addition, the Po pools in the 15–40 cm layer had declined significantly, by 22 kg P ha⁻¹. Total P at this depth had increased by 41 kg ha⁻¹, of which about half was in the NaOH Pi fraction. Thus, there had been some downward movement of P from the top 15 cm of soil, even in the absence of applied P following the introduction of arable cropping. Where P had been applied, there was a considerable increase (328 kg ha⁻¹) in the total P content of the soil at the greater depth. Most of this increase was in the P extracted

by NaOH (205 kg) and the recalcitrant P fractions. Resin and bicarbonate P increased by only 13 and 44 kg P ha⁻¹, respectively. This suggests either that water-soluble P transported downwards reacted with soil constituents at depth, or that on this coarse-textured soil, soil particles with which this P was associated moved down through the soil profile in drainage. If P at this depth

TABLE A1.15
Phosphorus balance (0–40 cm) for 31 crops in a fertilized and non-fertilized cropping system after 13 years on a sandy soil in the humid tropics in Peru

	Non-fertilized	Fertilized
	(kg P ha ⁻¹)	
Phosphorus applied		
Ash and biomass	23	23
Fertilizer	80	1 248
Total	103	1 271
Phosphorus removed by crops		
Grain (31 harvests)	22	453
Residue (26 harvests)	3	88
Total	25	541
Net change in soil P	46	534
P unaccounted for	32	196

Source: Adapted from Beck and Sanchez (1996).

TABLE A1.16

Change in six soil P fractions in the 0–40 cm depth of soil after 13 years of fertilized and non-fertilized cropping at Yurimaguas, Peru

	1972	Forest	Cropland
		Net changes 1972 to 1985	
		Non-fertilized	Fertilized
		(kg P ha ⁻¹)	
Phosphorus fraction			
Resin	7.7	-5.6	25.8**
Bicarbonate	69.1	-27.4	85.4**
0.1 M NaOH	270.7	-21.1	277.0**
0.1 M NaOH-soni.	17.8	5.5	24.8**
HCl	4.0	0.9	39.6**
Sum	369.3	-47.7	452.6
Residual P	236.7	93.9	81.8*
Total P	606.0	46.2	534.4**

*, ** Statistically different at the < 0.05 and < 0.01 level, respectively.

Source: Adapted from Beck and Sanchez (1994).

is available to deep-rooted crops, then this may be a benefit provided that there are adequate amounts of water at depth to ensure root growth and P uptake.

Soil P fractions

As was the case previously, where Pi and Po were determined separately, the values have been summed for presentation here. Beck and Sanchez (1996) had to make allowances for the change in depth of soil cultivation during the period of the experiment. Consequently, Table A1.16 uses only data for the 0–40 cm soil depth.

In 1972, there was a total of 606 kg P ha⁻¹ in the soil to 40 cm depth, and of this only about 13 percent was in the resin and bicarbonate fractions, i.e. likely to be readily available for crop uptake. Of the remainder of the total P, about 45 percent was in the 0.1 M NaOH fraction, i.e. a less-labile fraction, and about 40 percent was in the residual or recalcitrant P fraction. By 1985, the resin-P, bicarbonate-P, and 0.1 M NaOH-P fractions in the soil of the unfertilized control plot had all declined, as would be expected. However, there was an increase in residual P, which, in part, could be explained by the inadvertent addition of 80 kg P ha⁻¹ and errors in sampling and analysis. Where SP had been applied, the amount of P in all P fractions had increased, with the largest increase in the bicarbonate and 0.1 M NaOH fractions. Again, these data support the concept of the distribution of P residues into all the soil P fractions that are extracted by sequential fractionation. The P in these fractions will be released over time and be available for crop uptake. However, the rate of release may not be fast enough to meet the annual needs of cultivars with a large yield potential, but this suggestion needs to be tested in different farming systems on a range of soil types and in different climates.

TABLE A1.17

Cropping sequences and amounts of P evaluated on summer and winter crops or on both crops each year, 1975–2000

Period and winter crop*	P rate (kg P ha ⁻¹)
1975/76 – 1981/82, 7 years winter wheat	0, 13, 26, 39 for summer and winter crop
1982/83 – 1983/84, 2 years mustard	no P applied
1984/85 – 1991/92, 8 years mustard	0, 9, 18, 26 for summer and winter crop
1992/93 – 1999/2000, 8 years rapeseed	0, 9, 13, 18 for summer and winter crop**

* Summer crop always groundnut.

** No P applied to groundnut 1992/93.

Source: Adapted from Aulakh *et al.* (2003).

HUMID TROPICS, MIXED CROPPING IN INDIA

Aulakh *et al.* (2003) presented data on the P balance and changes in soil P fractions for 25 years of cropping on a coarse-textured soil at pH_{water} 8.7 in Ludhiana, India. At this site, two crops can be grown each year, one in the warm summer months, the other in the cooler winter months. During the 25-year period of this experiment, groundnut was grown each year in summer; in winter, winter wheat, mustard or rapeseed was grown in different years (Table A1.17).

Three methods of applying P were evaluated: (i) P was applied only for the summer crop (the residual effect was tested on the winter crop); (ii) P was applied only for the winter crop (the residual effect was tested on the summer crop); and (iii) P was applied for both winter and summer crops. The amounts of P applied during the period of the experiment were reduced as the less P-responsive oilseeds replaced wheat and because P reserves were accumulating in the soil where P was applied. Table A1.17 lists the amounts of P applied to each crop. Each application of P was cultivated into the top 15 cm of soil. The total amounts applied to treatments P1, P2 and P3 were: 209, 387 and 564 kg P ha⁻¹ for summer-grown groundnut; 231, 426 and 621 kg P ha⁻¹ for winter-grown crops; and 440, 813 and 1 185 kg P ha⁻¹ for both crops. The data for the whole 25 years are mainly discussed here. The authors presented the soil analysis data in terms of kilograms per hectare by converting concentrations determined by analysis to quantities using known soil weights.

Crop yields

Aulakh *et al.* (2003) discussed the yields for all treatments in detail. Only the winter-grown crops responded consistently to freshly-applied P and the response was larger than that to the residue of P applied to the groundnut. Summer-grown groundnut gave as large a yield with the residue of P applied for the preceding winter crop as it did with freshly-applied P, with only one exception, namely when groundnut followed mustard given 18 kg P ha⁻¹. Table A1.18 summarizes the average yields of winter wheat, mustard and rapeseed given fresh P, and the yields of groundnut grown: (i) on the residues of P applied to the winter-grown

TABLE A1.18

Yield of winter-wheat grain, mustard and rapeseed grown in winter and groundnut pods grown in summer and given different amounts of P fertilizer

P applied (kg P ha ⁻¹)		Groundnut pods	
		P applied to previous winter crop	P applied to groundnut
		(kg ha ⁻¹)	
	Wheat grain*		
	(kg ha ⁻¹)		
Control	3 020	1 870	1 870
13	4 070	1 870	1 950
26	4 530	2 020	1 930
39	4 660	1 950	2 002
	Mustard seed**		
	(kg ha ⁻¹)		
Control	947	691	691
9	1 254	709	714
18	1 451	608	710
36	1 452	734	699
	Rapeseed*** seed		
	(kg ha ⁻¹)		
Control	1 360	968	968
9	1 801	1 312	1 429
13	1 986	1 418	1 430
18	2 060	1 457	1 466

* Average winter wheat yield 1976/77 – 1981/82.

** Average mustard seed yield 1984/85 – 1990/91.

*** Average rapeseed seed yield 1993/94 – 1999/2000.

Source: Adapted from Aulakh *et al.* (2003).

TABLE A1.19

Total P uptake by all crops grown in 25 years when P was applied only to the winter-grown crop, and estimates of P recovery by the difference method

Total fertilizer P applied (kg P ha ⁻¹)	Total	P in crop	
		P from fertilizer	Recovery of added P
		(kg P ha ⁻¹)	(%)
None	361		
231	485	124	54
426	538	177	42
621	624	263	42

Source: Adapted from Aulakh *et al.* (2003).

crop; and (ii) with P applied to that crop. The considerable variation in groundnut yields in the different periods reflects the use of cultivars with very different yield potentials. The yields of wheat, mustard and rapeseed responded up to 26, 18 and 18 kg P ha⁻¹, respectively. Applying 9 kg P ha⁻¹ to groundnut grown following rapeseed increased the yield compared with that where no P was applied.

Phosphorus offtake and recovery by the difference and balance methods

Table A1.19 presents the total amount of P added during the course of the experiment when it was applied only to the winter-grown crop, the total offtake of P by all the crops grown with this treatment and the recovery of P by both the difference method. A large amount of P (361 kg ha^{-1}), was removed in the crops grown without added P and the additional amounts of P removed where P was applied were not large. Nevertheless, percent P recovery by the difference method ranged from 42 to 54 percent, which is much larger than the often quoted 10–25 percent. When the balance method is used for treatments P1 and P2, percent P recovery was larger than 100 percent, indicating that offtake exceeded the amount of P applied and, thus, that soil P reserves were being depleted. The amount of P applied and the P offtake were just in balance for the P3 treatment.

Soil analysis

Samples from the top 15 cm of soil were collected after the 3rd, 8th and 25th years. The analytical values (in milligrams per kilogram) were converted to amounts (kilograms per hectare) using the known weight of soil to 15 cm of $2.325 \times 10^6 \text{ kg ha}^{-1}$.

Olsen P was determined in order to estimate readily plant-available soil P. From the soils to which no P was applied, 361 kg P ha^{-1} was removed in the harvested crops in the 25 years yet Olsen P changed little. Initially, there was $11.6 \text{ kg P ha}^{-1}$ and this declined to 10.5, 9.0 and 7.0 kg ha^{-1} after 3, 8 and 25 years, respectively.

Where P was applied, Olsen P reached an apparent “equilibrium” value, something not always found in other experiments. Although there was a negative P balance with treatments P1 and P2, Olsen P increased a little during the course of the experiment and there was a larger increase in Olsen P with the P3 treatment where the P balance was zero. No explanation for this phenomenon of Olsen P increasing with a negative P balance is obvious, except to suggest that more P was released from the less-readily-available pool of P than was taken up by the crops.

Sequential extraction of soil P

Several authors (e.g. Cross and Schlessinger, 1995) have defined the various P fractions somewhat differently to the way used in this report. Aulakh *et al.* (2003) followed this other method. For example, resin and $\text{NaHCO}_3\text{-P}$ are considered to constitute a labile pool, P extracted by two NaOH treatments (without and with sonification) represents a moderately-labile pool, while the remaining P represents a non-labile P pool.

The method of sequential extraction used for the soils taken from this experiment was the same as that used in the Peru case study (above), i.e. 0.1 M NaOH followed by sonified 0.1 M NaOH. In this method, following the first extraction with 0.1 M NaOH, a second aliquot of the reagent was added to the soil, which was then sonicated at 75 W for 2 minutes in an ice bath. It is assumed that this breaks down small soil aggregates so that P on internal surfaces is exposed and extracted.

TABLE A1.20

The various soil P fractions after 25 years of cropping

P applied to the P2 treatment (kg P ha ⁻¹)	P in the different soil P fractions						Sum of P fractions
	Resin	NaHCO ₃	NaOH	Sonified NaOH	HCl	Residue	
Control	9.1	5.5	16.9	11.7	76.2	117.9	237.3
Summer	387	13.7	15.9	39.8	19.0	108.4	333.5
Winter	426	12.9	14.9	40.2	18.2	107.0	320.7
Both	813	13.7	21.8	46.4	27.0	125.5	405.0

Note: Data for the soil at the start of the experiment are not available.

Source: Adapted from Aulakh *et al.* (2003).

Of the total P extracted by NaHCO₃ and NaOH, some is inorganic (Pi) and the remainder is organic (Po) P. Thus, both Pi and Po can be determined. This organic P represents a labile pool of P that is readily mineralized (Bowman and Cole, 1978) and contributes to plant-available P (Beck and Sanchez, 1996). However, the rate and amount of P mineralized will vary considerably from site to site and year to year. Therefore, it will not be as immediately available as inorganic P. Aulakh *et al.* (2003) determined Pi and Po, but this report gives only the sum of the two. Table A1.20 presents the sequential P fractionation data for the soils taken at the end of the 25th year and only for the P2 treatment when the P was applied for the summer-grown, the winter-grown, and for both summer-grown and winter-grown crops each year.

Aulakh *et al.* (2003) did not provide the P fractionation data for the soil at the start of the experiment. Therefore, it is not possible to see how the amount of P in each fraction changed in the control soil as a result of the large negative P balance over the 25-year period. However, at the end of this period, the data in Table A1.20 indicate that, compared with the control, there were differences in the amount of P in all the P fractions in soils where P was added, proportionally more being in the least-labile than in the most-labile fractions. For the very similar amount of P applied once per year to the summer or winter crop, the change in each P fraction was very similar. Because there was a negative P balance for both these treatments, it can be assumed that the amount of P in each fraction has decreased but probably less than in the control soil. Where twice the amount of P was applied, the P balance was zero, and presumably the amount of P in each fraction might be near to that in the different fractions at the beginning of the experiment. There was no extra P in the resin fraction and very little more in the 0.1 M NaOH fraction compared with the smaller rate of added P, but there was more P in the NaHCO₃ and sonified 0.1 M NaOH fractions, and in the least-labile fractions. For the P2 treatment, Aulakh *et al.* (2003) constructed a balance sheet for the P taken up from the fertilizer, and the fertilizer P remaining in the soil. They found that 12–13 percent of the P applied to the summer-grown and winter-grown crops, respectively, could not be accounted for, while 22 percent of the P applied for both crops could not be accounted for by crop uptake and P in the top 15 cm of soil. They suggested that some of the “lost” P could have migrated below 15 cm.

ARABLE CROPPING IN A RANGE OF AGRO-ECOLOGICAL ZONES IN CHINA

The two sets of data from China considered here include experiments that have continued for a number of years using typical farming systems in different provinces. Full details of the experiments are not available. However, from the data on P applied, crop yields, and P in the harvested crops, it has been possible to calculate P recoveries by the difference and balance methods. None of the experiments appears to have assessed residual effects of the applied P fertilizers.

Three experiments (Shi *et al.*, 2002; Wang *et al.*, 2002; Yang *et al.*, 2002) had NK and NPK treatments, and the data illustrate the effect of soil P status and yield on percent recovery of added P when crops receive adequate amounts of N and K. First, P recovery was calculated using the difference method. It was 18 percent at Beibei, which is within the normal range for many experiments with average yields. At Yangling, plant-available soil P was not large but yields were high and P recovery was 45 percent. At Hangzhou, where available soil P was large and total annual grain yield exceeded 12 tonnes ha⁻¹, P recovery was only 7 percent. However, when P recovery was estimated by the balance method, the values were much larger at all three sites, 56, 60 and 83 percent, respectively.

A rice–wheat rotation at Beibei, Chongqing

In a six-year (1991–96) experiment on a Purple soil at Beibei in a subtropical, humid region, rice and wheat were grown in rotation, both crops being grown in one year (Shi *et al.*, 2002). Soil pH was 7.7 and Olsen P and available K were 4.3 and 88 mg kg⁻¹, respectively. Total P applied in six years was 327.5 kg ha⁻¹. Yields of wheat were 2.08 and 2.52 tonnes ha⁻¹ with the NK and NPK treatments, respectively, and the corresponding yields of rice were 5.98 and 6.56 tonnes ha⁻¹. The total amount of P removed in the harvested crops that were grown with NK and NPK was 124.6 and 183.9 kg P ha⁻¹, respectively. The calculated P recovery by the difference method was 18 percent, and by the balance method it was 56 percent.

A maize–wheat rotation at Yangling, Shaanxi

Data for an eight-year experiment (1991–98) with maize and wheat in rotation were given by Yang *et al.* (2002) for a cool temperate, subhumid site at Yangling. The soil was formed on loess and had a pH value of 8.6. The yields of both wheat and maize were increased by applying 57.6 and 24.6 kg P ha⁻¹ to the wheat and maize, respectively, with totals of 461 and 197 kg P ha⁻¹ over the 8 years. Wheat yields with NK and NPK were 1.43 and 4.60 tonnes ha⁻¹, respectively, and the maize yields were 3.63 and 6.05 tonnes ha⁻¹, respectively. The P offtakes in the wheat crop were 46 and 208 kg ha⁻¹ for the NK and NPK treatments, respectively. Thus, P recovery was 35 percent by the difference method and 45 percent by the balance method. The P offtakes by the maize were 58 and 190 kg ha⁻¹ for the NK and NPK treatments, and P recovery was 67 percent by the difference method and 97 percent by the balance method. For the combined cropping, a total of 657 kg P ha⁻¹ was applied in eight years and the P offtakes were 104 and 398 kg P ha⁻¹ with

the NK and NPK treatments, respectively, giving P recoveries of 45 and 60 percent by the difference and balance methods, respectively.

Triple-cropped rice–rice–barley at Zhejiang, Hangzhou

Wang *et al.* (2002) gave data for ten years for an annual triple-cropping system, rice–rice–barley, at Hangzhou in a subtropical, subhumid region. The soil had a pH of 6.6 and the available P and exchangeable K values were 374 and 68 mg kg⁻¹, respectively, in the top 20 cm of soil. The annual inputs of P and K were 69 kg P ha⁻¹ and 140 kg K ha⁻¹, and the total P applied in ten years was 690 kg ha⁻¹. Total annual grain yields were 12.12 and 12.70 tonnes ha⁻¹ for the NK and NPK treatments, respectively, and the corresponding P offtakes were 523 and 573 kg ha⁻¹. The P recovery estimated by the difference method was only 7 percent but by the balance method it was 83 percent.

The following, additional long-term data sets were made available through Dr Jin Jiyan, PPI/PPIC, China, by Dr Liang Guo-qing and Dr Shutian Li of the Soil and Fertilizer Institute, Chinese Academy of Agricultural Sciences. The data are summarized here to illustrate percent P recovery in experiments in the many different agro-ecological zones in China, with varying soils and farming systems. As in the three published data sets, there were considerable variations in the estimates of percent P recovery. They range from 1 to 72 percent when measured by the difference method, and from 18 to 122 percent when measured by the balance method. These ranges were caused by wide variations in yield and, hence, P uptake, and soil P status. The data can be divided into two subsets; those where both NK and NPK treatments were tested, and those where there were only N and NP treatments. It may have been thought that the soils of the latter set contained adequate amounts of plant-available K.

A maize–wheat–soybean rotation at Harbin, Heilongjiang

An experiment from 1980 to 2003 on a Phaeozem (Black soil) at Harbin City, Heilongjiang Province, had NK and NPK treatments in a maize–wheat–soybean rotation. Annually, P was applied to wheat and maize at 33 kg P ha⁻¹ and to soybean at 66 kg P ha⁻¹; all three crops received 62 kg K ha⁻¹. The soil initially contained 5.1 and 210 mg kg⁻¹ available P and K, respectively. Wheat, soybean and maize were each grown for eight years. The respective yields with NK and NPK were: wheat 3.00 and 3.11 tonnes ha⁻¹; soybean 2.08 and 2.5 tonnes ha⁻¹; and maize 7.69 and 7.93 tonnes ha⁻¹. The total P added in eight years was 264 kg P ha⁻¹ to wheat and maize and 528 kg P ha⁻¹ to soybean. The amounts of P taken off in the crop with the treatments of NK and NPK were: wheat 59 and 53 kg P ha⁻¹; soybean 80 and 98 kg P ha⁻¹; and maize 195 and 247 kg P ha⁻¹. The rates of P recovery by the difference method for the soybean and maize were 3 and 20 percent, respectively. By the balance method, the P recovery rates for wheat, soybean and maize were 20, 19 and 95 percent, respectively. For the whole rotation over eight years, the total P applied was 1 045 kg P ha⁻¹ and the amounts of P removed were 346 and 398 kg P ha⁻¹ for the NK and NPK treatments, respectively. Thus, for the whole

rotation over eight years, the P-efficiency levels as determined by the difference and balance methods were 5 and 38 percent, respectively.

Double-cropped paddy rice in Wangchang, Hunan

In an experiment from 1981 to 2002 on a Ferralsol (Red soil) in Wangchang County, Hunan Province, early and late paddy rice were grown each year. Both crops received 40 kg P ha⁻¹ from 1981 to 1990. From 1991, the amount was halved to 20 kg P ha⁻¹ and applied to both crops in 1992, 1995–97, and 2000–02, but only to early rice in 1994. Initially, the soil had 10.2 and 62.3 mg kg⁻¹ of available P and K, respectively. The average yields over 22 years with the NK and NPK treatments were: early rice 3.70 and 5.56 tonnes ha⁻¹; and late rice 4.87 and 5.58 tonnes ha⁻¹. The total amounts P in the harvested crop, grain plus straw, for the whole period of the experiment with the NK and NPK treatments were 276 and 674 kg P ha⁻¹ with early rice and with late rice was 325 and 530 kg P ha⁻¹, respectively. Thus, P recovery rates by the difference method were 72 and 38 percent for early and late rice, respectively, while for both crops combined it was 55 percent. When P recovery was estimated by the balance method, it was 122 and 100 percent for the early and late crops, respectively. Calculating P recovery in this way indicates that the total P removed was larger than that applied and, thus, that P reserves were being depleted.

Double-cropped paddy rice in Jinxian, Jianxi

For 21 years (1981–2001), an experiment in Jinxian County, Jiangxi Province, on a Ferralsol (Red soil) measured the effects of NK and NPK treatments on the yields of early and late rice, both grown each year on a paddy soil. Both crops received 20 kg P ha⁻¹ and 67 kg K ha⁻¹. Initially, the soil contained 9.5 and 97.8 mg kg⁻¹ of available P and K, respectively. With the NK and NPK treatments, the yields of early rice were 3.74 and 4.48 tonnes ha⁻¹, and those of late rice were 4.00 and 4.33 tonnes ha⁻¹, respectively. The total P applied to each crop in the 21 years was 420 kg P ha⁻¹. The total amounts of P in the harvested crop of early rice were 242 and 311 kg P ha⁻¹ for the NK and NPK treatments, respectively, and in the late rice 299 and 384 kg ha⁻¹. The calculated P recovery rates for the early and late rice by the difference method were 17 and 21 percent, respectively. For the balance method, the corresponding values were 75 and 93 percent.

A maize–wheat rotation at Zhengzhou, Henan

Maize and wheat were grown in rotation, i.e. two crops per year, in a 22-year experiment in Zhengzhou City, Henan Province. The soil was a Fluvo-aquic Calcaric Cambisol, which in 1980 contained 20.0 and 127 mg kg⁻¹ of available P and K, respectively. Data are available for 1981 to 2002. Only the wheat received P and K, the amounts were 52 kg ha⁻¹ P from 1981 to 1991, then 65 kg ha⁻¹ from 1992, and the total P applied was 1 296 kg ha⁻¹. The yields of wheat with NK and NPK were 3.42 and 5.23 tonnes ha⁻¹, respectively, and the corresponding P

offtakes were 244 and 473 kg ha⁻¹. Thus, P recovery rates as determined by the difference and balance methods were 18 and 36 percent, respectively. The yields of maize, to which no K was added, were 4.67 and 5.40 tonnes ha⁻¹ for the N and NP treatments, respectively, and the corresponding P offtakes were 381 and 574 kg ha⁻¹. Thus, the total P offtakes by both crops on the NK or N and NPK or NP treatments were 625 and 1047 kg ha⁻¹, giving P recoveries of 32 and 81 percent by the difference and balance methods, respectively.

A maize–wheat rotation at Xinji, Hebei

In Xinji City, Hebei Province, there was another experiment with a maize–wheat rotation, with N and NP treatments without added K, starting in 1979. The soil was a Fluvo-aquic Calcaric Cambisol that initially had 4.0 and 87 mg kg⁻¹ of available P and K, respectively. Each year, P was applied once to the wheat at 65 kg P ha⁻¹. In the period 1980–2002, 1 505 kg P ha⁻¹ was applied, and the average grain yields of wheat given N and NP were 2.73 and 6.16 tonnes ha⁻¹, respectively. The amounts of P removed in the harvested crop were 218 and 503 kg ha⁻¹ with and without added P, respectively. Thus, recovery of the added P was 19 percent by the difference method and 33 percent by the balance method. For the maize crop, the yields were 3.47 and 4.20 tonnes ha⁻¹ with the N and NP treatments, respectively. Of the 1 505 kg P ha⁻¹ added, 503 kg was removed in the wheat, leaving a residue of 1 210 kg P ha⁻¹. The P offtakes in the maize were 210 and 256 kg P ha⁻¹ with the N and NP treatments, respectively. Thus, only 4 percent of the residue was recovered. When both crops are considered together, the total offtakes of P were 428 and 759 kg ha⁻¹, and this represents a recovery of 22 percent by the difference method and one of 50 percent by the balance method.

A rice–wheat rotation at Wuchang, Hubei

In an experiment on an Acrisol (Yellow brown earth) at Wuchang City, Hubei Province, rice and wheat were grown each year from 1981 to 2001. The soil initially had 4.5 and 97 mg kg⁻¹ of available P and K, respectively. Both rice and wheat received P (20 and 13 kg ha⁻¹ to the rice and wheat, respectively) and K. Thus, a total of 420 kg P ha⁻¹ was given to the rice and 270 kg P ha⁻¹ to the wheat. Yields of rice with the N and NP treatments were 5.14 and 5.67 tonnes ha⁻¹, and the corresponding P offtakes were 353 and 484 kg ha⁻¹. The P recovery was 31 percent by the difference method, and 115 percent by the balance method. By comparison with the rice yields, wheat yields were small, only 0.76 and 1.50 tonnes ha⁻¹ with the N and NP treatments, and the corresponding P offtakes were also small, 36 and 74 kg ha⁻¹. The P recovery rates were 14 and 27 percent by the difference and balance methods, respectively. Combining the two sets of data, the total P applied was 690 kg ha⁻¹, and the total P offtakes were 389 and 558 kg ha⁻¹ for the N and NP treatments. Thus, for the whole period and both crops, the P-use efficiency rates were 24 and 81 percent by the difference and balance methods, respectively.

Double-cropped maize in Jinxian, Jiangxi

In 1986, an experiment with N and NP treatments on early and late maize, both crops grown each year, was started in Jinxian County, Jiangxi Province. In 1986, the available P and K values were 12.9 and 102 mg kg⁻¹, respectively. Both crops of maize received 13 kg ha⁻¹ P, and in 21 years the total P applied was 273 kg P ha⁻¹ to each maize crop. With the N and NP treatments, the yields of early maize were 2.53 and 2.96 tonnes ha⁻¹ and those of late maize were 1.55 and 1.84 tonnes ha⁻¹. The corresponding P offtakes were 252 and 255 kg ha⁻¹ by the early maize and 60 and 70 kg ha⁻¹ by the late maize for the N and NP treatments, respectively. The calculated P recovery rates for the early maize were 1 and 93 percent by the difference and balance methods, respectively, and for the late maize they were 4 and 26 percent by the two methods. Combining the data for the two crops, the P-use efficiency by the difference method was only 2 percent, but it was 60 percent by the balance method.

SEMI-ARID REGIONS AND RANGE OF ARABLE CROPS IN THE UNITED STATES OF AMERICA

North Carolina

McCollum (1991) described an experiment in North Carolina started in 1955 in which the buildup (8 years) and decline (26 years) of plant-available P was measured. The soil was a Portsmouth soil, a fine sandy loam topsoil over sandy or sandy skeletal, mixed, thermic Typic Umbraquult. During the experiment there were periodic additions of dolomitic lime, K, sulphur (S), and manganese (Mn), and other micronutrients in order to ensure that these were not yield-limiting. Crop yields and extractable soil P were measured both while the P balance was positive (first 8 years) and then negative (the following 26 years). Throughout the experiment, soils were analysed by a Mehlich method, but different extractants were used. McCollum described how all the results were converted to Mehlich-1 (M-1 P) equivalents and expressed on a soil volume basis.

In 1955, four levels of soil P were established by broadcasting 0, 162, 324 and 648 kg P ha⁻¹ and incorporating it into the top 20 cm of soil (plough depth). Five annual P fertilizer treatments (0, 10, 20, 40 and 60 kg P ha⁻¹) at each of the four levels of soil P were started in the following year (1956) and continued for eight years. This P was band-placed in rows 107 cm apart. The experiment had two blocks; maize and soybean were grown in a two-year rotation with each crop grown each year on one of two blocks.

The top 15 cm of soil was sampled each year after crop establishment so that tillage would have partially mixed the band-placed fertilizer of the previous year. Tillage consisted of post-harvest discing, ploughing (spring or autumn), and discing once or twice before planting. Soil samples were taken between the planted rows after drilling.

During the first eight years, on average, the only effect of P on maize yields was between the no P (none broadcast, none banded) and some P. Yields were

more related to rainfall; the average maize yield was 6.77 tonnes ha⁻¹ (range 4.51 to 9.35 tonnes ha⁻¹). There was no effect of P on the yield of soybean. Because the band-applied P treatments had little effect on yield, they were discontinued after the eighth year, and the experiment started its residual phase with no further applications of P fertilizers. Both yields and extractable soil P are of interest.

Yields and extractable soil P

Yields are available for both the P buildup and residual phases. For the buildup phase, the yield given by each treatment was expressed relative to the optimum for that year in order to remove seasonal yield fluctuations due to rainfall. Yields were then plotted against M-1 P; the response function had a highly significant, quadratic component, and the relative yield was maximal when M-1 P was 22 g m⁻³.

In the first four residual years, the maize–soybean rotation and annual soil sampling continued on soils with a wide range of M-1 P (from < 8 to > 80 g P m⁻³). Table A1.21 gives the yields of both crops associated with different soil test values. The maximum yield of both crops was when M-1 P was between 18 and 22 g m⁻³.

Visual P-deficiency symptoms began to appear about 14 years after the last P application and were pronounced in the 16th year, when the whole experiment was cropped with maize. In the 17th and 19th residual years, the whole experiment was again cropped with maize, but 20 kg P ha⁻¹ was band-placed on alternate blocks each year. Mean yields and P-treatment effects were similar in the two years, and the yields are summarized in Table A1.22. Comparing maize yields in the two tables for the early and later residual years shows that maximum yields were achieved at M-1 P values of 18–22 g P m⁻³ in both periods. This observation supports the “critical soil P” concept. On soils where the extractable P was close to this critical value, it could be maintained by

TABLE A1.21

Yields of maize and soybean at different levels of Mehlich-1 P in the first four years after the last application of fertilizer P

M-1 P (g m ⁻³)	Maize yield (tonnes ha ⁻¹)	Soybean yield
< 8	5.03	2.09
8–12	5.85	2.69
13–17	7.36	2.90
18–22	7.92	2.76
> 22	7.61	2.69

Source: Adapted from McCollum (1991).

TABLE A1.22

Effect of band-applying 20 kg P ha⁻¹ on the yield of maize grown on soils with a range of Mehlich-1 extractable P levels

M-1 P (g m ⁻³)	Fertilizer P band-applied (kg P ha ⁻¹)	
	0	20
< 8	3.02	5.97
8–12	6.16	7.48
13–17	7.86	8.30
18–22	8.68	8.61
> 22	8.74	8.80

Source: Adapted from McCollum (1991).

applying the amount of P removed in the harvested crop. On soils with more than 22 g m^{-3} M-1 P, there was no response to the band-applied P (Table A1.22). Although banding 20 kg P ha^{-1} doubled yield on the low-P soils, the yield was not increased to the level on the soils adequately supplied with P. This observation is the same as that reported by Johnston, Warren and Penny (1970).

Changes in soil P

In the first nine years when P was being applied, the amount of P removed annually averaged 16 kg P ha^{-1} , the P balance was positive, and M-1 P increased. In this experiment, the total amount of P added in the nine buildup years ranged from 0 to $1\,128 \text{ kg P ha}^{-1}$, and McCollum (1991) showed that the M-1 method extracted about 20 percent of this total P at the end of the nine years. The calculation did not allow for the 16 kg P ha^{-1} removed annually in the harvested crop, but this amount was small relative to the P applied. The result is similar to one reported by Johnston (2001). These data sets support strongly the view that much of the residue from an application of P fertilizer is transferred to pools of soil P that are not measured by routine analytical methods for plant-available P. Although the M-1 reagent extracted only a small proportion of the residual P, McCollum (1991) showed that P had not been leached below the 20-cm depth of soil. McCollum (1991) postulated that the greater contribution to the net decline in M-1 P was a consequence of chemical reactions with soil constituents.

By the ninth year, M-1 P ranged from less than 8 to more than 80 g m^{-3} , and in the next 19 years the soil was sampled ten times. In the absence of applied P, M-1 P declined, and for each soil with its different initial level of M-1 P, an exponential decline curve could be fitted. McCollum calculated that if the annual rate of P removal in harvested crops continued at 16 kg P ha^{-1} , the accumulated residues would last for 70 years. However, McCollum also noted that it was unlikely that this amount of P would be released from the residues throughout a 70-year period, and, thus, maximum yields would not be achieved for all of this time. However, a continued, but slower, rate of release of P from the reserves to the plant-available P pool would likely be based on the evidence in the case study on arable cropping in the United Kingdom (above), so that all the residues could be recovered in time. From the P decline curves for this Portsmouth soil, McCollum postulated that, with an initial M-1 P of 100 g m^{-3} , M-1 P would decline to the limiting value of 22 mg litre^{-1} in 14–16 years. It would be necessary to apply some P each year to achieve maximum yield. This result is very similar to the one discussed in the case study on arable cropping in the United Kingdom (above).

Thus, the results from this case study support the view that on certain soil types, P residues from past applications of P fertilizers can accumulate in soil in plant-available forms. Provided that plant-available P is maintained above the critical value for that soil and farming system, applying more P does not increase the yield of the crops for which that critical value is appropriate. The evidence from this case study is that for soils at the critical P level, applying the same amount of P as was removed in the harvested crop will maintain the plant-available P at the critical level.

The case study also shows that when available soil P is below the critical level, then fresh applications of P will be required in order to increase yield, but the yield will not necessarily be increased to that achieved on a soil at or just above the critical soil P value. Thus, on very impoverished soils, there would be every justification to apply more P than that removed in the harvested crop in order to increase the P level to nearer the critical value.

In addition, there is evidence to show that, to maintain very large levels of available P, it is necessary to add much more P than is removed (McCollum, 1991; Saarela, 1991; Bertilsson, 1994; Nielsen, 1994; Wendt, Jungk and Claassen, 1996). However, maintaining very large levels of available P will almost certainly result in the inefficient use of P.

Kamprath (1999) gave data on the response to P fertilizers by maize and soybean grown in rotation on a Norfolk loamy sand (Typic Kandiudult), a Lynchburg loamy fine sand (Aeric Paleaquult), and a Davidson clay loam (Rhodic Kandiudult). On the Davidson soil, which initially contained 10 mg kg⁻¹ M-1 P, it was not until the 13th year and the removal of some 178 kg P ha⁻¹ that the crops responded to applied P fertilizer. Similarly, there was no response to the applied P fertilizer on the Norfolk soil, which initially contained 55 mg kg⁻¹ M-1 P, until the 14th year and following the removal of some 227 kg P ha⁻¹. An application of 20 kg P ha⁻¹ maintained the initial M-1 P on both the Davidson and Norfolk soils. There was no response to fresh P even in the 14th year on the Lynchburg soil that initially contained 105 mg kg⁻¹ M-1 P. It was necessary to apply 40 kg P ha⁻¹ on this soil to maintain the initial M-1 P level. For the reasons noted above, applying this large amount of P to maintain an unnecessarily high level of plant-available soil P is an inefficient use of P when yields are not increased with this addition of P.

Montana

Glacial till soils in the northern Great Plains of North America inherently contain little plant-available P, and crops respond to the application of P fertilizers (Snider, Bauer and Norum, 1968; Black, 1970; Alessi and Power, 1980). Crops are known to respond to the residues of these P applications but most measurements have lasted for only six to eight crops (Alessi and Power, 1980; Bailey *et al.*, 1977; Black, 1982; Read *et al.*, 1973, 1977; Sadler and Stewart, 1974). Sadler and Stewart (1974) reviewing data from Western Canada, concluded that about 75 percent of the fertilizer P not used by the crop to which it was applied remains in a chemical form available to succeeding crops. They also projected that more than three years would be needed for fertilizer P residues to be transformed to forms similar to “native P minerals”. However, they did not indicate the form of these “native” P minerals or the extent to which they might supply sufficient P to grow acceptable yields of crops. In the present report, the case is made that P is retained in soil mainly by adsorption and absorption reactions with a wide range of bonding energies. Phosphorus held with a low-bonding energy by soil mineral components is the P that is most readily available for uptake by crop roots.

Halvorson and Black (1985a, 1985b) reported data for a six-year continuation of the residual-P experiment reported by Black (1982). This experiment, on a glacial till Williams loam (fine-loamy mixed Typic Argiborolls), was started on identical sets of plots in 1967 and 1968. For the first 11 years, spring wheat was grown in a wheat-fallow rotation. Then after the 6th crop, the plots were cropped annually, mainly with cereals. The initial and only application of P was broadcast and incorporated by disc cultivation into the top 15 cm of soil. Phosphorus was applied at 0, 22, 45, 90 and 180 kg P ha⁻¹. Nitrogen at 0, 45 and 90 kg N ha⁻¹ was tested on each crop in the wheat-fallow rotation. During the annual cropping that followed, N rates varied depending on the amount of mineral N in the soil. In general, yield was not increased by the largest amount of N tested. Consequently, this summary discusses only data obtained with the middle rate of N, usually 45 kg ha⁻¹.

The initial Olsen P value was 6 mg kg⁻¹. Following the application of 0, 22, 45, 90 and 180 kg P ha⁻¹, Olsen P values were 6, 9, 12, 26 and 40 mg P kg⁻¹. Sixteen years later following the harvest of 10 or 11 crops, Olsen P had declined to 5, 6, 7, 9 and 13 mg kg⁻¹, respectively. It appears that the Olsen P decay curves shown by Halvorson and Black (1985a) could be shifted horizontally to produce a unified decay curve similar to that shown by Johnston and Poulton (1992), and in the present report at Figure 2.

Olsen P in the soil initially given 180 kg P ha⁻¹ was about 15 mg kg⁻¹ after the seventh crop in the wheat-fallow system. Black (1982) suggested that this level of Olsen P was the crucial threshold for maximum grain yield for a wheat-fallow rotation in the northern Great Plains. This value of 15 mg kg⁻¹ Olsen P is very similar to the critical value for winter wheat in the UK. There was no treatment in this experiment in Montana in which P was applied to each crop grown. If there had been, the residual P could have been evaluated, not only against a nil treatment but also against a fresh application of P.

TABLE A1.23

Grain yields with 45 kg N ha⁻¹ in 1982 and 1983 on soils given different amounts of P in 1967

	Initial P application (kg P ha ⁻¹)				
	0	22	45	90	180
	Grain yield (tonnes ha ⁻¹)				
1967 Plot series					
1982, Spring barley	2.54	2.48	2.63	2.78	2.70
1983, Spring wheat	1.34	1.22	1.50	1.48	1.51
1968 Plot series					
1982, Spring wheat	1.61	1.85	1.90	1.82	1.92
1983, Winter wheat	1.40	1.46	1.44	1.47	1.76

Source: Adapted from Halvorson and Black (1985b).

TABLE A1.24

Cumulative P uptake and fertilizer P recovery from a single application of P fertilizer by cereals given 45 kg N ha⁻¹

P added (kg P ha ⁻¹)	1967 Series (11 crops)		1968 Series (10 crops)		Average both Series	
	Uptake (kg P ha ⁻¹)	Recovery (%)	Uptake (kg P ha ⁻¹)	Recovery (%)	Uptake (kg P ha ⁻¹)	Recovery (%)
0	71.1		62.3		66.7	
22	77.1	27	76.0	62	76.6	45
45	81.6	23	86.0	53	83.8	38
90	98.0	30	101.7	44	99.8	37
180	104.2	18	116.7	30	110.4	24

Source: Adapted from Halvorson and Black (1985b).

Grain yields for the first six crops, each grown after summer fallow, increased significantly with increasing soil P level with or without N fertilizer (Black, 1982). Subsequently, during annual cropping, average grain yields generally increased (but the increase was not always statistically significant) with residual P. Table A1.23 shows the yields for 1982 and 1983 for crops given 45 kg N ha⁻¹ and grown on plots started in 1967 and 1968.

Table A1.24 shows that cumulative P uptake by 11 crops (1967 plot series) and 10 crops (1968 plot series) given 45 kg N ha⁻¹ increased with increasing amounts of P applied. It also shows the percent recovery by these crops calculated by the difference method. Percent recovery was very much smaller on the 1967 plot series because cumulative P uptake on the no-P plot was much larger than on the equivalent plot in the 1968 plot series. However, cumulative P uptake on the P-treated plots was, in most cases, very similar on the two series of plots. Consequently, Table A1.24 also shows percent recovery when the data for the two series of plots are averaged, and as expected, percent recovery decreased as P applied increased. Halvorson and Black (1985b) noted that the P recoveries obtained were in general agreement with those of Alessi and Power (1980), Bailey *et al.* (1977), Read *et al.* (1973, 1977), and Sadler and Stewart (1974) for northern Great Plains dryland conditions. Although this study lasted for 16 years, including some fallow years, less than 50 percent of the applied P was recovered at application rates exceeding 45 kg P ha⁻¹. However, the authors expressed the belief that the residual P would continue to be released over many years.

Prior to Halvorson and Black (1985a, 1985 b), Cambell (1965) measured the residual effects over eight years of 0, 29, 58, 116 and 235 kg P ha⁻¹ applied to barley. In the following six years, barley, alfalfa (three years), maize and sugar beet were grown in rotation on a Thurlow clay loam soil. The total P removed in the harvested crops in nine years was 108, 122, 139, 152 and 201 kg P ha⁻¹. Percent recovery of the applied P by the difference method was 49, 54, 38 and 40 percent. Most of the initial application of 29 kg P ha⁻¹ had been removed from the soil in the first four years. Percent P recovery by the balance method exceeded 100 percent for all rates of P applied except the largest. As noted previously, this indicates that soil P reserves were being mined; a process that would eventually lead to smaller yields.

Indiana

Barber (1979) drew an important conclusion from the results of a rotation- fertility experiment that continued for 25 years (1952–1977) at Purdue University Agronomy Farm. This was that the increase in soil P level by fertilizer addition and decrease in P level by cropping appeared to be reversible processes. The soil was a Raub silt loam (Aquic Argiudoll) (Barber, 1958). At the start of the experiment, the soil had a pH value of 5.8 and total and Bray-1 P values of 454 and 18 mg P kg⁻¹, respectively. Phosphorus was applied at 0–54 kg P ha⁻¹ annually, but was applied at four times the annual rate only once every four years in the four-course cropping rotation. Near maximum yields were obtained with the equivalent of 22 kg P ha⁻¹ annually. All the harvested crops were analysed for P during the 25 years, and the average annual P uptake was calculated for each rate of P addition. For near maximum yields with the 22 kg P ha⁻¹ per year treatment, the recovery of P by the difference method was 33 percent, but by the balance method it was 79 percent. Applying P at the 54 kg P ha⁻¹ rate gave little extra yield and, in consequence, P recovery by the difference and balance methods was smaller, 22 and 40 percent, respectively.

Soil samples taken at the start of the experiment and after 25 years were analysed for resin P, Bray-1 P, and total P in 1977. The results showed that there was a linear relationship between the P balance and Bray-1 P. In 1973, the application of P was discontinued on some of the plots that had been receiving, on average, 22 and 49 kg P ha⁻¹ annually since 1952. When the soils on these plots were sampled in 1977, some had not received P for 8, 7, 6 and 5 years because the P was applied only once in four years, i.e. plots without P for 8 years had last received P in 1969. The total P removed by cropping on these plots increased as the number of years since the last P application increased. For both the 22 and 49 kg P ha⁻¹ treatments, resin P declined linearly as the amount of P removed increased, and the decrease in resin P was larger on the 49 kg P treatment than where 22 kg P was applied. Thus, as the level of resin P declined, the decrease in resin P per kilogram of P removed also decreased. This strongly suggests that there was more buffering of the resin P by the less readily-available pool of soil P as resin P declined.

Iowa

Dodd and Mallarino (2005) reported on the effects of P fertilization and cropping with maize and soybean in experiments in Iowa at various times between the 1970s and 2002. The soils at Boone in central Iowa were Aquic Hapludolls. At Kanawha in northern Iowa, they were Typic Endoaquolls; and at Ty and Nashua, in northeast Iowa they were Typic Hapludolls. At Boone and Kanawha, the treatments were a combination of three initial soil P test values, 17–96 mg kg⁻¹ Bray-1 P and four rates of P fertilizer, 0–33 kg P ha⁻¹. When the experiment started at Nashua, the soil contained 28 mg kg⁻¹ Bray-1 P, and there were three annual P treatments, 0, 22 and 44 kg P ha⁻¹. Ten to twenty years of cropping were needed on soils containing 43–96 mg P kg⁻¹ before there was any yield response to freshly-applied P fertilizer. Initially, the readily plant-available P in these soils was well above the critical

value. Critical soil P test concentrations (Bray-1 P) identified across sites and years were 15–21 mg P kg⁻¹ for maize and 12–18 mg P kg⁻¹ for soybean.

South Dakota

South Dakota State University has provided data from a 12-year residual P study at the SE Research Farm. Maize and soybean were grown in rotation with a no-till soil cultivation system. In 1993, four soil P test levels, appropriate to South Dakota standards, were established by incorporating varying amounts of a P-containing fertilizer (10–34–0) into the surface soil using a chisel plough. The levels described as low, medium, high and very high were 5, 8, 13 and 25 mg kg⁻¹ Olsen P. At each of these levels of soil P, 0, 10, 20 and 30 kg P ha⁻¹ were band-placed annually for both maize and soybean. Applying P broadcast was compared with banding at the medium soil P level, using the same four amounts of P. Where P was broadcast at 20 and 30 kg P ha⁻¹, Olsen P increased to 17.6 and 32 mg kg⁻¹ by 2005 as a result of positive P balances with these treatments.

Olsen P was maintained by the 10 kg P ha⁻¹ treatment but declined where no P was applied. To maintain the initial high and very high Olsen P levels required 20 and 30 kg P ha⁻¹ applications, the latter was larger than the P needed for optimal yield. The need for large P inputs to maintain unnecessarily high levels of plant-available P in soil supports a similar observation in the first case study reported in this section. Soils with initial Olsen P values of 5 and 8 mg kg⁻¹ showed a decline to 3.0 and 3.8 mg kg⁻¹ while the two soils with 13 and 25 mg kg⁻¹ showed a decline to 5.3 and 7.7 mg kg⁻¹, respectively. In all cases, these declines, when expressed in kilograms per hectare, were less than the P removed in the harvested grain. This supports the view that less readily-plant-available P can be released to support P uptake by the crop as readily-available-P levels decline. By 2004, when Olsen P levels had declined on soils at all four soil P test values, maize yields responded to both a banded and broadcast annual application of 20 kg P ha⁻¹.

Also available are the data on the total P offtakes in the 6 maize crops, 5 soybean crops, and 1 bean crop grown between 1993 and 2004 for the four soil P test treatments without annual P additions. Total P applied in 1993 for these treatments ranged from 104 to 335 kg P ha⁻¹. Total P offtake where no P had been applied since 1992 was 98 kg P ha⁻¹. Where P had been applied, it ranged from 102 to 160 kg P ha⁻¹. Percent P recovery by the difference method ranged from 23 to 34 percent, the larger values usually being for the smaller amounts of added P. When determined by the balance method, percent P recovery ranged from 42 to 81 percent for all but 3 of the 13 values. These three values exceeded 100 percent (range 101–123 percent), indicating that yield or P concentration in the grain or both were larger than anticipated for the amount of P applied and, in consequence, that P was being mined from soil P reserves.

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of soil phosphorus behaviour
with agronomic information

The efficient use of phosphorus (P) is essential to many agricultural and environmental issues. These include maintaining or improving the P fertility of soils by the judicious use of P fertilizers and other sources of P, such as organic manures including animal manures, composts and biosolids. There is also the need to conserve the finite global P resource. This bulletin 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 bulletin also outlines strategies for improving P-use efficiency. 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. The main conclusion of this bulletin is that the efficiency of fertilizer P use is often high when evaluated over an adequate time scale using the balance method.

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