Chapter 9
SOIL AND FERTILIZER PHOSPHORUS IN RELATION TO CROP NUTRITION

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INTRODUCTION

Phosphorus (P) plays a pivotal role in the nutrition of all plants as an essential element participating in a wide array of physiological and biochemical processes occurring in all living organisms (Vance *et al.* 2003). Historically, of all the nutrients required by plants, P was frequently the one that most limited growth; until P deficiency was corrected many crops did not respond to nitrogen (N), and this is still the case for many soils worldwide. Most crops grown for human food, animal feed, fiber and now for biofuels contain between 0.2% and 0.5% P in their dry matter when sufficient P is available in the soil (Sanchez 2007). In intensive agriculture much of this P can be applied in inorganic P fertilizers and organic manures. Inorganic P fertilizers were first available some 160 years ago after JB Lawes, of Rothamsted (UK), patented a commercially successful method of producing superphosphate, containing water-soluble monocalcium phosphate, from phosphate rock (PR). From the mid 19th century, superphosphate quickly proved to be effective in providing plant-available P on almost all soil types in the UK (Johnston 1994) and has since been used worldwide for this purpose. With the opportunity to use inorganic P fertilizers and organic manures to minimize the risk of soil P deficiency limiting crop growth, there exists the possibility of increasing crop yields to improve food security for an increasing world population.

However, the global distribution of PR, the consumption of inorganic P fertilizers and the distribution of P-deficient soils are all poorly matched. Currently, over 70% of the PR reserves that are economically exploitable are located in three countries: the USA, Morocco and Western Sahara, and South Africa (Heffer *et al.* 2006). The production of PR reached 171 million tonnes (Mt) in 2005, the main producers being USA (24%), China (20%) and Morocco (19%). About 85% of this production was processed for use in agriculture (80% as fertilizer and 5% as animal feed supplement), whilst 15% was used for industrial products, such as detergents (12%; Heffer *et al.* 2006). In 2005/2006, the annual consumption of P fertilizer was estimated to be 36.8 Mt P_2O_5 of which 74% was consumed in four regions: East Asia, South Asia, Latin America and North America. Almost 32% was consumed in China and Vietnam, which the International Fertilizer Industry Association's regional classification includes in East Asia (Heffer *et al.* 2006).

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Phosphate fertilizers are essential for maintaining the production of staple foods. On a global scale, P is often regarded as the main mineral nutrient restricting plant growth in acid, neutral and calcareous soils. About 67% of the total farmland used worldwide contains too little readily plant-available P (Batjes 1997) and it is thought that some 30–40% of all soils growing arable crops are deficient in P (Runge-Metzger 1995; von Uexküll and Mutert 1995).

Phosphorus is a non-renewable resource and, although estimates of global reserves of PR and how they will be used vary, it is not disputed that P reserves are limited (Heffer *et al.* 2006). The US Geological Survey's Commodity Summary Report estimated that the world reserve base of PR was 46,000 Mt in 2005 (Heffer *et al.* 2006). This reserve base is sufficient to supply more than 300 years' consumption at the current rate but the "reserves" (that part of the reserve base that can be economically exploited with current technology with the present relative costs of production and value of product) is sufficient for only 100 years (Heffer *et al.* 2006). However, as yet unknown deposits may be discovered in the future, to benefit the continued existence of mankind. Vance *et al.* (2003) have drawn attention to the four- to five-fold increase in the use of P fertilizer between 1960 and 2000 and a projected further annual increase of 20 Mt by 2030. This projected increase in the use of P fertilizer will be required to meet the food needs of an increasing world population. This will be mainly in the tropics and subtropics, where the majority of the population of the world live already and where farmers are resource poor and the infrastructure to purchase and distribute fertilizers is only weakly developed.

Vance *et al.* (2003) distinguish clearly between problems associated with the use of P fertilizers in intensive agriculture and the lack of P inputs in extensive agriculture. In both of these very different systems there is a need to manage P in crop nutrition better to achieve sustainable yields and food security. The latter goal requires the achievement of two objectives. The first is a better understanding of the behavior of P in soils. The second is developing "P-efficient" cultivars of crop plants that can use soil and fertilizer P more effectively. Success in both these objectives will benefit both the use of P on soils where P supply is limited and crop yields are small, and the recovery of soil P reserves, which have accumulated in soil over many years from past applications of fertilizers and manures. Plant roots take up P as inorganic phosphate (Pi) from the soil solution and factors that influence the concentration of Pi in the soil solution and its rate of replenishment will affect yield. Thus, when P is strongly bonded to soil constituents Pi concentration may be less than required for optimal yield. The concentration of Pi in the soil solution can be increased by the addition of P as a water-soluble P fertilizer, or as a water-insoluble P compound which in an acid environment of either the rhizosphere or the bulk soil allows the release of Pi. The root system must be of an adequate size and any factors, biological, chemical or physical, and interactions between them that adversely affect root growth, size and function will decrease above ground growth and final yield. It also has to be clearly recognized that any improvement in P uptake from the soils reserves that is not replaced depletes ("mines") these reserves and cannot go on indefinitely without jeopardizing the ability of the soil to produce crops.

It is still widely believed that P fertilizers are used inefficiently in crop production. In part, this is because the recovery of P applied to a crop as ^{32}P-labelled fertilizer, is usually only 10–15%, rarely 25%, of that applied (Syers *et al.* 2007). It has generally been assumed that one reason for this poor recovery is because the P has become "fixed" by soil components and is unavailable for crop use. However, current thinking is that P is used efficiently, with recoveries of between 50% and 90%, if an appropriate time scale and method of estimation is used (Syers *et al.* 2007). The belief that fertilizer P is used inefficiently has led to the frequently held view that the transfer of P from soil to surface water bodies, with the consequent adverse effect of eutrophication on the biological balance in the water body, is due to the excessive use of P fertilizers. This is not totally correct, as is discussed later in this chapter.

In intensive agriculture, large yields of modern cultivars of arable crops annually remove 20–35 kg P ha^{-1}. For example, using the P content, kg P t^{-1} in fresh harvested material (MAFF 2000), the amount of P removed in 10 t ha^{-1} cereal grain is 34 kg, in 4 t ha^{-1} oilseed rape seed it is 24 kg, in 70 t ha^{-1} potatoes it is 30 kg and in 70 t ha^{-1} sugar beet roots it is 25 kg. In the past and often today, a varying, but frequently substantial amount of this P is completely lost from the soil when a crop is consumed directly or indirectly by humans because their excreta, containing most of the ingested P, is collected in a sewage treatment works. Traditionally, water-soluble phosphates have been discharged in the effluent to an adjacent river, where the bioavailable P is potentially able to cause environmental problems through eutrophication before being lost irreversibly to the sea (Neeteson *et al.* 2006). This one-way movement of P means that to maintain crop production new P has to be introduced into the system by application of fertilizer P obtained from the finite reserve of PR. Recently introduced changes of sewage treatment should be beneficial in allowing P recycling in agriculture because larger sewage treatment works are now required to use a tertiary treatment to remove P from the effluent. To further close the cycle of P use will require smaller treatment works to recover P from the effluent water. The solid sewage sludge remaining after treatment has traditionally been returned to the land and although the organic P it contains mineralizes slowly it does eventually increase the readily plant-available P in the soil (Johnston 1975). Fears about the return to soil of heavy metals in sewage sludge have largely been assuaged by the strict controls on their concentration in sludge.

This chapter is divided into seven sections. Following the Introduction we give an up-to-date account of the interactions between soil and fertilizer P in relation to the availability of P to plants. This summarizes the findings of part of a comprehensive review on the efficiency of soil and fertilizer P use commissioned by FAO and four other institutions (Syers *et al.* 2007). The acquisition of P by the roots of crop plants is then considered in relation to its availability in soil. In the following two sections we discuss first crop nutrition and the efficient use of P where soil P is adequate, and then the acquisition of P by plants where P supply is limited and to the adaptive mechanisms induced in plants by P deficiency and their possible exploitation. In both these sections, which discuss crop production in very different agro-environments, we present some possible ways to increase the efficiency of use of both soil and fertilizer P. In the final two sections we deal briefly with environmental and ecological aspects related to the use of P in crop production.

INTERACTIONS BETWEEN SOIL AND FERTILIZER P AND THEIR CONSEQUENCES FOR P AVAILABILITY TO CROPS

No attempt is made here to present a comprehensive account of the chemistry of soil P, nor give in detail the changing concepts of the behavior of soil and fertilizer P, as these have been reviewed recently by Syers *et al*. (2007). Instead, we consider recent concepts about the behavior of soil and fertilizer P in relation to plant nutrition and crop production.

Early views on the behavior of soil and fertilizer P

Until recently there was a long-held and persistent view that when a water-soluble P compound, like monocalcium phosphate, was added to soil any residue of the P remaining after P was taken up by the crop was to a large extent retained ("fixed") in the soil in forms that were unavailable to subsequent crops. This view can be traced back to a paper by Way (1850) and since that time soil scientists have been intrigued by, experimented on, and discussed at great length, the fate of P added to soils. Way (1850) percolated solutions of water-soluble potassium (K) and ammonium (NH_4) phosphates through columns of soil and found that the Pi was retained in the soil whereas other anions, often chloride or sulfate, appeared in the leachate. To explain the observed retention of Pi, Way (1850) proposed that the accompanying K and NH_4 cations had been retained by exchange with the divalent calcium (Ca) cation and that the Pi had combined with the free Ca cation to produce a water-insoluble phosphate of lime. He conjectured, that this calcium phosphate (not specified in his paper) would be soluble in the dilute carbonic acid solution, occurring in soil, so that Pi would be released into the soil solution for uptake by roots. The amount of Pi solubilized by this process, however, is probably very small judged by the results from the early years of the Rothamsted experiments, which showed that adding superphosphate fertilizer gave large increases in crop yields (Johnston 1994).

Using data from P balance studies (P applied *minus* P removed in harvested crops) for two long-term experiments at Rothamsted, Dyer (1894, 1902) concluded that much of the positive P balance in these experiments was retained or "fixed" in the surface soil. Also at this time, field experiments assessing the value to crops of the P retained in soil showed that it had very little or no effect on subsequent crop yields. In other words, there was no residual effect of the applied P fertilizer. This was taken as further evidence that P residues were fixed in soil in forms that were not available for uptake by plant roots. Based perhaps in part on these observations, Russell (1912) supported the view that the retention of P applied to soil as water-soluble monocalcium phosphate was due to the precipitation of a water-insoluble calcium phosphate.

Beginning in the 1920s, there were many studies on the reactions and fate of fertilizer P added to soil that produced conflicting results and conclusions (see reviews by Pierre and Norman 1953; Larsen 1967; Khasawneh *et al.* 1980). From the 1950s, especially in the USA, many laboratory experiments and modeling exercises were performed on the reactions that occur when water-soluble phosphates are added to soil. Laboratory experiments showed the formation of "discrete-phase", water-insoluble minerals like variscite (aluminium phosphate) and strengite (iron phosphate) under acid conditions and a range of calcium phosphates under near-neutral and alkaline conditions when monocalcium phosphate was added to soil. It was widely assumed that these water-insoluble minerals were formed when water-soluble, fertilizer P reacted with soil components, and this would explain why the plant availability of fertilizer P was so small in many soils (Kurtz 1953; Hemwall 1957; Jackson 1963; Huffman 1962, 1968; Larsen 1967; Sample *et al.* 1980). In attempts to show that such compounds were produced, soil P was sequentially extracted with reagents thought to extract distinct phase, inorganic P compounds. The latter included iron, aluminium and calcium phosphates, the type and amounts formed depending on the acidity of the soil (Dean 1938; Chang and Jackson 1958). Barrow (1983a) suggested that the formation of these insoluble compounds was debatable because the conditions used in many of these laboratory experiments were far removed from the conditions in the heterogeneous environment of the soil.

In the late 1950s and 1960s, thermodynamic models, particularly solubility isotherms, were combined with laboratory data to produce elegant descriptions for the formation of pure crystalline compounds in equilibrium with Pi in solution (Lindsay and Moreno 1960; Larsen 1967; Lindsay 1979). However, these models often ignored the conditions that exist in soil and Barber (1995) suggested that P compounds in soil are likely to be impure and of unknown solubility and, therefore, not likely to be the reaction products following addition of water-soluble P to soil.

Evidence for the need to review ideas about the behavior of P in soil

Two earlier papers that questioned the assumption of P fixation appear to have received little attention. Coleman (1942) noted that the failure of a crop to respond to fertilizer P was not necessarily due to the rapid fixation of P by soil. Rather, it could be because there was already sufficient plant-available P in the soil and that large amounts of soil P "formerly considered fixed" are available to plants. Kurtz (1953) also argued that the results of experiments that implied that P was held in soil by simple precipitation reactions sometimes led to rather questionable conclusions. He noted that, "Contrary to the apparent belief of two decades ago, more recent evidence indicates that the reactions of phosphorus with soils are not entirely irreversible and that for most soils the term "fixation" is an exaggeration". Major changes in the concepts of the behavior of P in soil came in the late 1960s and 1970s with the work of Posner and Barrow (1982) and Barrow (1983b) on the adsorption/absorption and desorption of Pi in soils. The slow reaction between Pi and soil was attributed to the diffusive penetration of adsorbed phosphate ions into soil components as shown by Evans and Syers (1971). This explained the decrease in extractability, isotopic exchangeability and plant availability of P added to soil over time (Barrow 1980).

In a comprehensive review of the literature, Sample *et al.* (1980) concluded that both sorption and precipitation reactions were likely to occur simultaneously following the addition of fertilizer P to soil. These authors also considered that initial P reaction products and the initially adsorbed Pi may be metastable with important changes over time such that there would be lower concentrations of Pi in the soil solution.

Barrow (1983b) used data from Leamer (1963) to support his suggestion that absorbed Pi could be released over time (i.e. that adsorption/absorption was largely reversible), but that this could be a slow process. Data from the Exhaustion Land experiment at Rothamsted, using "Olsen P" (P extracted from the soil with 0.5 M $NaHCO_3$, pH 8.5) as an estimate of plant available P, provides evidence for the reversibility of adsorption/absorption of P in soil (Johnston and Poulton 1977). From 1856 to 1901, P was added first as fertilizer to wheat (1856–1875) and then as both fertilizer and farmyard manure (FYM) to potatoes (1876–1901). The P balance was positive with both P treatments, but only about 15% of this P was extracted by the Olsen method, the remainder being in forms that were no longer immediately plant available. After 1901 no more P was applied, and from 1901 to 1958 the P balance was negative. However, only about 37% of this negative balance could be accounted for by a decline in Olsen P. This implies that some P that was not measured as plant available in 1901 had become available over time. Both sets of data indicate a degree of reversibility of sorbed P. Further evidence for reversible transfer of P between fractions of soil P is provided by experiments in North America (Barber 1979; Halvorson and Black 1985; McCollum 1991).

Additional evidence for the release of plant-available P that was not initially measured as Olsen P comes for an experiment on a sandy clay loam soil at Saxmundham in Suffolk, England. From 1965–1968, differential P fertilization established eight soils with Olsen P ranging from 3–67 mg kg^{-1}. For the next 16 years these soils were cropped with potatoes, sugar beet, spring barley, winter wheat and field beans grown in rotation and without addition of P but with adequate N and K. The cumulative P offtake in the crops was determined and, in alternate years, the top 23 cm soil was sampled to determine Olsen P. The decline in Olsen P ranged from 43% on the most P enriched soil to less than 10% on least P enriched soil. However, the decrease in Olsen P did not account for all the P removed in the harvested crops. Thus, P measured by the Olsen method was being replenished by P from P reserves not measured by the Olsen method in 1968. Of equal interest was the observation that the individual decay curves for Olsen P from each of the eight

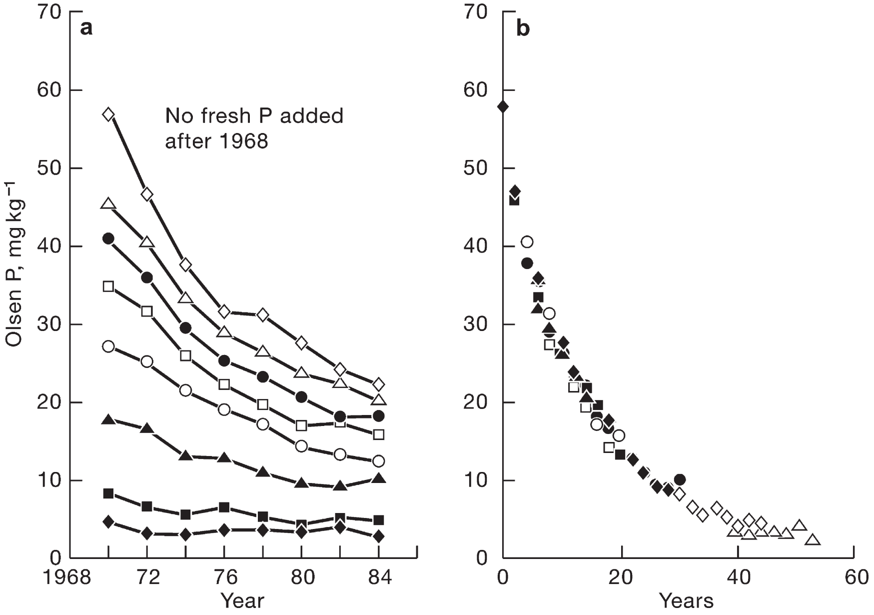

Fig. 9.1 Decline in Olsen P during 16 years in eight soils having different Olsen P (**a**). Development of a coincident decline curve by making horizontal shifts (**b**). Data are from an experiment at Saxmundham, UK. (Adapted from Johnston and Syers 2006.)

soils (Figure 9.1a) could be brought into coincidence by horizontal shifts to produce a unified decay curve for a 50-year period (Figure 9.1b; Johnston and Poulton 1992). This is critically important to the present discussion for it indicates that there are different pools of soil P in equilibrium with one another. As P in one pool is being depleted it is replenished (buffered) by P from other pools and the faster the replenishment the greater the buffer capacity of the soil. A unified decay curve from a large initial value of Olsen P supports the contention that there are no specific, well-defined and discrete fractions of soil P, as was previously widely believed. If there were discrete fractions of soil P it is probable that decay curves, such as those presented in Figure 9.1, would be a series of steps rather that a smooth curve.

Current concepts of the behavior of P in soil

The view that water-soluble P added to soil in fertilizers and not used by the crop to which it was applied became mostly fixed in soil in forms unavailable to future crops was largely supported by work prior to the 1950s. Subsequently, this view began to be challenged for a number of reasons. Field experiments showed that plant-available P residues could accumulate, at least in some soils, and that these residues increased crop yields. It was also realized that the results from many of the laboratory experiments were unlikely to relate to what happened in field soils because the conditions used for the laboratory experiments were inappropriate. This suggested that new concepts about the behavior of P in soil needed to be formulated.

These new concepts, accepted at least among many involved in soil and fertilizer P research, relate to P equilibria in soils which explain reasonably well changes in the extractability of soil P, and the decrease in plant availability of added P with time. These equilibria primarily involve adsorption and absorption reactions that may be largely reversible with time. For P, which in the short- and long-term will be plant available, the current concept is that this P is held by soil components with a continuum of bonding energies. Building on this concept, pools of soil P related to the accessibility and extractability, and thus the plant-availability of the P, can be categorized and conceptualized and expressed diagrammatically (Figure 9.2). Phosphorus in the soil solution, the first pool, is immediately available for uptake by plant roots and is present in solution in ionic forms. The second pool represents Pi that is only weakly bonded to the surfaces of soil components. This Pi is readily available because it is in equilibrium with Pi in the soil solution and is readily transferred to the soil solution as plant roots take up Pi. Readily available Pi was often described as labile P in papers published in the 1950s. The P in the third pool is less readily available for plant uptake, but it can become available over time. This P is more strongly bonded to soil components, or is present within the matrices of soil components as absorbed P (i.e. P adsorbed on internal surfaces). The P in the fourth pool is only very slowly available, often over periods of many years. It has a low or very low extractability. It is P that is very strongly bonded to soil components, or is P that has been precipitated as slightly-soluble P compounds, or it is part of the soil mineral complex, or it is unavailable due to its position within the soil matrix.

The most important feature of this conceptual model is the reversible transfer of P between the first three pools and it is this that clearly confronts the concept of irreversible fixation of P in soil. However, when a water-soluble P source is added

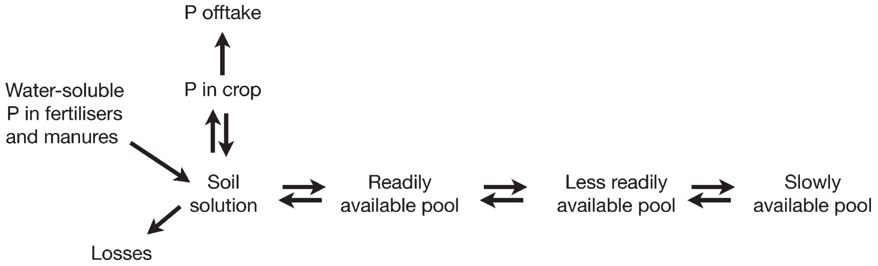

Fig. 9.2 A simple schematic representation of phosphorus pools in the plant-soil system. Soil analysis to estimate P in the readily available pool includes that in the soil solution. (Adapted from Syers *et al*. 2007.)

to soil only a small fraction remains in the soil solution, the remaining P becomes distributed between the readily- and less readily-available pools. For example in the long-term experiments at Rothamsted, Woburn and Saxmundham, where P has been applied as fertilizer or FYM for over 40 years, only about 13% of the increase in soil P is Olsen P (Johnston *et al.* 2001).

It is P in the soil solution and the readily available pool that is measured by routine soil analysis, and many different methods are used for this purpose. These include equilibration with resin and the methods of Olsen, Bray, Mehlich, Morgan and CAL (Kamprath and Watson 1980). Although these reagents all extract weakly bonded P, the amount of P extracted varies from reagent to reagent, which suggests that the readily available pool is not a finite quantity or a specific form of P. However, provided that the method characterizes the soil well, such that there is a strong relationship between the amount of P extracted and the response of a crop to an application of P fertilizer, then this fraction of P can be thought of as being well defined.

There is no routine method of soil analysis employed to estimate the amount of P in the less-readily available pool, and there is little information on the relation between the amounts of P in the readily- and less-readily-available pools of P. Recently sequential extraction of soil P has been used to follow the changes in different P fractions as the P balance has changed over time (Beck and Sanchez 1996; Blake *et al.* 2003). In these experiments, the quantity of P in all soil P fractions extracted increased as P accumulated in the soil and decreased as soil P reserves were depleted. However, no clear relationships have yet been shown between the amounts of P extracted by each reagent, or the rates of transfer of P between P pools. Both require further investigation, realizing that sequential extraction is time consuming and does not lend itself to routine soil analyses.

This concept of soil P existing in various pools related to the availability of Pi for plant uptake applies to all soils and may be considered in relation to crop production in two greatly contrasting agro-environments. One is where intensive agricultural systems operate, mainly in some developed countries. Here, large amounts of plant-available P have accumulated in soil from past additions of P in fertilizers and manures, and crop genotypes have been selected on the basis of a large yield potential. The requirement in this situation is to use soil and fertilizer P most efficiently. The other, contrasting, agro-environment is where the soil contains only very small amounts of plant-available P, which limits crop production, and where the availability of P fertilizer is often restricted by its cost or lack of infrastructure to transport it to where it is required. Estimates suggest that globally perhaps 67% of total farmland contains too little plant-available P (Batjes 1997) and much of this land is in less developed countries. Native plants that grow in many of these soils have adapted to the low P conditions in various ways. These adaptations and what can be learnt from them of benefit to the growth of crops is discussed later in this chapter, and in other chapters of this book (Lynch and Brown 2008; Raven 2008; White and Hammond 2008). For both these very different agro-environments it is possible to consider how soil and fertilizer P can best be made more accessible and available for plant uptake.

P ACQUISITION BY ROOTS OF CROP PLANTS

Plants acquire P by the roots taking up orthophosphate anions (Pi), mainly $H_2PO_4^-$ and to a lesser extent HPO_4^{2-}, from the soil solution. The size and efficacy of the root system and the presence of these anions at the soil-root interface therefore control the ability of the plant to take up sufficient P to achieve its yield potential when all other factors affecting growth are optimum. Plant and soil factors that directly or indirectly affect to availability and uptake of P by crops are summarized in Table 9.1.

Transport of Pi from the bulk soil to the rhizosphere

The concentration of Pi in the soil solution is very small and even in the most fertile soils rarely exceeds 8 μM (Barber 1995). In soils that are highly weathered, sandy or alkaline, Pi concentrations are commonly less than 1 μM (Reisenauer 1966). Thus, the amount of P in the soil solution that is immediately available for crop uptake as Pi is very small and, without frequent replenishment, is inadequate to meet a crop's large demand for P for optimal growth. This is illustrated by the data in Table 9.2. Based on the assumption that the concentration of Pi in the soil solution is 1 mg L^{-1} (approximately 3 μM), and that a crop producing a large yield requires a

Table 9.1 Plant and soil properties that control the availability of P uptake by crops either directly or indirectly. (Adapted from Horst *et al*. 2001.)

Plant properties	Soil properties
Root uptake efficiency	**Chemical**
Uptake capacity	pH
Uptake affinity	Organic ligands
Minimal concentration for uptake	Cation exchange capacity
Root morphology	CO_2
Root length density	Redox potential
Root fineness	Buffer capacity
Root hairs	Toxicity (e.g. Al)
Infection with mycorrhizal fungi	Deficiency (e.g. K, Ca)
Rhizosphere modification	**Physical**
H^+/OH^- balance	Temperature
Excretion of organic acid anions	Moisture
Increase in reduction capacity	Bulk density
Phosphatase production	Mechanical impedance
	Biological
	Microbial activity
	Soil fauna
	Pathogenic fungi

Table 9.2 Illustration, using two different approaches (A and B), of the inability of the P in the soil solution to supply the P requirement of a crop based on a total requirement of 30 kg P ha^{-1}. (After Kirkby and Römheld 2006.)

A	**P requirement:** 30 kg P ha^{-1}	
	(10 t DM with 0.3% P; 100 day growth period)	**300 g P ha^{-1} day^{-1}**
	P concentration in soil solution: 0.1 mg P L^{-1} (~3 µM)	↓↓ *f = 5*
	(soil - bulk density 1.3 g cm^{-3}; depth 25 cm, water content 18%)	↓↓
	= 0.6×10^6 L → 0.1 mg × (0.6×10^6 L)	↓ **60 g P ha^{-1}**
	Spatial availability	↓ *f = 25*
	(only 20% of topsoil exploited by roots)	**12 g P ha^{-1}**
B	**Water requirement:** 500 L kg^{-1} shoot dry weight produced	
	(transpiration coefficient: 300–600)	
	P solubility: 0.1 mg P L^{-1} → 0.1 mg × 500	**50 mg P kg^{-1} DM**
		↓ *f = 60*
	P requirement: 0.3% P in leaf DM	**3 g P kg^{-1} DM**

total P uptake of about 30 kg P ha^{-1} over a growth period of about 100 days, even allowing for complete spatial accessibility of Pi to the roots, the Pi in soil solution must be replenished five times each day. However, because not more than 20% of the topsoil is explored by roots during a growing season, the Pi in the soil solution has to be replenished at least 25 times daily to meet plant demand (Marschner 1995). A very similar conclusion is reached using another theoretical calculation. This calculation is based on the water use by a crop, the Pi concentration in the soil solution and the actual P concentration in the plant. The data clearly demonstrate that the amount of Pi transported by convective flow of water to plant roots (mass flow), is far too small to meet plant demand. Lambers *et al.* (1998) consider that mass flow accounts for less than 5% of the P demand of a plant and the amount of P intercepted by plant roots as they push their way through the soil is only half this amount.

The principle method by which Pi is replenished in the soil solution is by diffusion (Jungk 1994). Uptake of Pi by plant roots from the surrounding solution, which is not usually a growth limiting step, is energy demanding and takes place very rapidly against a steep concentration gradient between the soil solution and the cytoplasm of the plant cell (Schachtman *et al.* 1998; Amtmann *et al.* 2006). In this process, two different but equally important effects are induced. The removal of Pi from the root surface creates a gradient in the concentration of Pi between the root surface and the bulk soil. This gradient is the driving force for the diffusion of Pi in the soil solution and results in the transport of Pi from the bulk soil to the root surface. This, in turn, disturbs the equilibrium between the Pi concentration in the soil solution and that in the readily plant-available pool, resulting in the release of Pi from the latter to maintain the Pi concentration in the soil solution. If delivery of Pi to the root by this process of diffusion is too slow to meet plant demand for normal growth, zones of Pi depletion around roots are created, indicative of deprivation of Pi supply (Mengel and Kirkby 2001).

Maintaining Pi concentrations in the soil solution

Maintaining the concentration of Pi in the soil solution is dependent on the Pi buffer capacity of the soil. This can vary greatly between soils depending to a large extent on the amount of P in the readily plant-available pool of soil P. The latter is likely to be larger in heavy textured, clayey soils than in light textured sandy soils. Schofield (1955) introduced the concept of an intensity factor, which represents the concentration of Pi in the soil solution, and a capacity factor, indicative of the amount of more strongly held P in the soil. The approach accords with current thinking of P being held by soil components with a continuum of bonding energies (Figure 9.2). Generally the main component of the capacity factor as envisaged by Schofield is the pool of low energy sorbed P together with the readily-mineralizable organic P. This organically bound P may be important in relation to the P nutrition of crops in some soils but it is not taken into account in most routine methods of soil analysis used to estimate P availability. In part this is because the mineralization of organic P is highly dependent on ambient conditions in the field, such as soil temperature and moisture, which cannot be measured by extracting dry soils in the laboratory. In addition, the capacity factor is also dependent on the volume of soil occupied by roots. However, as discussed above, soil analysis using an appropriate method can provide an assessment in most agricultural soils of P that is potentially available to plants under conditions favorable for root growth and activity.

P acquisition over the growth period

Young plants have a very large demand for nutrients but only small root systems. Consequently, in the early stages of growth, the rate of nutrient uptake per unit length of root is extremely high. For example, the P uptake rate per unit length of root by 20-day-old maize plants is about ten times that of 30-day-old plants (Mengel and Barber 1974). Further evidence for the importance of maintaining a sufficient level of readily plant-available P in the soil appropriate to the growth stage to optimize both yield and efficient use of P is illustrated by the data presented in Figure 9.3. This shows the daily rate of P uptake throughout the growth of spring barley crop grown on two soils, one with 100 mg kg^{-1} and the other with only 5 mg kg^{-1} Olsen P. The larger Olsen P value is more than sufficient for all arable crops, and the maximum daily P uptake rate was 0.6 kg ha^{-1} compared with only 0.2 kg ha^{-1} when the soil was deficient in available P. This difference was reflected in the grain yields at harvest which were 6.4 and 2.9 t ha^{-1}, respectively (Leigh and Johnston 1986).

Modeling P acquisition by plants

Mechanistic mathematical models to estimate Pi transfer from the soil into the plant have been developed based on the assumption that Pi transport from the soil to the root is equal to Pi uptake by the plant (Claassen *et al.* 1986; Barber 1995). Transport

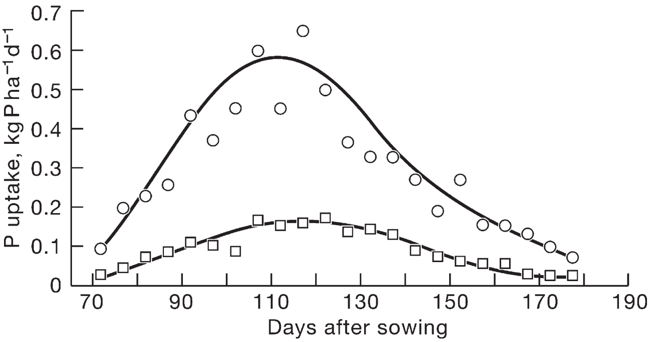

Fig. 9.3 Daily phosphorus uptake rate of spring barley grown on a soil with adequate P reserves (○) and too little readily available soil P (□). (Adapted from Leigh and Johnston 1986.)

from soil to roots is assumed to proceed by mass flow and diffusion, and Pi uptake into the root follows Michaelis-Menten kinetics. The higher the rate of Pi uptake, the faster is the decrease in Pi concentration outside the root and this, in turn, results in a steeper Pi concentration gradient between the root surface and the bulk soil. Thus the diffusive flux of Pi from the soil towards the root increases. At the same time, as the Pi concentration at the root surface is depleted, Pi uptake into the root slows. The model also takes into account various root parameters because of the low mobility of Pi in soil and the need for roots to grow into regions where Pi is located to acquire Pi (see Jungk 1994).

The Barber-Claassen model has shown good agreement between actual and predicted P uptake by plants, particularly for cereals where soil Pi was adequate and the supply of Pi via diffusion was sufficient to meet the demands of the crop. However, where soil P was less than adequate, and the rate of Pi supply via diffusion was likely to have been limiting, the crop acquired more P than was predicted by the model (Jungk and Claassen 1989). This discrepancy has been interpreted by those developing the model as an indication that under conditions of low Pi supply, roots develop properties that enhance Pi acquisition and these properties are not taken into consideration by the model that has a physico-chemical basis only. Such properties include the acquisition of relatively large amounts of P by VA mycorrhiza that effectively increase the surface area of roots (Jungk and Claassen 1989) and the possible release of organic anions from the roots into the rhizosphere, thereby increasing the availability of Pi in the rhizosphere (Ryan *et al.* 2001). Such processes will be discussed later in this chapter.

EFFICIENCY OF P USE WHERE SOIL P SUPPLY IS ADEQUATE

In developed countries, and in particular those with a long history of productive agriculture, plant nutrients, as organic manures or fertilizers, have been added to the soil over many years and, since the 1950s, their amounts have increased dramatically.

In the case of P, the balance between that applied to the soil and that removed by the harvested crops became positive, with more being P applied than is removed. Consequently the level of plant-available P in soils has increased, so that the need to achieve economically optimum crop yields in environmentally benign ways needs to be reconsidered. In this section, the principles involved in achieving this are considered. Various measurements of P-use efficiency are discussed and, using data from long-term experiments with known P fertilizer inputs, evidence is provided of much greater efficiency of P fertilizer use than is commonly recognized. This is followed by a brief description of P modeling aimed at efficient P fertilizer programming. Finally, some of the more agronomic aspects which are or could be available to improve the efficient use of soil and fertilizer P are mentioned.

Critical levels of soil P for crop production

There is an important outcome to the conceptual model that soil P exists in a number of pools of different extractability and, therefore, of differing availability to plants (Figure 9.2). If the P in the readily extractable pool supplies the bulk of Pi for plant uptake then it is only necessary to accumulate a certain amount of P in this pool to achieve optimum crop yield. This is consistent with the concept of a critical P value for a particular crop in a given situation. This point is well illustrated by the asymptotic relationship between yield and Olsen P for sugar beet, barley and winter wheat crops grown at three sites in Southeast England (Figure 9.4; Johnston 2005). As Olsen P was increased from very low levels, yield increased rapidly at first and then more slowly to reach an asymptote. The Olsen P associated with yield reaching the asymptote can be considered as the critical value. Below this value there is a loss of yield, representing a financial loss to the farmer. Above the critical value there is no increase in crop yield with further P additions. Adding more P is not only a financial loss and a squandering of a precious resource but may lead to the risk of adverse environmental effects (Johnston and Dawson 2005). Importantly, even though the yields of each of the three crops differed appreciably between years due to weather and N supply, the critical value for Olsen P was very similar for all years for each crop (Figure 9.4). Ideally, the critical value should be determined for each soil type, crop and farming system. In the UK, however, experience suggests that, in the absence of detailed information, a general value can be used as a first approximation. For soils growing arable crops, Olsen P values in the range of 15–25 mg kg^{-1} are satisfactory (MAFF 2000). Other examples of critical values for farming systems and different crops taken from the international literature are given by Syers *et al.* (2007). Applying the concept of a critical P value for crops and farming systems leads to greater agronomic efficiency of P use. Maintenance of the critical level is dependent on replacing the amount of P removed from the field in the harvested crop. This amount can be calculated from the yield and the P content per unit of yield removed from the field. The P concentrations of specific crops and cultivars can vary considerably (Sanchez 2007), indicating that locally determined

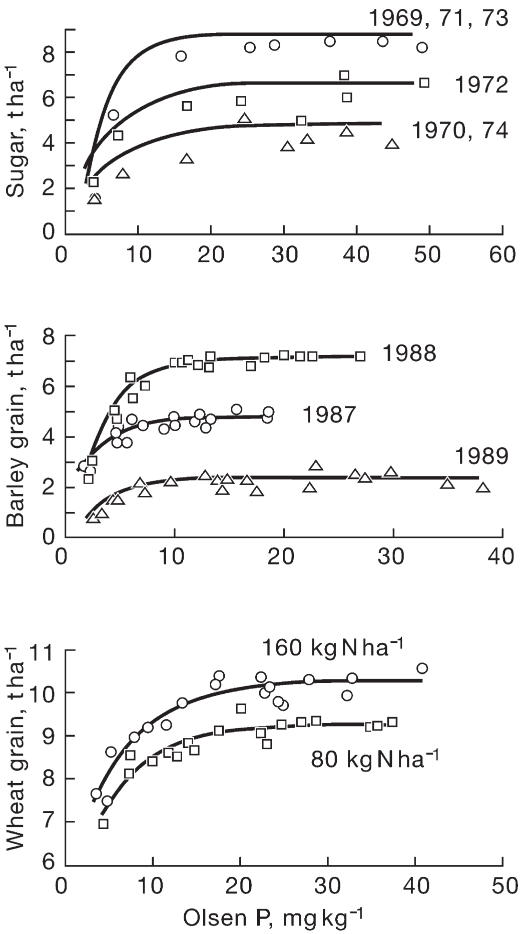

Fig. 9.4 Response of sugar beet, barley and winter wheat to increasing Olsen P in several years on three sites in southeast England. (Data from Johnston 2005.)

values should be used if available. This approach of maintenance P applications is now becoming widely adopted. Consistency of soil sampling and analytical techniques across years is essential, and soil sampling needs to be done on a frequent and regular basis to ensure that the soil is maintained at or about the critical level.

Measuring the efficient use of P fertilizer

The efficient use of fertilizers in crop production has always been important. In recent decades, however, it has become an issue of even greater importance especially for N and P fertilizers. This is because the presumption that they are not used efficiently has been linked with the loss of N and P from the crop-soil system and the risk that such losses pose to the wider environment. The new concepts about the behavior of soil and fertilizer P have led to a reappraisal of measuring the efficiency with which P is used in agriculture.

Frequently a large percentage recovery of an added nutrient is taken to imply an efficient use of that nutrient by a crop (Cassman *et al.* 1998). Several methods have been used for calculating the recovery of applied nutrients, including direct methods that employ uncommon isotopes to label the added nutrient or indirect methods that calculate differences between nutrient inputs and their concentrations in crops and soils. Direct methods generally use a fertilizer containing a tracer element, such as ^{15}N or ^{32}P, to estimate the uptake of a nutrient originating from the fertilizer applied. Nowadays, this is rarely used for P because of its expense, and the relatively short half-life of ^{32}P means that reliable results can only be obtained for crops grown for short periods. The difference method allows an apparent recovery of a nutrient to be determined, but includes a contribution from nutrient already in the soil in addition to the fertilizer applied. The difference method is widely used in agronomic studies (see Crowther *et al.* 1951 for earlier reviews). It is calculated as the nutrient content of a crop given the nutrient minus the nutrient content of a crop not given the nutrient divided by the amount of nutrient applied, and expressed as a percentage. Calculated in this way, the percentage recovery of P and, by inference, the efficiency with which the P has been used by a crop can vary greatly between experiments. This variability can be due to a combination of many factors. These include: (a) the yields of the crops with the two treatments, since these can be affected differently by weather, availability of other nutrients and soil physical conditions; (b) the amount of readily plant-available P in the soil to which no P is applied, because this greatly influences P uptake by the crop grown on this soil; (c) the extent to which the freshly applied P is mixed with the volume of soil where roots are taking up nutrients.

The balance method proposed and used by Syers *et al.* (2007) is another and better method of estimating the efficiency with which P fertilizers are used. It has been appreciated since the beginning of the 20th century that most or all of the P residues from fertilizers and manures accumulated in the topsoil. Since then this observation has been confirmed for many soils with the exception of very sandy soils in high rainfall areas. The direct method (^{32}P) for estimating percentage recovery gives values no larger than 20–25% and underestimates the P content of the crop. The remainder of the P in the crop comes from the reserve of plant-available P in the soil, mainly the topsoil. If soil fertility in terms of available P is not to be depleted then this P must be replaced. Hence added P that is taken up by the crop together with that which has gone to replace the P taken up from the soil reserves may be considered as part of the efficient use of added P fertilizer. The balance method simply calculates percentage P recovery of the added P. This method invariably gives higher percentage P recoveries and hence P use efficiencies than those calculated by the difference method. However, the actual value will still vary depending on the factors noted in the preceding paragraph.

Some examples comparing the difference and balance methods are given in Tables 9.3 and 9.4. Table 9.3 uses data from the Broadbalk winter wheat experiment at Rothamsted, in which the amounts of P and N added each year have remained unchanged since 1852. The yield potential of the cultivars grown has increased appreciably and the data for three separate periods shows how yield affects the estimates of P recovery. There was little increase in yield without N and percentage P recovery changed little when estimated by either of the two methods. Where N was applied yield increased and so did P uptake and hence the estimate of percent P recovery, which was always greater by the balance method. The effect of the existing level of plant-available soil P on the estimate of percentage P recovery is shown in Table 9.4. In this experiment, a four-course rotation of sugar beet, barley, potatoes and barley was grown on two soils with 4 and 33 mg kg^{-1} Olsen P, respectively. Three amounts of P, 27.5, 55.0 and 82.5 kg P ha^{-1} were tested on the sugar beet and potatoes. Thus in each four-year period the total P applied was 55, 110 and 165 kg P ha^{-1}. The rotations were phased, with one starting in 1969 and the other in 1970. The data in Table 9.4 are the mean of both rotations. All the crops were analyzed to prepare a P balance. Percent recovery was calculated by both the difference and balance methods and, for appropriate comparisons was always larger by the balance method. For both methods the percentage recovery always declined with increasing P application. For the soil with 33 mg kg^{-1} Olsen P, percentage P recovery was small when calculated by the difference method and for the balance method one value exceeded 140%. Any value over 100% implies that the amount of P removed in the harvested crop was larger than the amount of P applied. If P removed exceeds P added over a number of years especially when the soils are at or about the critical value, then this will decrease the amount of plant-available P and jeopardize soil fertility.

Table 9.3 Comparison of the difference and balance methods for estimating recovery of added phosphorus illustrating the effect of nitrogen (by increasing yield) and growing cultivars with a larger yield potential. Data from the Broadbalk Experiment, Rothamsted. (Adapted from Johnston and Syers 2006.)

		Annual treatment[b]				
		Without N		With N		
Period & cultivar	P in crop[a] & P recovery	None	PK	None	P	PK
1852–1871	P in crop (kg ha^{-1})	4.9	6.6	6.5	9.2	11.3
Red	Difference method (%)	–	5	–	8	14
Rostock	Balance method (%)	–	20	–	28	34
1970–1975	P in crop (kg ha^{-1})	6.2	6.8	9.0	13.1	17.3
Capelle	Difference method (%)	–	2	–	12	24
Desprez	Balance method (%)	–	21	–	40	52
1985–2000	P in crop (kg ha^{-1})	3.7	4.7	5.7	12.7	17.4
Brimstone	Difference method (%)	–	3	–	20	33
	Balance method (%)	–	13	–	36	50

[a] Total P in grain plus straw

[b] Annual treatment (kg ha^{-1}): N = 96, P = 33 (35 since 1974), K = 90

Table 9.4 Comparison of two methods of estimating phosphorus recovery when phosphorus was applied at three amounts to a sandy clay loam soil at two levels of Olsen P at Saxmundham, UK. Data are means of two four-year rotations (1969–1972 and 1970–1973) of sugar beet, barley, potatoes and barley. (Data from Johnston and Syers 2006.)

	Soil Olsen P (mg kg^{-1})					
	4	33	4	33	4	33
P applied (kg ha^{-1})[a]	P uptake in four years (kg P ha^{-1})		Recovery (%) by difference method		Recovery (%) by balance method	
0	23.3	75.2				
55	46.9	77.0	43	3	85	140
110	57.2	79.4	31	4	52	72
165	63.8	82.2	24	4	39	50

[a] P applied at 27.5, 55 and 82.5 kg P ha^{-1} to potatoes and sugar beet only

Large P recoveries are found for a wide variety of crops grown on different soils (Syers *et al.* 2007). This is even the case for soils of high P adsorbing capacity that were initially acid and deficient in P as in the Cerrado (Savannah) semi-arid region of Brazil. Once soil acidity in the topsoil was corrected to 50% base saturation resulting in the absence of free Al ions in the soil solution, crops responded well to additions of water-soluble P fertilizers. In two experiments, the residual P from a single application of P fertilizer increased yields for the next 13 and 17 years. Recovery of the added P, as measured by the balance method, over this time period ranged from 35–62% with all-arable cropping and from 52–69% when a pasture grass was included in the rotation. Percent recovery was larger with the smaller amounts of P applied. Similarly Heinemann (1996, quoted by Singh and Lal 2005), reported that as much as 68% of a 150 kg P ha^{-1} application of diammonium phosphate was recovered by a maize-bean rotation over five years on an Oxisol in western Kenya.

It can be concluded that the long and widely held belief that P in fertilizers is irreversibly fixed in the soil is no longer tenable. Applied P is used most efficiently if the amount of P in the readily available pool is sufficient to ensure optimum yields. This critical value may vary for different crops and soil types, but it can be maintained by replacing the P removed in the harvested crop. Soil sampling and analysis should be carried out on a regular and frequent basis to ensure that sufficient P is applied to maintain the critical value. Percent recovery or use of the added P in the year of application can then be calculated as the P removed in the harvested crop relative to the P applied – the balance method. Percent recovery calculated in this way frequently exceeds 50% indicating that P is used much more efficiently than previously thought.

Modeling P fertilization

The need for using P fertilizers efficiently has also driven the development of models that predict the effects of P fertilization on crop yield, crop P content and long-term changes of soil P, enabling the consequences of different P fertilization strategies to be assessed *in silico*. Greenwood *et al*. (2001) have proposed a mechanistic model based on the maintenance of three active pools of soil P with an input for the net P addition, close in concept to that described earlier (Figure 9.2). The equations have been calibrated for some crops from the results of fertilizer experiments and underpin a dynamic version of the model that permits annual inputs and calculates the time course of the various P pools. The model includes equations for the dependence of crop P uptake on the content of P already in the plant and of the effects of the distribution of P in soil and its diffusive transport to the roots. Inputs to the model are Olsen-P, a measure of soil P buffer capacity, initial soil water content and the water content at field capacity, the dates of planting and harvesting, and daily pan evaporation, temperature and rainfall. The model was calibrated using data from one set of field experiments and tested against the results of independent experiments. With the aid of the model PHOSMOD, which runs interactively at www.qpais.co.uk/phosmod/phos.htm, it is possible to simulate plant growth and phosphate uptake from day to day. Recently the model has been successfully assessed using data from a set of field fertilizer trials with spring barley (*Hordeum vulgare* L.) in Norway (Kristoffersen *et al*. 2006). Plant growth and P concentrations were recorded at three stages of growth and the model was able to reproduce the observed beneficial responses to placed P and starter fertilizer P, and to predict difference in soil types in the response to applied fertilizers. The model has also been integrated with similar models predicting crop responses to N and K fertilization, thereby enabling strategies for the synergistic application of P, N and K fertilizers (Zhang *et al*. 2007). The model appears to be a promising tool for predicting effects of P fertilizer strategies and may well play a role in planning future fertilization programs.

Agronomic strategies to improve the efficiency of soil and fertilizer P use

Using P inefficiently is to waste a valuable and dwindling resource and there are a number of options for improving P-use efficiency. For soils well supplied with P the question of when and how much P to add has already been discussed. Another question is whether agronomic practices can be altered or modified to improve the accessibility of soil and fertilizer P for root uptake. The methods to achieve this mentioned here and in the next section of this chapter are not exclusive but are discussed separately for convenience. Where appropriate they can be used for increasing crop production on soils well supplied with P and those where yield is restricted by lack of P.

Maintaining a well structured soil with adequate soil moisture and aeration is of paramount importance for the efficient use of soil and added P. Many soils have approximately equal volumes of mineral matter and voids or pores. The latter contain air and water and the relationship between these two is vitally important because roots need oxygen to respire and water for both growth and the transport of nutrients to the roots by diffusion.

Some soil properties that affect the accessibility and availability of P to crops are to a significant extent inherent characteristics of the soil, related to its chemical and physical properties, such as the distribution of P between the various soil P pools and the retention of P in soil in forms that are not immediately available to plants. These could be difficult to change or modify. Many soil properties, however, can be modified comparatively easily to ensure that there is no restriction to root growth and/or the availability of P. Whether such modifications are adopted or not will be determined largely by costs and benefits.

Root growth is restricted in compacted surface soil and by the presence of dense subsurface layers, such as plough pans. Compacted soil tends to have few large pores, restricting water and air movement, and too many pores with diameters too small for root tips to enter. This restricts spatial access to Pi within the soil mass and also slows the rate of Pi diffusion to the roots. Such compaction can be avoided by timely soil cultivation, by minimum-tillage and by maintaining a permanent crop or crop-residue cover on the soil surface. Also, traffic over the soil surface and poaching by livestock when the soil is wet, as occurs on heavy-textured soils in humid temperate regions, should be avoided.

Minimum or zero tillage allows the maintenance of a vegetative cover on the soil and is also an approach to minimizing soil erosion. The impact of no-till systems on the availability of soil and fertilizer P has been studied extensively in the USA and the Canadian Prairies. Initial fears that because P was not cultivated into the soil profile its availability to crops would decline, with adverse effect on yield, have been overestimated (P. Fixen (2007), personal communication). Any adverse effects of P stratification may be countered by better root exploitation of the surface soil to take up P due to improved physical structure of the surface soil under reduced tillage.

In acid soils aluminium (Al) toxicity can limit root growth. Largely eliminating free Al ions in the soil solution by liming acid soils to increase base saturation to 50% is usually sufficient. The effects of modifying the pH of acid soils (usually by lime application) on P retention and extractability has been studied widely but the results have been inconsistent (Haynes 1982; Sumner and Farina 1986; Mansell *et al.* 1984; Holford *et al.* 1994; Curtin and Syers 2001).

Surface soil structure and structural stability also affect both soil moisture content and root growth. Soil structure is particularly important in the case of P because, in contrast to N, Pi moves to only a limited extent in most soils (Barber 1995). Structural stability is related to particle-size distribution and to the calcium carbonate and organic matter (SOM) contents of the soil. In an experiment at Rothamsted, spring barley, potatoes and sugar beet were grown in the same field on soils with two levels of soil organic matter (SOM). The same yield could be obtained on both soils, but much larger concentrations of Olsen P were required for maximal yield on the soil with less SOM (Johnston and Poulton 2005). In a subsequent glasshouse experiment it was observed that the effect of differences in SOM on crop (ryegrass) growth was eliminated after passing these soils through a 2 mm sieve. The authors concluded that the extra SOM improved soil structure in the field and, thereby, the ability of the roots of the three crops to acquire sufficient P for maximum growth at a lower Olsen P.

Soil water content controls the acquisition of P both by favoring root growth so that a greater volume of soil can be exploited and also by allowing transport of Pi to the root surface by diffusion. The predominant effect appears to be that on root growth *per se*. Mackay and Barber (1985) showed that when the volumetric water content declined from 27% (medium) to 22% (low), P uptake decreased by 50–56% as a consequence of a decrease in root growth but only by 27–32% due to a decrease in transport of P by diffusion to the root surface.

Soil lost by water or wind erosion also removes nutrients and, where soils contain little P, such losses can be serious. Erosion is more severe on sloping land and in high rainfall areas. Controlling such losses is important from a water-quality aspect because the transfer of even small amounts of P, insignificant from an agronomic standpoint, from soil to water can cause the adverse effects of eutrophication of surface waters. Well-tested technologies are available to minimize such losses. These include terracing the land, planting trees periodically along the contour and cultivating and planting annual crops along the contour. Additionally, maintaining a soil cover of actively-growing vegetation or plant residues can minimize soil erosion and this can often be achieved with minimum and zero tillage practices. 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.

Applying P as fertilizer, organic manure or biosolids (i.e. sewage sludge) 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 P. 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. There are many logistical problems in storing and applying animal manures and biosolids, mainly because of their bulk, and farmers should be encouraged to follow codes of good agricultural practice in using them.

Much of the P in such manures is Pi (often dicalcium phosphate) added to the animal feed. Opportunities exist to improve the efficiency of P use in these systems. The digestibility of organic P in animal feeds can be improved by adding the enzyme phytase, so that less Pi has to be added, and consequently less Pi will be present in manures (Steén 2006). Improved management of grazed pasture could improve recycling of P by a more uniform distribution of animal excreta (Gillingham *et al.* 1980). Similarly, where manure is collected from housed animals, the manure could be spread more uniformly on arable land and grassland.

Organic manures and biosolids should be considered as sources of P and other nutrients rather than as wastes to be disposed of and making more effective use of them might allow a decrease in 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 to land in the manure. As with fertilizers, organic manures and biosolids should be used to maintain the critical level of plant-available P in soil.

When P is required, both the type of fertilizer, the amount applied and the timing of the application is important for improving the efficiency with which the P is used. 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. Generally water-soluble P fertilizers are appropriate for most soils with pH above about 6. Phosphate rock (PR) could be used as a source of P for crop production but its effectiveness depends on its reactivity in the soil, i.e. the speed at which soil acidity releases the P and the fineness of grinding which increases the surface area. It can be very effective on acid soils (Johnston and Syers 1998 and references therein). There is a tradition in some countries of composting PR with organic manure. It can also be mixed with elemental sulphur, which on oxidation mobilizes P with the production of "biosuperphosphate" (Stockdale *et al.* 2006). There is abundant evidence that PR is not effective on neutral and calcareous soils. There may be a place for slow-release P fertilizers, for example PR on acid soils, and at least one new slow-release product containing water-soluble P is currently being marketed (see http://deltafarmpress.com/news/nutrisphere-bz-pg/). The main use for slow-release P fertilizers would be in situations where P is at risk of loss by leaching, for example on coarse-textured soils in high-rainfall areas.

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 offtake with the larger yield results in a smaller amount of plant-available P remaining 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 GPS to apply the appropriate amount of fertilizer to different areas within the field.

Temporal and spatial factors have a considerable influence on the acquisition of P by plants. Consequently the timing and placement of P fertilizers is important and the recovery of P is usually increased when the fertilizer is placed near the seed, for example by band placement and seed priming. Such applications can be extremely effective in providing a sufficiently high Pi concentration near the emerging root system to supply a young plant until the root system is capable of accessing a sufficiently large volume of soil with a lower Pi concentration. Benefits from placing water-soluble P fertilizers depend on the speed of the adsorption and absorption reactions that occur in soil 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 significantly improves the recovery of fertilizer P, especially in the year of application (Sewell and Ozanne 1970; Barrow 1980; McKenzie and Roberts 1990; Stone 1998). Singh *et al.* (2005) showed that placing 10–40 kg P ha^{-1} at 10–15 cm depth in the semi-arid cropping region of northern Australia increased winter wheat yield by up to 43% because the P remained in more moist soil as the surface soil layer dried out. Bundy *et al.* (2005) reported that a small amount of starter fertilizer is a well established practice for grain crops, especially maize, in the USA. Dramatic benefits of seed-placed NPK starter fertilizer on the early development of sorghum and grain yields were reported by Lamont and Whitney (1991).

Changing agricultural practices

There is increasing interest in growing crops for the production of biofuels. There is a long-established industry producing ethanol from sugar cane, especially in Brazil. As fossil fuel reserves decline there are suggestions for growing crops other than sugar cane to process for bioethanol and to grow appropriate crops for processing for biodiesel. This could result in large areas of land currently growing food crops being used for growing such crops. Already a number of bioethanol plants based on using maize are in production in the USA. Such changes will impact significantly, probably within the next few years, on nutrient use and management. In a scenario of possible change in the USA, Fixen (2007) looked at four possible ethanol sources and the effects on nutrient use. The sources were maize replacing soybean and other crops, refineries using maize stover and fourthly biomass crops like switchgrass or Miscanthus. Such a change could result in an annual increase in P use of some 130,000 t, equal to 6.5% of current use in the USA. As none of the P in the crop will be in the biofuel it will be essential to look at ways to ensure that the P in the residue is returned to the land.

P ACQUISITION BY PLANTS WHERE P SUPPLY IS LIMITED

Phosphorus deficiency is a worldwide problem affecting crop production. It is estimated that crop growth on 5.7 billion hectares of land (equivalent to about 67% of the total farmland used worldwide) is limited by P availability (Batjes 1997). Nearly all the acid soils of tropical Africa, America, Asia and Australia are P deficient (Fairhurst *et al*. 1999). On these highly weathered soils of the humid and semi humid tropics, P deficiency relates to the inherently low levels of available P in soils characterized by a high capacity for P sorption. Cultivation of these acid soils is also restricted in particular by high Al concentrations in the soil solution, which are toxic to plants. Additionally the soils can suffer from lack of major nutrients including N, Ca, Mg and Mo, all of which limit crop growth.

In stark contrast to soils of the developed countries, where P has accumulated in soils, there is a negative P balance in the tropical soils of the poorer countries of the world. Here only small amounts of P fertilizer, if any, are applied to replace the P removed by harvested crops and that lost by soil erosion (Singh and Lal 2005). These soils are also in those areas of the world with the largest populations, where crop production is limited to the extensive agricultural systems with both small inputs and yields. Recommendations made to farmers have therefore to be easily adaptable in practice. Fertilizers, because of their relatively high cost to farmers, must be used very efficiently. On these low input, low yielding systems it is often more practical to make the plant "fit the soil" than the soil "fit the plant". For this reason there is a need to understand how plants are able to adapt to extreme environments not usually encountered in the temperate regions.

Phosphorus deficiency occurs on calcareous soils as well as on acid soils. These soils too are very widespread including areas of semi-arid and arid regions and cover more than 30% of the earth's surface (Chen and Barak 1982). The soils of most of north China and the Great Plains of the west USA are all calcareous. On these soils, which contain free $CaCO_3$ with a pH range from 7.5 to 8.5, crop growth can be limited by the low availability of Zn, Fe and Mn as well as P. Recommendations for the alleviation of P deficiency on these calcareous soils can thus be very different from those for acid P-deficient soils.

Plants grow and thrive in soils where P supply is limited by invoking a diverse array of adaptive mechanisms – morphological, physiological, biochemical and molecular which either conserve the use of P within the plant or enhance its acquisition from the soil (Vance *et al.* 2003). There is considerable research activity investigating these responses because knowledge gained about these adaptive mechanisms allows their exploitation to improve P acquisition by plants. This can be achieved by developing P-efficient crops both by targeted breeding as well as by gene transfer and manipulation. Additionally an understanding of how plants adapt to a lack of P provides the basis for management strategies and for efficient P fertilization both on adequately supplied soils as well as on low P soils. In this section some of these responses are considered and how they are being, and can be, exploited to improve utilization of soil and fertilizer P in agronomic practice is illustrated using a few selected examples.

Response of plants to a lack of P

A typical physiological response of plants to lack of P in the shoot is the diversion of a greater proportion of photosynthates to the root, thereby increasing the root: shoot biomass ratio (Hermans *et al.* 2006; Kirkby and Römheld 2006). This leads to an increase in P uptake that is achieved in two ways. First, the increased root surface area gives a greater contact between soil and root for Pi uptake and, second, metabolic changes in the root mobilize Pi in the rhizosphere, which can then be taken up by the plant. For recent excellent detailed accounts of these responses readers are referred to Vance *et al.* (2003), Amtmann *et al.* (2006) and Lambers *et al.* (2006).

Increased root growth in P-deficient soil is accompanied by marked changes in morphology. Roots are longer and more slender, thus increasing specific root length and surface area as they continuously explore the soil searching for nutrients. This strategy of increasing root exploration of a greater soil volume is highly effective in the acquisition of Pi, which is relatively immobile and unevenly distributed both in the soil and in the soil profile. In most soils, the topsoil contains more P than the subsoil and it is in the topsoil that profusely branched lateral roots with long root hairs proliferate especially in P rich patches (Drew 1975). An increase in root hair abundance and length under P deficiency also greatly increases the ability of roots to exploit the rhizosphere for P acquisition (Föhse and Jungk 1983; Bates and Lynch 1996).

Root hairs are produced more or less abundantly by most plant species particularly among the agronomically important crops of the Graminaceae, Chenopodeaceae and Brassicaceae (Jungk 2001). For plants lacking mycorrhizae, root hairs are the primary site for nutrient uptake. In many cases they may contribute up to 70% of the total root surface, thus increasing the surface area of the root cylinder by nearly 27 times (Jungk 2001). Also, under P deficiency the plasma membrane of root hairs is enriched in high-affinity Pi transporters (Liu *et al.* 1998). Of the possible ways of increasing effective root surface area, a change in root hair morphology is considered least costly metabolically (Hetrick 1991).

The importance of root hair length for P acquisition from the rhizosphere is illustrated well by an experiment contrasting Pi concentrations at varying distances from the roots of barley cultivars grown in soil (Figure 9.5; Gahoonia and Nielsen 1997). The cultivar Salka with long root hairs (1.00 ± 0.26 mm) exploited the rhizosphere twice as effectively as the cultivar Zita with short root hairs (0.63 ± 0.24 mm) by reducing the distance of Pi diffusion to the root. Accordingly, Salka also absorbed more P than Zita when grown in a low-P soil and also produced more shoot biomass (Gahoonia *et al.* 1999). More recent field experiments by these workers have shown that barley cultivars with long root hairs maintained stable

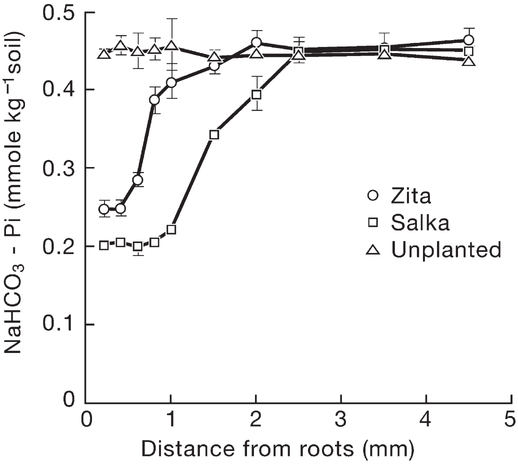

Fig. 9.5 Depletion of inorganic P (extracted with 0.5 M $NaHCO_3$) at varying distances from the roots of two barley cultivars, Salka (with long root hairs) and Zita (with short root hairs). (Figure redrawn from Gahoonia and Nielsen 1997.)

economic grain yields both in P-limited and P-sufficient soils. In contrast, cultivars with short root hairs produced small grain yields in P-limited soils and produced large grain yields only in P-sufficient soils (Gahoonia and Nielsen 2004).

A highly successful line of research that has exploited root adaptation to limited P supply has been the development of P-efficient genotypes of common bean (*Phaseolus vulgaris*) varying in root architecture (Lynch 1995; Lynch and Brown 2008). Several influential root traits underpinning genetic differences in P acquisition efficiency have been identified including topsoil foraging, via shallower basal roots and greater adventitious rooting, greater rhizosphere exploitation, via increased length and density of root hairs, and decreased root metabolic costs, via the formation of root cortical aerenchyma and root etiolation (Bates and Lynch 2001; Lynch and Brown 2008). Genotypic variation in basal root shallowness accounted for a 600% difference in P uptake from soil and was significantly correlated with yield when crops were grown in low P soils in field experiments. Genotypic variation in root hair length accounted for a 250% difference in P uptake in the field and genotypic variations in root metabolic costs for a 200% difference in root biomass and root exploration. Lynch and colleagues have also studied the effects of these traits on agro-ecosystem processes including drought resistance, nutrient cycling and soil erosion in field trials in Central America. Phosphorus efficient genotypes that yield between 200% and 300% more than existing cultivars are being used as parents in bean breeding programs in Latin America and Africa (Lynch 2007). In collaboration with Chinese colleagues these researchers are applying their knowledge to breeding P-efficient soybean lines, which are yielded 15–50% more than existing genotypes in low-P soils in south China (Yan *et al.* 2006).

Increasing root growth at the expense of the shoot is a hallmark response of plants to P deficiency. Just how important root growth is for P acquisition for plants grown under water stress is illustrated by the work of Mackay and Barber (1985). These workers observed that water shortage decreased both the growth of maize roots and Pi diffusion in the soil. However, they calculated that over half the decrease in P uptake under water shortage could be attributed to a reduction in root growth, which restricted exploitation of the soil volume, whereas the lower rate of Pi diffusion in the soil accounted for less than a third. In this experiment there was an increase in root hair growth due to the lower moisture level and although this increased root surface area, this only partially offset the lower rate of root growth, which was the primary cause of the reduced P uptake.

This example illustrates the principle that any factor which restricts root growth depresses P uptake primarily by limiting the volume of soil explored by the roots. Roots frequently encounter adverse abiotic factors, such as low or high temperatures, salinity, drought, as well as adverse biotic conditions including microbial pathogens, nematodes, viruses and plant parasites. All the factors that adversely affect root growth, and particularly the spatial distribution of roots in soil, will depress P uptake. Understanding that a restriction in root growth limits P acquisition underpins many agronomic measures to improve the efficient use of soils and fertilizer P.

Mycorrhizal associations

The roots of most crop plants are infected by arbuscular mycorrhizal (AM) fungi which enhance the ability of plant roots to explore a much greater volume of soil for nutrients and water (Smith and Read 1997). This symbiotic association between the host plant and fungus, based on the reciprocal transfer of P from the fungus to the plant and carbon from the plant to the fungus can be considered as another plant adaptation to P deficiency. Estimates suggest that the extent of the fungal mycelium may range from 10 to 100 m per root or per gram of soil under field conditions in P-deficient soil (McGonigle and Miller 1999). The occurrence of mycorrhizae in agro-ecosystems is almost universal but crop species differ in their dependence. Interestingly, some crops from families that are non-mycorrhizal, such as the Brassicaceae (e.g. oilseed rape) and Chenopodiaceae (e.g. sugar beet) appear to compensate by producing abundant root hairs. Evidence indicates that root hairs and external hyphae act similarly by shortening the distance for the diffusion of Pi to the root surface (Schweiger *et al.* 1995).

Attempts to exploit this adaptation to improve crop growth in the field through inoculation of selective AM populations have frequently been unsuccessful, not least because of competitive indigenous soil fungi. However, at CIAT, Colombia, when 50 kg P ha^{-1} as PR was added to an acid, severely P-deficient Oxisol, the yield of a number of crops was increased by inoculation with isolates of a native AM fungi (Howeler *et al.* 1987). Yields of cassava (*Manihot esculentum*) roots increased, on average, by 20–25% with AM inoculation both at the experimental station and in farmers' fields. Inoculation of various pasture legumes and grasses with AM fungi also in combination with applications of PR improved early plant growth and establishment. A pot experiment in which cassava, bean and maize were grown on a tropical soil with high P sorption to which triplesuperphosphate (TSP) fertilizer was added, suggested that the mycorrhizal dependency of growth depended greatly on root morphology (Table 9.5). Even when a large amount of TSP was supplied, growth of cassava was still extremely dependent on AM fungi

Table 9.5 Effect of mycorrhizal inoculation and phosphorus (P) application on the shoot dry weight (g pot^{-1}) of several plant species grown in a sterilized, strongly P adsorbing tropical soil supplied with three levels of P (0, 100, 500 kg P ha^{-1}) applied as a soluble phosphate fertilizer (TSP). (Data from Howeler *et al.* 1987.)

		Dry weight		
Plant species	Inoculation	P0	P100	P500
Cassava	–	0.34	0.72	0.54
(*Manihot esculentum*)	+	4.33	14.21	16.36
Bean	–	1.11	3.44	8.29
(*Phaseolus vulgaris*)	+	3.08	18.79	25.01
Maize	–	1.19	8.74	59.39
(*Zea mays*)	+	4.84	34.75	56.67

because of its coarse and poorly branched root system. Bean, with both short roots and short root hairs, was less dependent, and maize, which has a much more highly branched root system, was almost independent of AM fungi when large amounts of TSP were supplied (Howeler *et al.* 1987). However, not all grasses behave in this way. Mycorrhizal fungi can also have other effects in improving crop growth and these include increasing tolerance to root pathogens, water stress and enhancing N fixation by rhizobia (Marschner 1995). Harnessing mycorrhizal fungi to improve the utilization of soil and fertilizer P where the supply is limited and thus sustain soil fertility is therefore a worthwhile but very difficult and daunting challenge.

Biochemical adaptations

Mechanisms that increase P acquisition efficiency of roots include enhancing the capacity of the root to take up Pi by increasing the abundance of high-affinity P uptake systems in the plasma membranes of epidermal cells and the release of various exudates, mainly organic acid anions, protons and enzymes, into the rhizosphere. These exudates can increase rhizosphere Pi concentration by mobilizing inorganic and organic forms of P in the soil.

Under conditions of P deficiency, genes encoding high-affinity Pi transporters are up-regulated (Liu *et al.* 1998; Sas *et al.* 2001; Vance *et al.* 2003) providing the plant with a greater capacity for Pi uptake. For plants growing in soil, however, this increased uptake capacity may be of little relevance because Pi diffusion from the bulk soil to the root surface is usually the rate limiting step in P acquisition (Silberbush and Barber 1983; Raghothama and Karthikeyan 2005). This may explain why over-expression of a gene encoding a high-affinity Pi transporter in transgenic barley had no effect on Pi uptake by plants growing in soil (Rae *et al.* 2004). Nevertheless, in China, Yan *et al.* (2006) have reported the development, by physiological and genetic approaches, of a P-efficient wheat cultivar, Xiaoyan 52, in which a Pi transporter is highly expressed under both normal and P deprived conditions. In this case, however, other adaptations including organic anion release from the roots might also have favored P acquisition.

A number of crop species, (including oilseed rape, chickpea, alfalfa, white lupin and other legumes), respond to P deficiency by exuding carboxylates, such as citrate, malate and oxalate, from the roots. These carboxylates released into the rhizosphere mobilize Pi by chelating with metal cations that bind Pi and by displacing Pi from the soil matrix by ligand exchange (Gerke *et al.* 2000). The released Pi is then taken up by high-affinity Pi transporters. Potentially, tricarboxylates and dicarboxylates are the most able to mobilize Pi because of the high stability constants of their corresponding Fe, Al and Ca-complexes (Ryan *et al.* 2001). Citrate, which is commonly found in root exudates, is highly effective in chelating not only Ca in calcareous soils (Dinkelaker *et al.* 1989) but also Fe and Al in acid soils (Gardner *et al.* 1982) and can mobilize Pi from a range of sparingly soluble inorganic P complexes. Restricting the release of organic anions to the apical zone of the root, as in oilseed rape (*Brassica napus*) is a highly efficient means of extracting soil P (Hoffland 1992). A similarly located release of malate and its chelation of Al also provide a mechanism enabling Al tolerant wheat cultivars to grow in acid soils (Delhaize *et al.* 1993).

It is still a matter of debate whether the rate of carboxylate exudation from plant roots is adequate to provide sufficient Pi to meet plant requirements in all but a few species (Hinsinger *et al.* 2003). Neumann and Römheld (2006) suggest that large concentrations of carboxylates (millimolar) are required to release significant amounts of Pi from soil complexes. Additionally, carboxylates released from roots may be utilized in other ways, for example as substrates for soil microorganisms. Much is still to be learned of the reactions and processes in the rhizosphere that are governed by the release of organic anions leading to improved P nutrition (Rengel and Marschner 2005).

One of the adaptive responses of plants to P deficiency is to release protons from the roots into the rhizosphere to mobilize Pi. This is a strategy that can be exploited in crop nutrition. By supplying crops with NH_4-N the same effect can be achieved because of a higher cation:anion uptake ratio by the plants (Kirkby 1981; Mengel and Kirkby 2001). Soil acidification by plant roots can be used to benefit on high pH, calcareous soils for the mobilization and uptake of Pi from sparingly-soluble, native CaP complexes in soil. On neutral and more acid soils Pi can be mobilized from applied PR. This is illustrated by an experiment with common bean plants supplied with NH_4-N or NO_3-N growing in a soil with pH 6.6 and supplied with PR (Table 9.6; Thomson *et al.* 1993). Depressing the rhizosphere pH not only mobilized and increased the uptake of P but also the uptake of Fe, Mn, Zn and Cu, all nutrients which cause crop deficiencies on neutral and calcareous soils.

It is much more difficult to increase the pH of acid soils by managing the rhizosphere of plants. Graminaceous monocots, including pasture grasses and cereals, increase rhizosphere pH when supplied with NO_3-N because of a much higher anion:cation uptake ratio. Their effectiveness under field conditions is very dependent on the pH of the bulk soil. In general, a tendency to increasing acidification is the common trend in cropping systems (Lambers *et al.* 2006). Nodulated legumes offer an enormous potential for the supply of biologically fixed N_2 to low input agricultural systems (Vance 2001), but on neutral and acid soils they suffer the serious disadvantage of depressing pH, which leads to the formation of monomeric Al^{3+} in the soil and Al toxicity. Nitrogen fixation and proton release are closely

Table 9.6 Effect of the form of N fertilizer applied to a sandy loam soil (pH 6.8) on rhizosphere pH and nutrient uptake by bean (*Phaseolus vulgaris* L.) plants. Nitrogen was applied as $Ca(NO_3)_2$ or $(NH_4)_2SO_4$ plus a nitrification inhibitor. (Data from Thomson *et al.* 1993.)

		Uptake (µg m^{-1} root length)				
Form of N	Rhizosphere pH	P	Fe	Mn	Zn	Cu
$Ca(NO_3)_2$	6.6	815	68	23	11	2.7
$(NH_4)_2SO_4$	4.5	1,818	184	37	21	3.7

related (Raven and Smith 1976). Soil amelioration by liming can be important but does not always address sub-soil acidity. Moreover, liming materials are not always available and even when they are used, as for example on tropical acid soils they may promote Pi adsorption by the formation of Al-P complexes (Haynes 1984). On soils where Pi is strongly adsorbed, band placement of P fertilizers is recommended (Werner and Scherer 1995) because this decreases the immediate adsorption of Pi by soil particles. The innovative use of PR where soils are acid, combined with the application of organic manure can be effective in increasing P uptake (Stockdale *et al.* 2006). Pigeon pea (*Cajanus cajan*) is one crop species that has an outstanding capacity for P acquisition in acid but not alkaline soils. The roots of this crop release piscidic acid which chelates strongly with Fe^{3+} and thus mobilizes sparingly-soluble Fe phosphates. It is therefore used very successfully as an intercrop with cereals on acidic soils (Alfisols) in the Indian subcontinent (Ae *et al.* 1990).

The development of specialized root structures known as cluster roots (proteoid roots or bottlebrush roots), found on a number of species that grow in P-deficient soils is another adaptation to P deficiency. The most well researched plant species of this type is white lupin (*Lupinus albus*). This is the sole cluster root forming species of agricultural importance and is grown for grain and forage. This adaptation combines a high C investment in the root structure with a highly specialized root physiology (Le Bayon *et al.* 2006). Cluster roots consist of short lateral roots covered by a dense mat of root hairs that make up to 60% of the root biomass and are developed in patches of soil where P is most available, even in fertile soils. The roots periodically release large amounts of citrate and protons together with acid phosphatases. This localized excretion restricts microbial degradation of the exudates and simultaneously allows an intensive extraction of a limited volume of soil. As much as 23% of the dry weight of the plant can be released as citrate (Dinkelaker *et al.* 1989). It is thought that carboxylates released through anion channels in the root plasma membranes are able to mobilize both Pi by chelation and ligand exchange as described above. Organic P is hydrolyzed by acid phosphatases once it has been mobilized by the carboxylates. Inorganic P is taken up by high-affinity Pi transporters (Sas *et al.* 2001).

Interest has focused recently on other native species of Proteaceae and Cyperaceae that have cluster roots and grow on some of the most P-impoverished acid soils in the world in Western Australia and South Africa (Lambers *et al.* 2006). These plants are characterized by a very small P requirement and tissue P concentrations of only 0.02–0.04% P in dry wt, a concentration about ten times lower than most crop plants. Interestingly, Proteaceae are particularly sensitive to P toxicity at external P concentrations that are harmless to other plants, mainly because they have little capacity to down-regulate P uptake in response to increased P supply (Shane *et al.* 2004). In contrast to white lupin, these species, which grow on highly weathered acid soils, do not release protons together with carboxylates into the rhizosphere (Roelofs *et al.* 2001). This is presumably an adaptation to prevent acidification of the rhizosphere and Al toxicity, while still enabling the release of Pi from Fe and Al complexes. The concentration of root clusters as mats in surface soil horizons aids the scavenging of P from organic matter. This feature is comparable to topsoil foraging for efficient P acquisition by the lateral roots of agriculturally successful common bean genotypes (Lynch 2007). The potential use of these cluster-rooted species in the development of new crops with common root adaptations to enhance P acquisition has been discussed by Lambers *et al.* (2006).

In most agricultural soils about 20–80% of P is present as organic P in soil organic matter. In the rhizosphere there is a considerable turnover of organic P in which microorganisms act both to mobilize P as well as to incorporate it into the organic fraction. Hydrolysis of organic P is also mediated by the release from the root of phosphatases, which are increased in the rhizosphere in response to P deficiency in the plant (Vance *et al.* 2003). Plant roots release very little, if any phytase, the enzyme that breaks down phytate (inositol hexaphosphate), which is the predominant form of organic P in most soils (George and Richardson 2008; Marschner 2008). Plant access to this form of P is therefore mainly dependent on soil microorganisms. The complex interactions between enzymes released into the rhizosphere and rhizosphere microorganisms involved in the turnover of organic P are still not well understood. Knowing how these interactions operate, however, is especially important for intercropping farming systems on soils with little plant-available P, where plants depend considerably on the cycling of organic P, as discussed below (Horst *et al.* 2001).

P-Efficient crops and cropping systems

Crop species and crop cultivars that can make the most efficient use of soil P by mobilizing it from less plant-available pools and from fertilizer additions can play a key role in sustainable cropping systems. Mention has already been made of such P-efficient crops, like white lupin, brassicas, buckwheat and pigeon pea, which release organic exudates or protons into the rhizosphere. Phosphate mobilized by these crops can be used by neighboring plants of other species or crops following in the rotation. In a classic pot experiment Horst and Waschkies (1987) demonstrated that when white lupin and wheat were grown together on a P-deficient soil supplied with PR, the white lupin despite its much lower root length density than wheat was able by the release of citric acid to mobilize sparingly-soluble P sources not only to meet its own demand but also to provide additional P for the wheat.

Horst *et al.* (2001) consider the most promising agronomic approach to P sustainability on low P soils is the integration of P-mobilizing plant species as intercrops or as crops within a crop rotation. These authors have shown, in field experiments in the Northern Guinea Savannah of Nigeria, the beneficial effect of P mobilization by a number of leguminous grain and cover crops in addition to white lupin. The growth and grain yields of cereals were increased when grown in rotation with legumes. This beneficial effect of P-mobilizing plant species may result from a direct shift in the equilibrium between the less available to the more readily plant-available pool of soil P (Lambers *et al.* 2006). The results of Horst *et al.* (2001), however, suggest that the effects relate to the recycling of the mobilized

P via crop residues, which increase organic matter and enhance biological activity. This suggestion accords with enhanced colonization of the rhizosphere with P-mobilizing microorganisms on the roots of crops grown subsequently in the rotation. Organic materials including crop residues, manures and composts are used traditionally on low-P tropical soils and have also been shown to reduce P adsorption through the presence of organic anions. Of the different plant species used as green manure, the deep rooted woody species *Tithonia diversifolia* appears to be especially valuable. This species not only mines the deeper layers of the soil for P but applying the foliage to the soil also increases soil P availability (Singh and Lal 2005). Much is still to be learnt about rhizosphere interactions between released exudates and microorganisms and their effects on P utilization by plants. What is clear though is that applications of fertilizer P are required to sustain these cropping systems and particularly so on strongly P adsorbing acid soils (Horst *et al.* 2001; Singh and Lal 2005).

The Brassicaceae are extremely effective in acquiring P from the soil (Greenwood *et al.* 2005, 2006a) which appears to relate not only to their ability to mobilize Pi via organic acid exudation (Hoffland 1992) but also by a very extensive root system able to scavenge P from the soil (Dechassa *et al.* 2003). The benefit of including brassicas in the crop rotation on soils in the UK has been described by Greenwood *et al.* (2006b). In glasshouse and field experiments, they studied the responses of 12 genotypes of *Brassica oleraceae* to various levels of P fertilizer. All genotypes grew well on a sandy loam soil containing 20 mg kg^{-1} Olsen P, a value close to the critical level discussed earlier. The authors propose that high-yielding rotations of brassicas and cereals, which can also yield well on low P soils, may be sustained indefinitely on some soils at about this level of available P. Applications of only slightly more P (about 12 kg P year^{-1}) would be required in addition to that removed by the crop to maintain the level of Olsen P. In these experiments, the efficiency of fertilizer P use was about 62% in the year of application.

P-Efficient germplasm

There is considerable genetic variation both between and within crop species for many of the root traits related to plant adaptation to P deficiency (White *et al.* 2005). There is, therefore, interest worldwide to develop improved crop germplasm adapted to low-P soils to allow more efficient uptake and utilization of soil and fertilizer P. Considerable success has already been achieved in modifying root architecture in bean, maize and soybean cultivars so that the plants grow better under P-deficient conditions, as discussed earlier in this chapter and by Lynch and Brown (2008).

Phosphorus deficiency does not occur in isolation from other growth limiting factors. Crop improvement programs have therefore developed cultivars with multiple stress resistance to give larger yields and greater yield stability in different environments, for example, in the maize and sorghum improvement programs of CYMMT in Brazil. The aim of these programs has been to pyramid the genes that control plant adaptation to acid soils. As well as tolerance to P stress and improved efficiency in P uptake, these include tolerance of Al and of water deficiency, greater efficiency in ammonium utilization and a larger root system.

There are few reports on variation between crop genotypes in root release of organic acids in relation to P acquisition (Gahoonia and Nielsen 2004). Yet this would seem a promising approach as organic acid release enhances P mobilization irrespective of the pH of the bulk soil and, as shown by Delhaize *et al.* (1993), provides a mechanism to detoxify Al. There is some evidence for the feasibility of this line of research from the finding of more organic acid secretion from P-efficient than from P-inefficient genotypes of wheat in China and the utilization of these P-efficient crops (Yan *et al.* 2006). For rice too it is recognized that developing cultivars that grow on P-deficient soils may represent a more sustainable solution for continued production than sole reliance on P fertilizer applications. In assessing genotypic variation for tolerance to P deficiency, Wissuwa and Ae (2001) observed great variation among rice genotypes in their tolerance to P deficiency. In general, traditional varieties were superior to modern ones. By appropriate crossing of a modern variety Nipponbar with the P deficiency-tolerant landrace Kasalath, an improved line was developed, which surpassed Nipponbar in P uptake by 170% and in grain yield by 250%. By combining the large P uptake capacity of Kasalath with the high harvest index of Nipponbar, it was possible to triple the grain yields of Nipponbar when grown under P deficiency. More recently, Wissuwa (2003) has modeled for rice the response and tolerance to P deficiency and separated the effects of greater root growth and higher external root efficiency (i.e. the rate of P uptake per unit of root surface area). This has shown large genotypic differences associated with greater P uptake can be caused by relatively small changes in tolerance mechanisms. These small changes are therefore likely to be difficult to detect because they are overshadowed by secondary root growth effects.

Phosphorus efficient species and cultivars can be of benefit in improving the use of native soil P and residues of P applied as fertilizer on both low P soils and on soils adequately supplied with P. On the latter soils, crops such as white lupin and brassicas that can provide greater access to the less readily-available pool of P, may play an important role in enhancing the rate of P acquisition from such soils. The tremendous potential of root cluster species in agriculture and their innovative use in the development of new crops with similar root adaptations has been discussed by Lambers *et al.* (2006).

Genetic modification of plants to increase exudation of chelating and other compounds into the rhizosphere to increase P acquisition presents another means of developing P efficient plants. So far, however, progress has been rather slow. There are contradictory reports concerning the effects of increased exudation of carboxylates and P uptake by transgenic plants (Rengel and Marschner 2005). In transgenic plants engineered to increase phytase production and exudation to access organic P in soil organic matter, there is often no correlation between exudation and P uptake (George and Richardson 2008). Much therefore is still to be learnt before these approaches can give consistent and beneficial results which might be used in crop production.

SOME ENVIRONMENTAL ASPECTS TO THE USE OF P FERTILIZERS

There are two main aspects of environmental concern in the use of P fertilizers for crop production. The first relates to elements which occur as impurities in PR and can carry through into the manufactured product, be applied to soil and enter the food chain. Some of these elements can be detrimental to human and animal health and those causing most concern are uranium (U) and cadmium (Cd). The second relates to the transfer of P from the soil into the aqueous environment and the consequent risk of eutrophication. There is an enormous literature on both these topics. Consequently, only a brief account is presented here.

Radionuclides

Radioactive elements, like U and radium (Ra), are normal trace constituents of the earth's crust (Scholten and Timmermans 1996) and occur in PR, particularly sedimentary PR, at higher than average concentrations. The treatment of PR with sulfuric acid to produce phosphoric acid in the wet oxidation process is the starting point in the production of nearly all P fertilizers. Varying proportions of the radionuclides can carry through into the processed fertilizers or remain in the co-product phosphogypsum (Rutherford *et al.* 1994; Leikam and Achorn 2005). Uranium and other radionuclides are found to a lesser degree in fertilizer products than in phosphogypsum, and radioactivity levels of most P fertilizers are only slightly greater than those in the soil (Falk and Wymer 2006).

From the older literature there is good evidence that U uptake by plants is very small. In long-term experiments at Rothamsted where known quantities of single superphosphate fertilizer have been applied to a silty clay loam soil annually for over 120 years, most of the U applied in the fertilizer (1,300 g U ha^{-1}) could be accounted for in the top 23 cm of soils growing arable crops and in the organic surface layer under permanent grassland. Similarly, most of the 330 g U ha^{-1} added in superphosphate to permanent grassland in New Zealand was found in the surface layer (Rothbaum *et al.* 1979). More recently it has been shown that U is taken up by plants less readily than other toxic heavy metals and there is general agreement that soil-plant transfer is of no risk for contamination in the food chain (Kratz and Schnug 2006). However, The possibility of ground and surface water contamination through soil erosion, surface run-off and leaching, which could impair the quality of drinking water, is receiving increasing attention. The accumulation of U in soil arises not only from the use of P fertilizers, but also from the factories where they are manufactured, fossil fuel power plants and U mines (De Kok and Schnug 2007).

Phosphogypsum (PG) consists mainly of calcium sulfate but also contains small quantities of phosphate, fluorine and radium derived from the phosphate rock. In the wet process for manufacturing phosphoric acid, 5 t of PG are created for every tonne of phosphoric acid produced. Because of its small Ra content, the use and movement of PG is restricted in the USA and several other countries. Consequently, many hundreds of millions of tonnes of PG have been stored on land in stacks near the site of production and as much as 160–200 Mt are likely to be produced every year for the foreseeable future. The long-term management, use and disposal of this material are one of the most challenging problems facing phosphoric acid producers. Hilton (2006) has reviewed the various possible uses for PG including agriculture, road construction and the building industry. While these latter uses have been controversial, largely because of the radioactivity, stacking has environmental problems also (Hilton 2006). However, the risk from the radioactivity in PG is being reassessed and it may become possible to use PG as described by Hilton (2006) rather than stack it.

Cadmium

A wide range of elements other than those that are radioactive occur naturally in PR (Van Kauwenbergh 1997). Again, these can either be transferred to the finished fertilizer product or be retained in the PG. Cadmium is the element of principle concern because of its toxicity to man and animals. The world's major reserves of PR are sedimentary rocks which contain very variable amounts of Cd, ranging from less than 10 mg Cd kg^{-1} to more than 50 mg Cd kg^{-1} PR. Fertilizers produced from igneous rocks, which contain little Cd, contain very low Cd concentrations. Unfortunately supplies of these rocks are very limited.

The Scientific Committee on Problems of the Environment (SCOPE) organized an Environmental Cadmium Project holding two workshops. The first was in Brussels in 2000 (*http://www.icsu-scope.org/projects/cluster3/cadmium/Cd%20Brussels%20report.pdf)* and the second in Ghent in 2003 *(http://www.icsu-scope.org/cdmeeting/2003meeting/cdindex.htn)*. Both meetings identified the importance of Cd as a toxic element and recognized that setting standards to protect soils, plants, animals and humans from exposure to Cd had become a high-profile policy issue. The project focused on two issues: (1) human and ecological health risks from cadmium and (2) impact of risk information on allowable levels of cadmium in P fertilizer. Any incorrect assessment of risk from Cd and its subsequent implementation through regulations on Cd applications could adversely affect the use of P, essential to food production worldwide, either as fertilizers and/or the recycling P through biosolids. The concern was that regulations introduced and designed to protect certain populations may have unforeseen effects on other populations involving nutrition, public health and social and economic factors. It was concluded that human exposure to Cd is largely driven by Cd in staple food crops, which originates from Cd in the soil. Of several potential sources of soil Cd that in P fertilizers received particular attention and it was agreed that there is no conclusive evidence of any adverse impact of Cd in P fertilizers on human health. This was the case even in Australia where there has been a long history of application of fertilizers with high Cd concentrations and a strict policy on their use.

Johnston and Jones (1995) discussed some agronomic aspects of Cd and P fertilizer use. One aspect on which there are divergent views is whether soil acidity affects the uptake of Cd by plants. Data from the Park Grass Experiment at Rothamsted suggests that it does. The Cd concentrations in the herbage harvested on these permanent grass plots during the past 150 years depends on soil pH and the addition of Cd in superphosphate and atmospheric deposition (Figure 9.6). On soils where the pH has been maintained at or slightly above 6.5, the concentration of Cd in the herbage is only a little larger where superphosphate has been applied than where none has been given since 1856. Conversely, where the soils have become acid, the concentration of Cd in the herbage is much larger where Cd has been added in superphosphate than where none has been applied. Interestingly, the Cd concentration in herbage grown on the acid plots receiving superphosphate has declined recently, possibly because the Cd taken up has been "diluted" by the increasing yield of dry matter on these plots (Nicholson *et al.* 1994). The discrepancy between these results and others that suggest that soil pH has no effect on herbage Cd content, may be due to experimental technique. Additions of lime that seek to change soil pH quickly in laboratory or field experiments may change the laboratory measurement of soil pH without affecting the chemistry of Cd in the soil and thus the uptake of Cd by the crop. Wu *et al.* (1989) showed that a difference in rhizosphere pH as a result of applying different sources of N affected the Cd content of *Lolium perenne* herbage. There was 4.2 mg Cd kg^{-1} dry matter at a rhizosphere pH of 6.8 and 12.2 mg Cd kg^{-1} dry matter at a rhizosphere pH of 5.5.

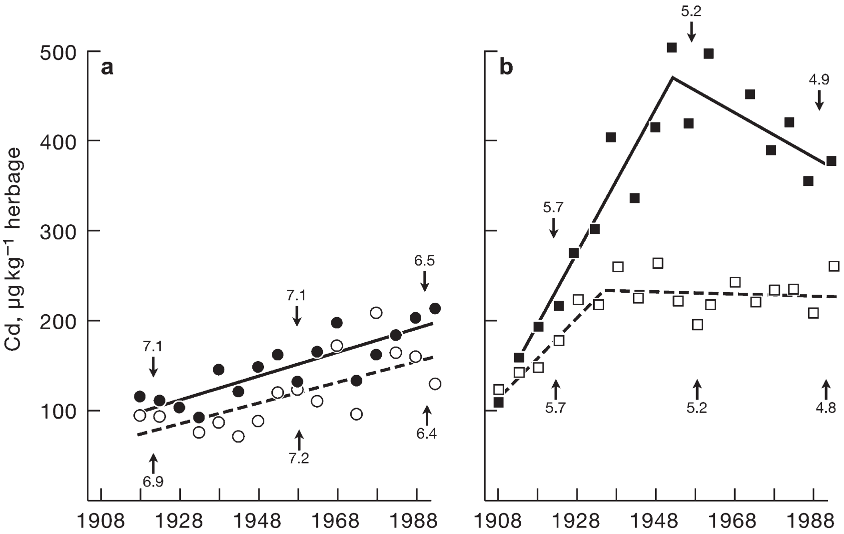

Fig. 9.6 Cadmium concentrations in herbage from the Park Grass Experiment at Rothamsted. Herbage from plots with neutral soils with (●) or without (○) superphosphate fertilizer applications (**a**). Herbage from plots with acid soils with (■) or without (□) superphosphate fertilizer applications (**b**). (Adapted from Nicholson *et al.* 1994.)

Transfer of P from soil to water

The increasing P concentration in some surface fresh water bodies and the adverse effects of this enrichment on the biological balance in the water body, has been attributed to the increasing use of P fertilizer in agriculture (Johnston and Dawson 2005). Current evidence suggests that P transferred from soils to water comes from three main sources. These are: (i) Surface runoff, especially in hilly terrain, when intense and prolonged rainfall follows the application of large amounts of slurry to either arable land or permanent grassland. (ii) Eroded soil that is excessively enriched with P as a result of the over, and often unnecessary, addition of P fertilizer and organic manures. (iii) Drainage water leaving the soil profile, which can be important on very coarse-textured, sandy soils where large amounts of P fertilizer or animal slurry have been applied. If the subsoil contains large amounts of clay the P can be retained there (Mattingly 1970). There is a relationship between Olsen P and very weakly bound soil P soluble in 0.01 M $CaCl_2$, which could move down the soil profile in drainage water (Heckrath *et al*. 1995; McDowell *et al*. 2001). The amount of P transferred from soil to water by these pathways can be minimized by the adoption of Codes of Good Practice as published in various countries.

Another major source of P entering water courses is that from sewage treatment works without a tertiary treatment facility that discharge the effluent to an adjoining river system. This could only be controlled if such a facility was installed and the cost effectiveness of doing this would have to be carefully assessed. However, recent evidence from 54 UK river catchments indicates that point sources of P from even small settlements, probably via sewage treatment works, provide a greater risk of river eutrophication than diffuse sources from agricultural land even where this has a large positive P balance (Jarvie *et al*. 2006). White and Hammond (2006) recently reassessed the data for the total P (TP) load on the waters of England, Wales and Scotland. Of the TP load, estimated to be between 41.6 and 51.1 kt year^{-1}, the contribution from agricultural land could be 22–28%. The larger TP loads, and lesser contribution from agriculture, assumed an annual discharge of 0.61 kg TP per capita from sewage treatment works.

SOME ECOLOGICAL ASPECTS TO THE USE OF P FERTILIZERS

There is considerable evidence that intensification of agriculture and the accompanying increase in soil fertility on sites previously of conservation value can lead to a loss of biological diversity because of the domination of invasive, vigorous plant species at the expense of existing, often slower growing species (Marrs 1993). In terms of fertilizer application the effects can depend in particular on changes in soil pH as well as increasing supplies of N, P and K. Interest, however, has focused mainly on P because the soils in many natural ecosystems contain much lower concentrations of this nutrient than are found in well-managed agricultural soils.

Withers *et al.* (2005) presented data from Critchley *et al.* (2002) for species richness measured in relation to plant-available soil P (Olsen P) taken from a survey of 571 grassland sites representing a wide rage of temperate grasslands in Environmentally Sensitive Areas in England, where fertilizer input would be low. Species rich grassland and high-value semi-natural grassland with large numbers of species well able to tolerate stress were found to occur mainly on soils with between 4–15 mg L^{-1} Olsen P. Grasslands with soil Olsen P less than 4 mg L^{-1} or greater than 15 mg L^{-1} were species poor and contained fewer stress-tolerant species. However, although, the maximum species abundance declines exponentially from 45–50 species m^{-2} to 5–10 species m^{-2} as Olsen P increases from 2 to 70 mg L^{-1}, species abundance ranges from less than 5 species m^{-2} to more than 40 species m^{-2} on soils with 4–12 mg P L^{-1}, and there are many more sites with species abundances between 5 and 10 species m^{-2} on soils with less than 10 mg P L^{-1} than on soils with more than 20 mg P L^{-1}. Thus, many sites with little plant-available P are species poor and this suggests that species richness in grassland swards is influenced by factors other than the level of Olsen P. Therefore, the ecological effects of P fertilizer need be considered additionally in relation to other components of soil fertility and nutrient availability.

Data from the Park Grass Experiment at Rothamsted provide convincing evidence for this view. This experiment, started in 1856 on a grass sward that had been established at least 200 years previously, can be described as the longest-running experiment in plant ecology anywhere in the world. Species richness on plots where Olsen P has been built up since the start of experiment can be compared directly with that on plots that have received no P. As well as P, other experimental inputs have included N and K as fertilizers and organic manures applied annually, with lime applied occasionally. These treatments have lead to an increase in plant biomass and where N was applied as ammonium sulfate to substantial decreases in soil pH. The soil is a silty clay loam and had a pH of about 5.5 in the 1850s. Each year, the sward is cut for hay in June/July and the aftermath cut for silage in September/October. It is never grazed. Thus, fertilizers have been the only nutrient additions other than those from the atmosphere. On some plots the fertilizer inputs have remained unchanged since 1856. Fertilizers are applied once each year, with 33 kg P ha^{-1} and 225 kg K ha^{-1} being applied in late winter. Where P and K are applied the plant available P and K in soil are well above the yield limiting value (~25 mg kg^{-1} Olsen P). Where no P or K is applied, plant available P and K in soil are very small (2–5 mg kg^{-1} Olsen P). Nitrogen is applied in early spring, and a comparison is made of 48 and 96 kg N ha^{-1}, applied as ammonium sulfate and sodium nitrate. The ammonium sulfate has greatly acidified the soil, the pH is now 3.7. A test of liming was first introduced in 1903, and a more comprehensive one in 1965. The latter aims to achieve and maintain pH values of 7, 6 and 5 on three subplots while that on a fourth subplot depends on the acidifying effect of the various inputs. Each year from 1991 to 2000 individual species of grasses, forbs and legumes were separated and their contribution to dry matter yield in swards from each experimental plot, was made just prior to them being cut for hay (Table 9.7; Crawley *et al.* 2005). Compared to with untreated plots, applying only P or PNaMg fertilizers decreased species richness only slightly, from 39 to 35 species

Table 9.7 Effects of soil phosphorus and acidity and applied nitrogen fertilizer on the total number of species identified in, and (in parentheses) the number of species contributing 10% or more to the total dry matter yield, of a permanent grass sward, Park Grass, Rothamsted. Average of ten years data, between 1991 and 2000. (Crawley *et al.* 2005.)

Treatment	Soil pH	Number of species	Soil pH	Number of species
None	7.2	39 (5)	5.2	36 (3)
P/PNaMg	7.0	35 (4)	5.2	30 (3)
N*1	7.1	32 (4)	5.8	34 (4)
N*1PK	6.7	25 (5)	5.4	27 (2)
N1	7.1	33 (4)	4.1	10 (2)
N2P	6.9	22 (3)	3.7	10 (2)
N2PK	6.9	22 (5)	3.7	3 (3)

N*1 = 48 kg N ha^{-1} as sodium nitrate
N1 = 48 kg N ha^{-1} as ammonium sulfate
N2 = 96 kg N ha^{-1} as ammonium sulfate
P = 33 kg P ha^{-1} each year since 1856
K = 225 kg K ha^{-1} each year since 1856

plot^{-1} on soils with pH about 7 and from 36 to 30 species plot^{-1} on soils with pH 5.2. In both cases the number of dominant species was small. Species richness was decreased from 39 to about 32 species plot^{-1} where only N (48 kg ha^{-1}) was applied either as sodium nitrate or ammonium sulfate and soil pH maintained at about 7. But species richness declined to 10 species plot^{-1} where the application of 48 kg N ha^{-1} as ammonium sulfate decreased soil pH to 4.1. Applying N at 96 kg ha^{-1} with P or PK fertilizer showed the greatest reduction of species richness, irrespective of whether the N was applied as sodium nitrate or as ammonium sulfate. Species richness declined to a little over 20 species plot^{-1} where soil pH was maintained at 6.9, but declined to 10 species plot^{-1} with P fertilizer and 3 species plot^{-1} with PK fertilizer where soil pH was 3.7. The data from this experiment suggest that small amounts of applied N fertilizer and a high level of plant-available soil P (200 mg kg^{-1} Olsen P) cause only a small decline in species richness in a permanent grass sward that is only harvested for hay in June/July with any subsequent growth removed in late autumn. It is the combination of N and P or PK fertilizer, especially on acid soils, that markedly reduces species richness.

An interesting feature of this set of data from the Park Grass Experiment are the changes in the species that contribute 10% or more to the dry matter yield as a result of the differences in nutrient inputs on the most acid soils for each treatment. On the untreated soil with pH 5.2 there are 36 species present but only two contribute more than 10% to dry matter yield. These are *Agrostis capillaries* (45%) and *Festuca rubra* (30%). On the ammonium sulfate treatments where only N is applied and soil pH is 4.1 there are 10 species plot^{-1} and two dominant species, *A. capillaries* which contributes 65% of the biomass and *Anthoxanthum odoratum* which contributes 30% of the biomass. Applying P in addition to N as ammonium sulfate and allowing soil pH to fall to 3.7 also results in 10 species plot^{-1} but *A. capillaris* now contributes only 30% and *A. odoratum* 70% of the biomass. On the treatment where 144 kg N ha^{-1} is given with PK, soil pH is still 3.7 but the sward is 100% *Holcus lanatus*.

SUMMARY

The global demand for P fertilizers to produce crops for food for man and animals is currently about 36.8 Mt P_2O_5 and is expected to increase by 2.6% per annum over the next five years. About 85% of all PR mined is processed for use in agriculture. Estimates vary as to how long known PR reserves will last, but it is universally recognized that they are finite and that this precious resource must be used as efficiently as possible.

It is now envisaged that soil P is held by a continuum of bonding energies to the surfaces of and within the matrix of soil components. Associated with the varying strengths of bonding, soil P can be considered to exist in four P pools of contrasting availability to plants (Figure 9.2). Much evidence from field experiments shows that there is a reversible transfer of P between the first three pools. Phosphorus removed from the soil solution by uptake by plant roots is replenished by P from the readily available pool. The widely and long held view that a large proportion of applied fertilizer P becomes irreversibly fixed in the soil is no longer tenable. Furthermore, the efficiency with which fertilizer P is acquired by crops over the long term is much higher than is generally appreciated.

In very broad terms, soils used for agriculture may be divided into those adequately supplied with P and managed intensively, as in many developed countries, and those with too little plant-available P on which extensive agriculture is practiced, as in many developing countries. The concept of exchanging pools of soil P relates well to the known responses of crops to soil and fertilizer P. It also allows the concept of critical levels of plant available P related to soil type and farming system to be developed, which is particularly useful for the management of intensive agricultural systems.

The need for crops to utilize P more efficiently has led to a re-examination of the way in which plants adapt, and even thrive, on low-P soils. The morphological, physiological, biochemical and molecular responses of plants to environments with low P availability are being examined by scientists of various disciplines. These responses have been successfully exploited to improve the use of soil and fertilizer P in crop nutrition in soils of both adequate and low P availability.

Environmental issues relating to the use of P fertilizers concern the fate of radionuclide and Cd impurities and P losses from soils to watercourses. It is suggested that improved management practices, the development of P-efficient crops and the implementation of Codes of Good Practice for agriculture should assuage concerns that use of P fertilizers may affect the environment detrimentally.

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