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 $CaCl_2$, 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

NTRODUCTION

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, personnal 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(×4)	140	31.3	55
0	70(×4)	280	46.0	47
140	35(×4)	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 recovered by	
P applied	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 $NaHCO_3$ (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 removed = 20 + 0.44 P 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 (Karlowsky, 1982). The maintenance requirement (Pm) to compensate for losses in crop products under steady-state conditions (i.e. stable levels of available P in the soil) is calculated as: Pm = P offtake / P utilization. It follows that P utilization (or P-use efficiency) is P offtake / Pm, 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	Slope	R2
	(kg P ha^{-1})	(kg P ha^{-1} year^{-1})	
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 (Condron 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

[1] Assuming P removals in wool and body tissue of 0.06 kg P/animal.

Source: Adapted from Williams and Haynes (1992).

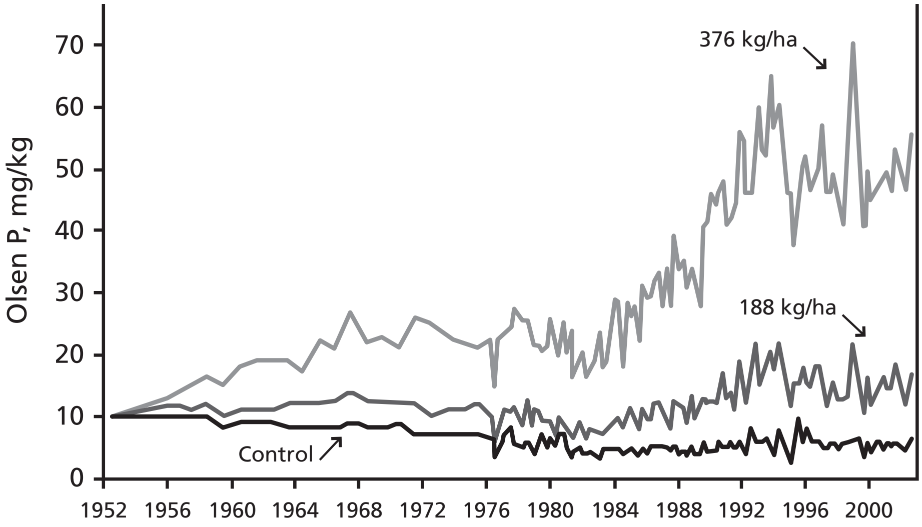
Where SP is applied at 188 and 376 kg ha^{-1}, there is a large annual P surplus. Part of this surplus P (estimated to be 4–5 kg ha^{-1}) is transferred in dung to sheep camp areas, resulting in some inefficiency in P recycling and excessively large amounts of P in the soil in the camp areas. Although 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 × 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 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 × 4 levels of P × 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 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
				(kg ha^{-1})		
		Total	Per year	Total	Per year	
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	Recovery	
		Balance method	Difference method
	(kg ha^{-1})	(%)	
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	P offtake	Recovery
	(kg ha^{-1})		(%)
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

		Forest	Cropland
		Net changes 1972 to 1985	
	1972	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		Groundnut pods P applied to previous winter crop	P applied to groundnut
(kg P ha^{-1})		(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

	P in crop		
Total fertilizer P applied	Total	P from fertilizer	Recovery of added P
(kg P ha^{-1})	(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 2.325×10^6 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 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 $NaHCO_3$-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		P in the different soil P fractions Resin	NaHCO3	NaOH	Sonified NaOH	HCl	Residue	Sum of P fractions
	(kg P ha^{-1})				(kg ha^{-1})			
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	136.7	333.5
Winter	426	12.9	14.9	40.2	18.2	107.0	127.5	320.7
Both	813	13.7	21.8	46.4	27.0	125.5	170.6	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 $NaHCO_3$ 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 $NaHCO_3$ 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 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	Maize yield	Soybean yield
(g m^{-3})	(tonnes ha^{-1})	
< 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

	Fertilizer P band-applied (kg P ha^{-1}	
	0	20
M-1 P (g m^{-3})	Yield, grain (tonnes ha^{-1})	
< 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 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}

	1967 Series (11 crops)		1968 Series (10 crops)		Average both Series	
P added	Uptake	Recovery	Uptake	Recovery	Uptake	Recovery
(kg P ha^{-1})	(kg P ha^{-1})	(%)	(kg P ha^{-1})	(%)	(kg P ha^{-1})	(%)
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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18

FAO FERTILIZER AND PLANT NUTRITION BULLETIN

Efficiency of soil and fertilizer phosphorus use

Reconciling changing concepts 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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