

Soil and Plant Phosphate

A.E. Johnston



Soil and Plant Phosphate

A.E. Johnston

International Fertilizer Industry Association

Paris, September 2000



Soil and Plant Phosphate
by A.E. Johnston
Published by the International Fertilizer Industry Association
Paris, September 2000.

Copyright. 2000 IFA. All rights reserved.
ISBN: 2-9506299-5-4

The text of the document is available on IFA's Internet site.

Further copies can be obtained from:

IFA
28, rue Marbeuf
75008 Paris, France
Tel: +33 153 930 500
Fax: +33 153 930 545 /546 /547
Email: publications@fertilizer.org
Web: www.fertilizer.org

Printed in France.
Layout: Claudine Aholou-Pütz, IFA

TABLE OF CONTENTS

Introduction	1
The Essential Role of Phosphorus in Living Organisms	1
Phosphorus in plants	2
Phosphorus in animals	2
The Occurrence of Phosphorus in Nature	3
The Uses of Phosphorus	4
Using phosphorus efficiently	4
Phosphorus and the Development of Farming Systems	5
Soil Phosphorus and its Availability	10
The availability of different forms of soil phosphorus	11
The effect of soil organic matter on phosphorus availability	13
Soil organic phosphorus	15
Soil physical properties and phosphorus availability	16
Phosphorus Acquisition by Roots	19
Plant root systems	19
Rate of phosphorus uptake by roots	20
Soil Phosphorus Reserves	20
The value of soil phosphorus reserves	23
Readily Available Soil Phosphorus and Fertilizer Recommendations	24
Soil analysis for readily available phosphorus	24
Fertilizer recommendations	24
Desired readily available soil phosphorus levels	24
The importance of maintaining the critical readily available soil phosphorus level	27
The Efficient Use of Phosphorus Fertilizers	29
Mineral Phosphorus Fertilizers	30
Chemical evaluation of phosphorus fertilizers	31
The principal phosphorus fertilizers used in agriculture	32
Changes in phosphorus fertilizer consumption	33

Phosphorus and Environmental Issues	33
Phosphorus and the aquatic environment	33
Phosphorus fertilizers and the terrestrial environment	40
Concluding Remarks	42
References and Further Reading	44
References	44
Further Reading	46

INTRODUCTION

Phosphorus is essential to all living organisms. The element phosphorus, however, does not occur by itself in nature, it is always combined with other elements to form many different phosphates, some of which are very complex. In this booklet the word phosphorus or the symbol for the element, P, will usually be used rather than attempting to define the particular phosphate involved.

Phosphorus passes from one organism to another in the various food chains. Humankind acquires its phosphorus from plants which directly, or indirectly through animals, provide the food we eat. In turn, plant roots take up phosphorus and most other elements from the soil solution - the water in the soil. The soil solution invariably contains too little phosphorus to meet the requirements of actively growing plants. Thus there has to be a supply of readily available phosphorus in the soil to replenish the phosphorus in the soil solution as it is removed by crop uptake. Most unimproved soils contain too little readily available phosphorus for crops to produce optimum yields. Thus, additional phosphorus must be added to soils if they are to produce enough food to provide an adequate diet both now and in the future. Most of this additional phosphorus must come from fertilizers because too little is available from other sources.

THE ESSENTIAL ROLE OF PHOSPHORUS IN LIVING ORGANISMS

Phosphorus is irreplaceable in those compounds on which life processes depend. Phosphorus occurs in enzymes which control the chemical reactions by which other molecules are built into the structure of plants and animals. For example, enzymes are responsible for the transfer and storage of energy which drives all growth processes. In plants these include the conversion of carbon dioxide to sugars in the green chlorophyll in leaves. Sugars are transported to developing storage organs, like the grain of wheat, rice and maize and potato tubers where the sugars are converted to starch. As sucrose, sugars are stored directly in sugar beet roots or the stems of sugar cane from which sugar is extracted by industrial processes.

Phosphorus is found in nucleic acids where complex DNA and RNA structures carry and translate the genetic information which controls all living processes. Very important amongst these is the production of proteins and essential vitamins.

Phosphorus in plants

Phosphorus is absorbed by plant roots from the soil solution mainly as orthophosphate ions, (principally dihydrogen phosphate, H_2PO_4^- and to a lesser extent HPO_4^{2-}). Uptake is controlled by plant demand because the phosphorus concentration in root cells can be 100 to 1000 times greater than that in the soil solution.

After uptake by the roots, phosphorus is transported to where it is needed and rapidly incorporated into those molecules for which there is a demand. Growing plants store very little of the simple phosphate ions taken up by the roots so there must be an ample supply in the soil. Plants unable to get sufficient phosphorus have their growth severely retarded. For annual crops like cereals - barley and wheat - very dark green or purple coloured older leaves are typical deficiency symptoms. Deficiency affects not only plant growth and development but eventually decreases the formation of fruits and seeds and invariably delays the ripening of cereals.

Unlike the growing plant, its reproductive parts - seeds and grains - must store phosphorus. This store supplies the developing seedling with an adequate supply of phosphorus before the developing roots begin to take up phosphorus from the soil. In seeds, phosphorus is stored mainly as polyphosphates like phytate. Phytate-phosphorus constitutes about 50% of the total phosphorus in legume seeds and 60-70% in cereal grains. In germinating seeds, phytate is converted by the enzyme phytase to provide phosphorus for incorporation into other molecules. In animal diets which contain a high proportion of cereal and legume grains, phytate is an important source of phosphorus.

Phosphorus in animals

Besides the role of phosphorus in living processes common to both plants and animals, phosphorus has another very important role in animals, including humans. Combined with calcium, calcium phosphates are a major constituent of the skeleton, about 85% in human skeletons.

As in germinating seeds, phytates supplied to animals in their diets have to be broken down by phytase to release phosphorus for its absorption from the gut. However, monogastric animals, like pigs and poultry, produce too little phytase so that much of the phosphorus in a diet containing legume and cereal grains is not made available for uptake into the animal. Because phosphorus deficiency limits many metabolic processes and affects appetite, growth, fertility and bone structure, many compounded or concentrated animal feedingstuffs often include supplementary calcium phosphates. Phytates can also interfere with the uptake from the intestine of mineral elements, especially zinc, but also iron and copper, which leads to a deficiency of these elements.

THE OCCURRENCE OF PHOSPHORUS IN NATURE

Phosphorus is not a rare element, it is eleventh in abundance in the rocks which constitute the earth's crust. However, the concentration of P in most rocks is so small that it has no commercial significance. Deposits sufficiently rich in P for commercial exploitation occur in both sedimentary and igneous rocks. These two types of rock have widely different mineralogical, chemical and textural characteristics. About 85% of world P production comes from sedimentary deposits which are derived from small particles compacted to a rock-like consistency. The remaining 15% comes from igneous rocks of volcanic origin. At present opencast, surface mining accounts for some 75% of global phosphate rock production. The remainder is mined. The main deposits being exploited at present are in the United States of America, Africa, China, the former Soviet Union and the Middle East.

It is very important to distinguish between reserves and resources of phosphate rock. Reserves can be broadly defined as deposits that can be exploited at the current costs of production in relation to the price at which the end product is traded on world markets. Resources (or potential reserves) are those deposits which could become commercially exploitable with changes in technology or the price consumers are prepared to pay for the product.

It is not easy to obtain reliable estimates of currently exploitable phosphate reserves for a number of reasons:

- The criteria on which the estimates are based often vary considerably. Those making estimates do not always use the same criteria.

- Producing countries/companies often consider that the information about their own reserves is confidential and commercially sensitive.
- Changes in technology and costs of production are extremely difficult to forecast.
- There is no certainty about future rates of consumption.

Current estimates of phosphate rock reserves exploitable at prices around today's level range from 60 and 250 years. Potential resources represent many centuries' supply. However large the world's phosphate resources may be they are a finite resource and must be used efficiently. (See also Benckroun, 1995).

THE USES OF PHOSPHORUS

Most of the mined phosphate rock is concentrated before it leaves the mine workings to provide a uniform product. There are three main uses:

- Currently 83% goes to produce fertilizer to supplement the small amounts of plant available phosphorus in soil.
- 6% goes to make phosphate additives for human and animal food grade products.
- 11% goes to make detergents and for other industrial applications.

Because 89% of the current use of mined phosphate rock is for food production the best opportunities to increase the life expectancy of the world's phosphorus resources are to use phosphorus more efficiently for this purpose.

Using phosphorus efficiently

Two approaches have the most promise for improving the efficiency of phosphorus in crop production:

- Increasing the efficiency of P fertilizer use in crop production by adjusting applications to allow for plant available P in soil.
- Recycling P in both animal manures and human sewage. All animals retain very little of the P they ingest, most is excreted in the faeces. Recycling this P to agricultural land helps to close the nutrient loop in the soil-crop-animal cycle.

There are, however, problems with recycling:

- Livestock production has become more intensive in many of the developed countries. Consequently, at the point of manure production, there is often too little land on which to apply the manure to achieve maximum benefit.
- Recycling sewage sludge from urban to agricultural areas may raise issues about food quality and hygiene. This could lead to the exclusion of treated sewage sludge from soils used for food production.
- Transport of both animal manures and sewage sludge over long distances has a cost in the use of another finite resource, fossil fuel. Transporting a tonne of fertilizer and animal manure may have the same cost but many more kilogrammes of P are carried in a tonne of fertilizer.

Although only a minor use, the efficiency with which dietary phosphorus is used by farm animals could be improved by adding the enzyme phytase to compounded feed formulations for monogastric animals. The effectiveness of doing this requires further testing. Currently it is more expensive in terms of feed costs than adding calcium phosphates.

PHOSPHORUS AND THE DEVELOPMENT OF FARMING SYSTEMS

It has been possible to feed an increasing number of people as the knowledge of plant nutrition and the ability to supply nutrients has developed.

About 10,000 years ago humans began to cultivate the soil to produce food crops. Invariably the productivity of land cleared of its natural vegetation declined quickly, in part due to a lack of nutrients and in part to weed competition. When yields no longer justified the labour to produce them, fresh land was cleared. This system of shifting cultivation removed much of the forests and native grasslands in many of the developed countries. It is still practised in parts of the developing world today and to protect the remaining resource of natural vegetation it is justified to increase the productivity of existing agricultural land provided this does not degrade this essential resource base.

As population increased in the Middle Ages, crops had to be grown more frequently on the same piece of land. But lack of nutrients was the limiting factor. This was overcome by cropping only in alternate years or twice in three years.

In the mid 18th century the Norfolk four-course rotation: turnips, spring barley, legume crop, winter wheat was developed in England and became the backbone of arable farming first in England then throughout Europe. It helped provide the food to feed the increasing urban population working in the industrial towns and cities. In this rotation there was a small input of nitrogen (N) by the legumes, which benefited the following winter wheat. However, the yield potential was still limited by lack of nutrients especially phosphorus (P) and potassium (K). This is well illustrated by the effects of relatively small inputs of N P K on the annual average yields of all four crops grown between 1852 and 1883 in the four-course rotation experiment at Rothamsted U.K. (Table 1).

Table 1. Average annual yields, t/ha, of turnips, spring barley, clover, beans and winter wheat, Agdell, Rothamsted. Eight rotations between 1852-1883. (Adapted from Johnston & Penny, 1972).

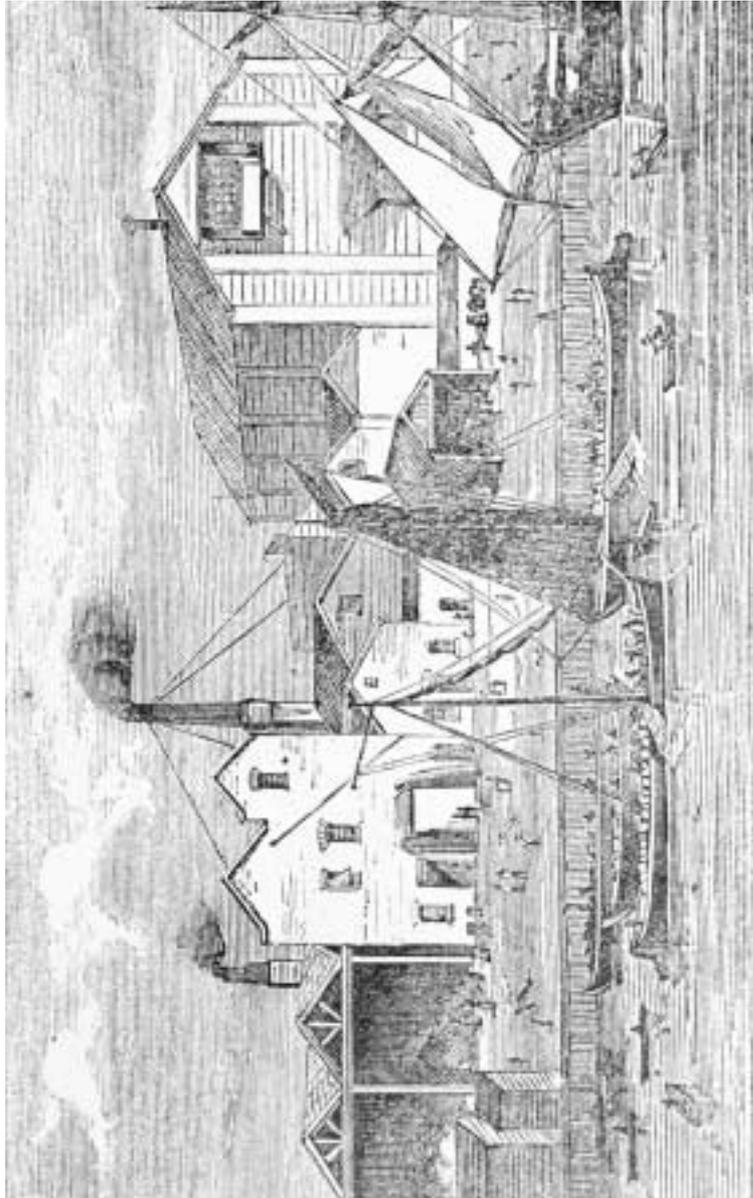
	Treatment once every four years [*]		
	None	P	NPK
Turnip roots, fresh	2.0	17.4	33.2
Spring barley, grain ^{**}	1.84	2.02	3.06
Clover hay ^{***}	2.41	5.81	7.59
Beans, grain	0.83	0.93	1.71
Winter wheat, grain	1.72	2.09	2.30

^{*} Treatments applied only to turnips, P, 40 kg P/ha; K, 225 kg K/ha; N 160 kg/ha (about 48 kg as ammonium salts, the rest as organic N in rape cake).

^{**} Grain yields at 85% dry matter.

^{***} Clover or beans, *Vicia faba*, grown in the third year. Spring beans replaced clover if the clover undersown in the barley failed to germinate sufficiently well to give a good crop.

On commercial farms the sale off the farm of cereal grain and animal products, milk and meat, would have depleted soil reserves of P and K. Without their replacement this rotation would not have been sustainable over the long term. In the UK, as in many other parts of Europe, nutrients were brought on to the farm in the form of imported animal feedingstuffs. Unless these were replaced, soil nutrients were being depleted in the countries producing the feedingstuffs.



Lawes' Works, Deptford 1843.

Early in the 19th century, some English farmers found that the trimmings from making bone handles for cutlery, when added to soil increased the yield of crops and a trade in bones developed. But bones were not effective on all soils. Treating bones with sulphuric acid to make superphosphate improved the effectiveness of the phosphorus on most soils. Making superphosphate, containing water soluble monocalcium phosphate, became a commercial practice in the mid 1840s. The P in fertilizers like superphosphate is referred to as inorganic P to distinguish it from organic P in complex organic molecules found in living tissues and in part in animal excreta.

J.B. Lawes of Rothamsted, a small agricultural estate near Harpenden, some 40 km north of London, was probably the first to produce superphosphate commercially. With J.H. Gilbert, Lawes started a succession of large-scale field experiments on the Rothamsted farm between 1843 and 1856 (Johnston, 1994). These experiments very quickly showed that crops require a supply of mineral nitrogen (ammonium or nitrate) in the soil. However, they showed that to achieve the optimum benefit from the nitrogen (N) fertilizer it was essential to apply P (Table 2). This was because the soils contained so little readily available P. These results from Rothamsted were supported by those from the experiments at Woburn started by the Royal Agricultural Society of England in 1876 (Table 2).

Table 2. Effect of nitrogen and phosphorus fertilizers on the yield of wheat and barley in early experiments. (Adapted from Johnston & Poulton, 1992).

Treatment	Rothamsted 1852-61		Woburn, 1877-86	
	Grain, t/ha		Grain, t/ha	
	Wheat	Barley	Wheat	Barley
None	1.12	1.43	1.10	1.44
N 96 kg/ha	1.63	2.13	1.56	2.34
P 33 kg/ha	1.30	1.74	1.13	1.35
NPK 96 kg N, 33 kg P [*]	2.42	3.20	2.48	3.09
FYM ^{**}	2.41	2.85	1.76	2.39

^{*} The response to K 90 kg/ha was negligible
^{**} 35 t/ha at Rothamsted, 20 t/ha at Woburn

Both sets of results illustrated a very important fact; namely that fertilizers could give the same or better yields than farmyard manure (FYM). Based on these results Lawes and Gilbert concluded that there was every hope that agriculture would be able to feed the rapidly increasing population once fertilizers became readily available and farmers used them. They stressed the need to use fertilizers because they realised that the very large amounts of FYM they applied annually in their experiments were not available on most farms. The need for large amounts of FYM is illustrated in Table 2 which shows that the smaller amount used at Woburn did not produce the same yields as did the fertilizers.

So great was the need to persuade farmers to use fertilizers that the results from the experiments at Saxmundham, started in 1899 by the Suffolk County Council, were given in terms of financial gains and losses (Table 3). Farmers lost money by applying only N to winter wheat and field beans, *Vicia faba*, and gained only a little when it was applied to spring barley. Although the cost of N plus P was greater than that of N alone there was a larger profit when both were applied together.

Table 3. Profit or loss, in shillings, from using fertilizers or farmyard manure. (Summarised and adapted from the annual reports 1899 to 1914 East Suffolk County Education Committee).

	Treatment			
	N	NP	NPK	FYM
Cost of fertilizer, shillings	20.0	26.0	35.0	30.0
<i>Profit (+) or loss (-) when growing:</i>				
Winter wheat	-7.5	+12.0	+13.6	+17.6
Spring barley	+6.6	+34.3	+31.3	+0.2
Field beans	-20.0	+37.2	+35.8	+60.0

It is interesting that, in six European countries in 1936, the average application of P (expressed as P_2O_5) was larger than that of N (Table 4). In part this was probably because the yield potential of most crops was small and crops were grown in rotation and some FYM was used.

Table 4. Fertilizer use in six European countries in 1936.
(Adapted from Crowther, 1945).

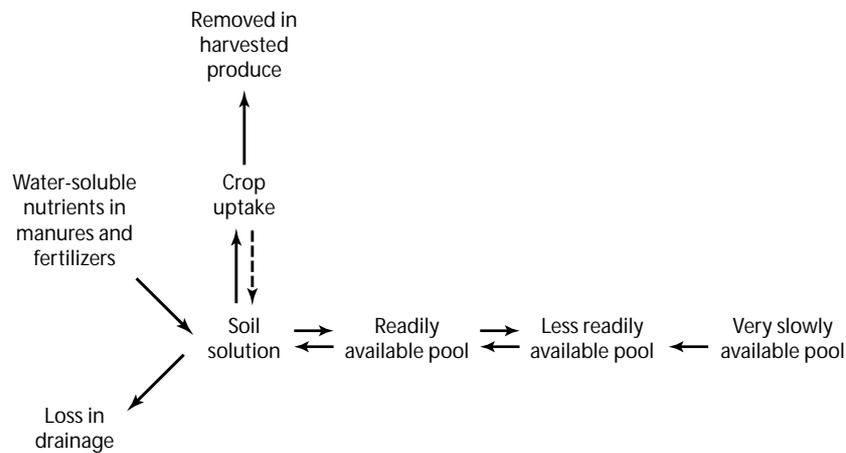
Country	kg/ha of arable land			Nutrient ratio		
	N	P ₂ O ₅	K ₂ O	N	P ₂ O ₅	K ₂ O
Holland	68	103	100	1	1.5	1.5
Belgium	53	51	44	1	1.0	0.8
Germany	25	32	50	1	1.3	2.0
Denmark	14	25	14	1	1.8	1.0
Great Britain	10	28	10	1	2.8	1.0
France	6	19	10	1	3.2	1.7

SOIL PHOSPHORUS AND ITS AVAILABILITY

Understanding the complexity of the chemistry of soil phosphorus is a challenge because P is held in soil in many different ways. Current thinking envisages a series of reactions when a phosphatic fertilizer is added to soil (Syers & Curtin, 1988). Initially the P in water soluble compounds, like monocalcium phosphate in superphosphate, goes into the soil solution as phosphate ions. The P is then taken up by the roots or is quickly adsorbed onto the mineral particles or organic matter which make up most of the soil. The P is held with a range of bonding energies or strengths to the surfaces of aluminium, iron or calcium compounds. The type and relative proportions of these compounds depends mainly on the nature of the clay sized particles and the acidity of the soil. After the initial adsorption further reactions take place slowly to produce less readily soluble calcium, iron and aluminium compounds. The speed with which the adsorbed P is released back into the soil solution to replenish the P taken up by plant roots depends on the strength of the bonding holding the P to the different surfaces.

The availability of different forms of soil phosphorus

Figure 1. A simple schematic representation of the phosphorus cycle in the plant soil system. Soil analysis to estimate the readily available soil P includes the small amount of P in the soil solution. The amount of P extracted varies with the extractant used. Using the analytical data soils are classified descriptively (e.g. deficient, sufficient) or by numerical indexes. These classes are related to the probable response of a crop to an application of an appropriate phosphatic fertilizer.



When thinking in agronomic terms about soil P it is helpful to visualise the phosphorus cycle in the plant-soil system as a series of 'pools' as in the diagrammatic representation in Figure 1. Water soluble phosphorus added in fertilizers and manures goes first into the soil solution. From there the P is either taken up by the plant roots or remains readily available or less readily available as a result of the reactions described above. The readily available P can be estimated by different methods of soil analysis, but there is no one universal extractant. The quantity of P extracted will vary with the reagent used. However, most widely used methods have been accepted because they adequately distinguish between soils on the basis of the responsiveness of crops to an application of phosphate fertilizer.

There is no routine method to determine the less readily available P but it is certain that the rate and amount of P released from this pool will vary greatly. In a recent research project at Rothamsted funded by the World Phosphate Rock Institute (IMPHOS), an eight-step sequential extraction procedure was developed to determine seven soil phosphorus fractions. The extractants in order are:

1, resin; 2, 0.5 M NaHCO₃; 3, 0.1 M NaOH; 4, 1.0 M NaOH; 5, 0.5 M H₂SO₄; 6, hot concentrated HCl; 7, residual P. In the solutions extracted by reagents 2, 3, 4 and 6 both organic (Po) and inorganic phosphorus (Pi) are determined. The residual P is also estimated as Pi and Po but they are determined sequentially using different procedures on the residue left after treatment with hot concentrated HCl.

In this sequential fractionation, the extraction with Olsen's reagent (0.5 M NaHCO₃ at pH 8.5) follows the equilibration with resin so that the amount of P extracted, called bicarbonate P, is different to that extracted when Olsen's reagent is used for routine soil testing, called Olsen P. When compared for routine soil testing on soils in England, the amount of resin P is about twice that of Olsen P. Why then does Olsen's reagent remove P following equilibration with resin in the sequential fractionation? The reason is that the Olsen method is an equilibrium method and, if a soil is extracted successively with fresh aliquots of Olsen's reagent, P continues to be removed but in ever decreasing amounts. Invariably the total P extracted exceeds that extracted with resin. So an extraction with Olsen's reagent following resin will remove some more P from the soil. The alkaline reagents probably extract P associated with iron and aluminium while that extracted by sulphuric acid is probably associated with calcium. The resin and bicarbonate P is likely to be the most readily plant available.

Soils from the Rothamsted long-term experiments growing grass or arable crops and where P has been added or removed over long periods have been used to assess the value of this method of soil P fractionation. The results show that P reserves accumulate in, and can be removed from, all of the fractions extracted by the first five extractants. Thus, soil P reserves are not held in a particular fraction of soil P. In these experiments the increase or decrease in all five fractions was well related to the positive or negative P balance (P applied minus P removed) (Blake et al., 1997).

The results of the P fractionation studies support an important feature of Figure 1, namely the reversible transfer of P between the soil solution and the readily- and less readily-available soil P pools. This seems to be true for many soils though it may not be so for all, especially those that have a considerable capacity to fix phosphorus. As well as the data above from soil P fractionation, the data in Table 5 are another example which shows that P not measured as readily available can nevertheless supply P to crops. Arable crops were grown in rotation for 16 years on a sandy clay loam soil containing different levels of Olsen P. The yield and amount of P removed in the harvested crop were both related to the level of Olsen P. Because the soil weight per hectare was known,

the change in concentration of Olsen P could be converted to an amount and this amount related to the phosphorus offtake in the harvested crop (Table 5). On soils with least Olsen P, very little of the P offtake was accounted for by a decrease in Olsen P, while on soils well supplied with Olsen P, the P offtake was about twice the decline. Thus readily available P not measured by the Olsen method, was nevertheless able to supply P for crop growth.

Table 5. Relationship between P removed by crops and decline in Olsen P when no P fertilizer was applied to a sandy clay loam soil, Saxmundham, 1969-1982. (Adapted from Johnston & Poulton, 1992).

Factor	Measured value for each of 8 soils							
Olsen P, mg/kg, in 1969	3	7	21	28	39	44	54	67
P removed in crops 1969-1982, kg/ha	94	153	217	237	253	256	263	263
Decrease in Olsen P kg/ha, 1969-1982 [*]	8	12	27	50	65	78	87	120
Change in Olsen P as a % of P offtake	8	8	12	21	26	30	33	46

^{*} Based on the measured soil weight for the top 25 cm.

The effect of soil organic matter on phosphorus availability

Soil organic matter (humus) plays an important role in the availability of P to agricultural crops which is not related to the mineralisation of organic phosphorus. Humus apparently provides sites with low bonding energies for P including that applied in fertilizers. Table 6 shows total, Olsen and CaCl_2 P in soils with different amounts of humus due to the addition of fertilizers and farmyard manure (FYM). The strength of the CaCl_2 extractant was only 0.01 M, similar to that of the soil solution in neutral soils. Thus the P extracted by this reagent is probably similar in amount to that released to the soil solution in the short term. Table 6 shows that the increases in both the total and Olsen P were very similar with the addition of either fertilizers or FYM. The increase in CaCl_2 P was, however, proportionally much larger on FYM treated soils, with more humus, than on those given fertilizers. Interestingly, the Barnfield experiment

was the only one in which both FYM and superphosphate were applied together on the same plot and where this was done the increase in CaCl_2 P was greater than the sum of the individual increases where these treatments were applied separately.

The Exhaustion Land and Woburn experiments (Table 6) provide additional, interesting evidence on the effect of humus on CaCl_2 P. The Exhaustion Land experiment was started in 1856 with superphosphate applied from then until

Table 6. Total, Olsen and CaCl_2 P in surface soils (0-23 cm) from various long-term experiments at Rothamsted and Woburn. (The increase over the control is in parentheses). (Adapted from Johnston & Poulton, 1992).

Experiment and year sampled	Treatment	% C	Total P mg/kg	Olsen P mg/kg	CaCl_2 P $\mu\text{g/l}$
Barnfield 1958	Control	0.80	670	18	0.5
	P*	1.00	1215(545)	69(51)	3.0(2.5)
	FYM*	2.40	1265(595)	86(68)	12.8(12.3)
	FYM + P	2.40	1875(1205)	145(127)	22.3(21.8)
Broadbalk 1966	Control	0.84	580	8	0.2
	P	1.04	1080(500)	81(73)	6.6(6.4)
	FYM	2.59	1215(635)	97(89)	19.5(19.3)
Hoosfield 1966	Control	0.93	630	6	0.3
	P	1.16	1175(545)	103(97)	14.4(14.1)
	FYM	3.06	1340(710)	102(96)	25.4(25.1)
Exhaustion Land** 1974	Control	0.88	480	2	0.1
	Residue of P	0.88	595(115)	10(8)	0.2(0.1)
	Residual FYM	1.10	630(150)	12(10)	0.3(0.2)
Woburn 1960	Control	1.02	1120	94	23
	FYM	2.12	1780(660)	176(82)	98
	SS*	2.87	3000(1880)	151(57)	43

* P, superphosphate; FYM, farmyard manure; SS, sewage sludge
 ** no superphosphate or FYM applied after 1901

1901 when the soil contained 0.80% C. FYM was only applied between 1876 and 1901 but the 25 applications of FYM at 35 t/ha increased the humus content appreciably, to 1.45% C. In 1903, when the soils were sampled, the increases in total P and Olsen P were very similar and, as on Barnfield, Broadbalk and Hoosfield, there was more CaCl_2 P in the FYM treated soil (not shown in Table 6). However, when the soils were sampled in 1974 much of the extra humus had mineralised and the humus content of the fertilizer- and FYM-treated soils was 0.88 and 1.10% C, respectively. Table 6 shows that in 1974 there was now very little difference in the CaCl_2 P content of these two, differently treated, soils now that they had a similar humus content. At Woburn, the sewage sludge treatment added much organic matter and phosphorus (Table 6). Compared to the FYM treated soil, the increase in total P was much larger but the increase in both Olsen and CaCl_2 P was less. The sewage had been anaerobically digested to leave very inert organic matter and little soluble P. The inert organic matter had done little to provide sites to hold extra CaCl_2 P from the P applied to all plots in superphosphate. These results suggest that soil organic matter developed in situ, from organic additions like FYM, has low energy bonding sites on which phosphate ions can be held, but added inert organic matter has few such sites.

Soil organic phosphorus

Organic P in soil can be associated either with soil organic matter (humus) or recently added organic debris coming from plants or animals. Before this organic P can be recycled and used by plants it has to be broken down by soil microbes - a process called mineralisation - to release inorganic phosphate ions. These can be either taken up by plant roots or they can enter into the same reactions with soil particles as fertilizer phosphate ions, or they can be used by soil microbes. Farmyard manure is classed as an organic manure but 60-80% of the P it contains is inorganic phosphate ions. In part, this is because of the addition of inorganic P feed supplements and much of this P is excreted.

The determination of total organic phosphorus in soil is notoriously difficult. The accurate estimation of changes in organic P, especially over short periods, is subject to large errors. Changes in organic P are always related to changes in total nitrogen and carbon but there is no evidence for a fixed ratio between the three elements either for gains or losses. In mainly arable soils changes in soil pH often have bigger effects on organic P than do changes in crop husbandry. There is often little difference in the proportion of the total soil P which is present as organic P between soils treated with fertilizers and farmyard manure or

between soils growing arable crops and under permanent grassland. The proportion can be as little as 10 to 15%.

The mineralisation of organic phosphorus is very important in the cycling of P in ecosystems supporting natural forest and grassland where the annual productivity is small. It may also be important in organic farming systems or systems with low inputs. The annual turnover of organic P through the soil microbial biomass in permanent grassland soils (~ 25 kg/ha) can equal the amount in herbage. However, in organic and low input systems the supply of P is not inexhaustible and P must be replaced if the system is to remain sustainable. For soils which have been under arable cropping for many years the net rate of mineralisation of organic P can range from less than 1 to about 10 kg P/ha annually. Even the larger amounts of P would only supply about half the P removed in 5 t/ha of cereal grain. Farming systems aiming to achieve larger optimum yields cannot rely solely on the mineralisation of soil organic P to supply the phosphorus needs of the crop (Chater & Mattingly, 1980; Mattingly et al., 1975).

Soil physical properties and phosphorus availability

When analysing a soil for its chemical constituents it is usual to analyse only that fraction which passes through a sieve having 2 mm diameter apertures. This soil fraction may consist of individual particles or small aggregates of particles. Soil texture is related to the relative proportions of the individual particles of sand, fine sand, silt and clay. Sandy and clayey soils have a preponderance of sand and clay sized particles, respectively, loams have a mixture of different sized particles. The clay and silt particles are important in much of the chemistry of soil P.

Interconnecting passage ways - pores - separate particles and crumbs. The total volume of the pores, the pore space, varies little between soils of different texture, about 60% in clayey soil and 50% in sandy soil. There are two important aspects to pore space:

- The proportion of pores occupied by air and water. Plant roots respire and therefore need the oxygen in the air. But they also take up the water and nutrients in the water. Generally sandy soils have more air filled pore space than clayey soils.
- The proportion of pores of different diameters. Water drains from pores larger than 50 μm under gravity allowing air to enter. Clayey soils have a greater proportion of pores with a small diameter than do loamy soils. As the pore size decreases water is held more strongly.

Because only soil passing a 2 mm sieve is analysed for readily available P the analytical data must be related to the amount of this soil in the field when giving recommendations about the amount of P to apply. The amount of fine soil to be considered is that into which most roots could grow. This amount, in part, will be related to the structure of the soil in the field which depends on the relative proportions of the inert particles and the amount of soil organic matter. Soil structure is important in relation to root growth and the ability of roots to exploit the soil to find nutrients. (See Johnston et al., 1998 and references therein).

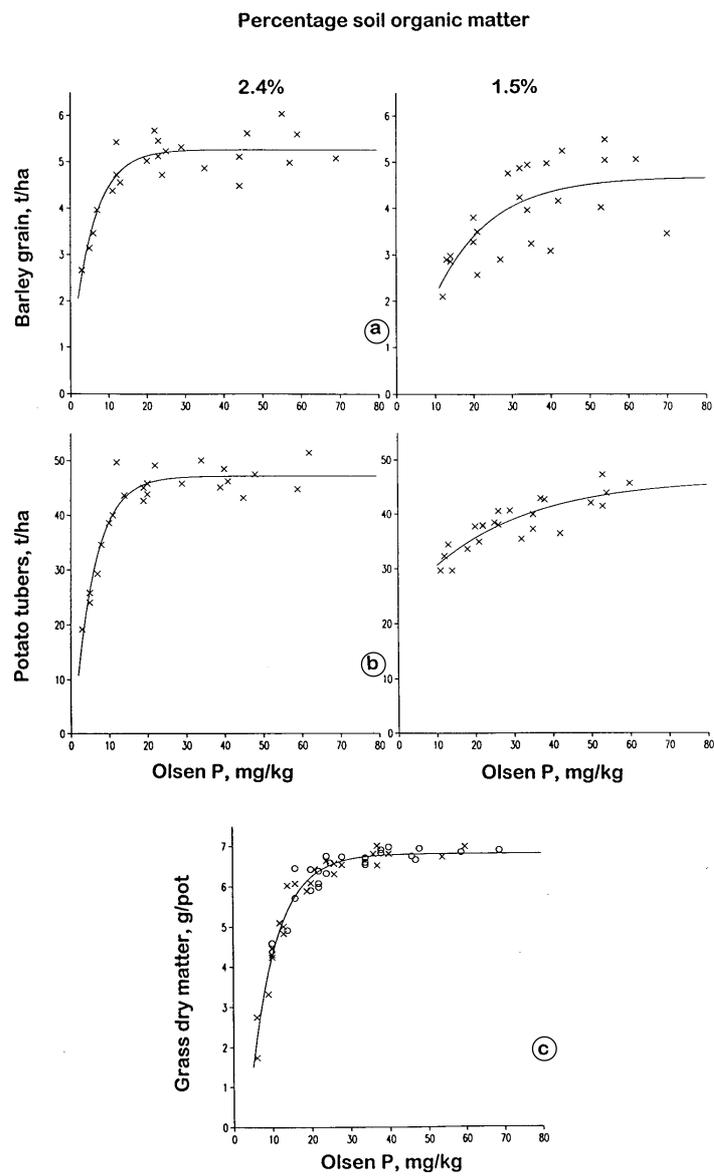
This effect of soil structure is well illustrated by data from a sandy loam soil with different levels of soil organic matter, determined as percentage carbon (%C) (Table 7). The soil contained a range of Olsen P values including concentrations much larger than the 25-30 mg/kg which would be considered adequate for most arable crops in the UK. At the same level of organic matter, yields increased as Olsen P increased from 15 to 32 mg/kg. Then with the larger concentrations of Olsen P, yields increased as soil organic matter increased.

Table 7. Yield of spring barley, potatoes and sugar from sugar beet when grown on soils with different levels of soil organic matter and Olsen P. (Adapted from Johnston & Poulton, 1992).

% carbon	0.68	0.68	1.08	1.44	1.82
Olsen P mg/kg	15	32	131	148	165
<i>Crops and yield, t/ha:</i>					
Spring barley, grain	3.40	3.98	4.93	5.15	5.23
Potato tubers	31.6	40.0	45.0	51.4	58.2
Sugar from sugar beet	5.78	6.46	6.72	8.24	8.15

An even more striking example of the beneficial effects of humus is shown in Figure 2. In one experiment during a 12-year period, soils with two levels of humus and a range of levels of Olsen P were established. Then potatoes, spring barley and sugar beet were grown in rotation. Figure 2 shows that the yields of both barley (Figure 2a) and potatoes (Figure 2b) approached an asymptote or plateau yield at much lower levels of Olsen P on the soil with more humus than on the soil with less.

Figure 2. The relationship between the yield of spring barley (Figure 2a) and potatoes (Figure 2b) and Olsen P on a silty clay loam soil with either 2.4% or 1.5% organic matter (SOM) and the relationship between the cumulative yield from five harvests of ryegrass and Olsen P when all 48 soils were cropped with ryegrass in the glasshouse (Figure 2c).



At each level of soil organic matter (%SOM), the yield at 95% of the asymptote yield (95% yield) and the Olsen P associated with this yield, together with the percentage variance accounted for in these relationships was:

Crop	%SOM	95% yield t/ha	Olsen P mg/kg	% variance accounted for
Spring barley	2.4	5.00	16	83
Grain (Fig 2a)	1.5	4.45	45	46
Potatoes	2.4	44.7	16	89
Tubers (Fig 2b)	1.5	44.1	61	72
Grass dry matter	2.4	6.46	23	96
(Fig 2c)	1.5	6.51	25	82

*The response curve at each level of soil organic matter was not visually different and yield is g/pot.

This difference in response to Olsen P on the two soils was almost certainly due to the effect of the extra humus on soil structure. The silty clay loam on which the field experiment was sited was not easy to cultivate, especially in early spring for a crop of barley. The data for spring barley (Figure 2a) show many small yields on soils with appreciable levels of Olsen P but less humus. This was because it was difficult to produce a satisfactory seedbed in early spring when the soil with more humus was fit to cultivate.

That these effects in the field experiment were due to soil structure is supported by results from a pot experiment in the glasshouse. Soil samples were collected from all 48 plots, 24 from the soil with each level of humus. The less than 2 mm soil was then mixed with quartz (2 soil:1 quartz) to give a good rooting medium, and then cropped with ryegrass in pots in the glasshouse. The dry matter yields from five harvests when plotted against Olsen P (Figure 2c) showed that there was a single relationship for all soils whereas in the field experiment there had been two. For the ryegrass the shape of the curve was similar to that for the field grown crops on the soil with more soil organic matter.

PHOSPHORUS ACQUISITION BY ROOTS

Plant root systems

There is great variation between the root systems of different species both in weight, length and depth to which roots penetrate. For example, winter wheat yielding 10 t/ha of grain increases its root system during growth to a maximum of about 1.5 t/ha root dry weight. In length this is about 100 m per plant at 300 plants per square metre. Roots can only grow along pores which the root tip can enter. The smallest roots of a cereal plant can probably not enter pores less than 50 μm in diameter (see Johnston et al., 1998 and references therein).

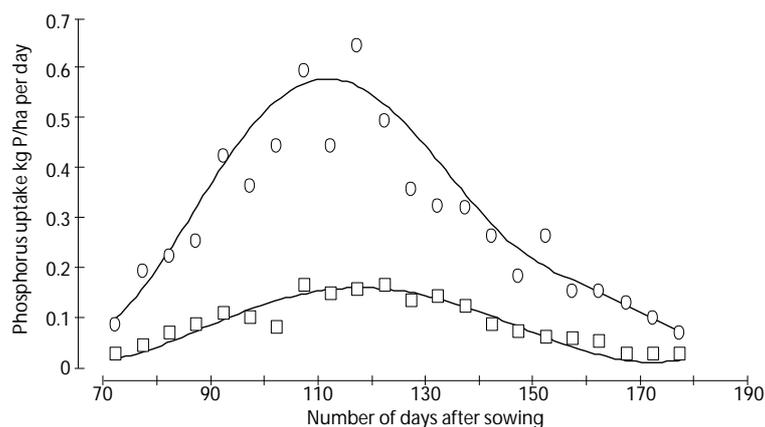
Nutrients held in the soil solution, especially in small pores, have to move - diffuse - towards the root. The driving force for this diffusive flow to the roots is the lowering of the nutrient concentration at the root surface as the root takes up nutrients from the solution. Thus there must be an adequate supply of nutrients within the volume of soil explored by the roots. Although most roots are in the topsoil, deep rooted crops like winter wheat, lucerne and sugar beet can acquire nutrients from the subsoil if they are there in readily available forms.

Rate of phosphorus uptake by roots

During their active growing period, many plants maintain between 0.3 and 0.5% P in the dry matter. To achieve this they need to take up from the soil solution between 0.5 and 1.0 kg P, as phosphate ions, per hectare each day. But, at any one time, even on soils well supplied with P, the total quantity of P in the soil solution may only be between 0.3 and 3.0 kg/ha, and not all of this P is readily available because the roots are not in contact with all the soil solution. Thus P in the soil solution must be replenished frequently, often several times a day, from the readily available P as illustrated in Figure 1 (Marschner, 1995).

Figure 3 shows the daily P uptake rate for a crop of spring barley given sufficient N and K but grown on two soils, one with adequate, the other with little readily available soil P. The maximum daily uptake rate occurred some 120 days after sowing and differed by a factor of three. This large difference was reflected in the final grain yield which was 6.38 t/ha on the soil with adequate P but only 2.88 t/ha on the other soil.

Figure 3. Daily phosphorus uptake rate, kg P/ha, by spring barley grown on a soil with adequate P reserves (O) and too little readily available soil P (□) (adapted from Leigh and Johnston, 1986).



SOIL PHOSPHORUS RESERVES

Early concepts of the behaviour of P added to soil in phosphatic fertilizers and organic manures considered that any unused residue of water soluble P reacted with soil constituents so that it was no longer water soluble but was permanently fixed in soil in forms which were unavailable to future crops. Research in the last 40 years or so has shown that this early concept was largely incorrect for many soils. As discussed in the section on 'Soil phosphorus and its availability', P is held in soil in many different ways and weakly held P is a reserve from which P is transferred to the soil solution. The extent to which readily available P can be increased is related to soil pH and the presence of various soil constituents. However, even on soils where readily available P will accumulate only a small proportion of each P residue is held with a small bonding energy. Therefore large increases in Olsen P only occur in many soils when they have been cultivated and fertilized and manured for many years.

The effect of P balances on Olsen P is illustrated for the silty clay loam soil (pH in water about 8.0) at Rothamsted. During a 47-year period there was a large positive P balance where FYM or superphosphate had been applied and this led to an increase in Olsen P (Table 8). The data in Table 8 again show that

where no P was applied for many years the decrease in Olsen P was very small (only 1 mg/kg), i.e. most of the 80 kg of P which was removed in the harvested crop had come from the less readily available P reserves.

Table 8. Increases in Olsen P in a silty clay loam soil (pH 8) due to large phosphorus balances over a 47 year period. (Adapted from Johnston & Poulton, 1997).

	Treatment		
	None	FYM	PK
P balance 1856-1902	-80	+1030	+1215
Olsen P, mg/kg			
In 1856	10	10	10
In 1903	9	66	65

From the data in Table 8 it is possible to calculate that the increase in Olsen P, in kg/ha, due to the large P balance, was not equal to the P balance, in fact it was much smaller because, as Figure 1 suggests, much of the P balance had been transferred to the less readily available pool. When the data from the long-term experiments on the silty clay loam soil at Rothamsted and the sandy loam at Woburn are combined then only about 13% of the increase in total soil P is Olsen P (Figure 4).

The value of soil phosphorus reserves

Research in the last 30-40 years has shown also that soils enriched with readily available P reserves gave larger yields of crops than similar soils without such reserves. Moreover, when a large amount of phosphorus fertilizer was applied to both soils, yields were larger on the enriched soil than on the impoverished one (Table 9). This benefit arises because the P in the soil solution is replenished quickly on soils with uniformly distributed, readily available P reserves. On an impoverished soil it is impossible to mix, say, 20 kg of phosphorus uniformly throughout the 2 million kg of surface soil on one hectare. Therefore, there is only a limited chance of the roots coming into contact with newly added phosphorus.

Figure 4. The relationship between the increase in Olsen P and the increase in total soil phosphorus in long-term experiments on a silty clay loam (○), a sandy loam (□) and a sandy clay loam (△) soil.

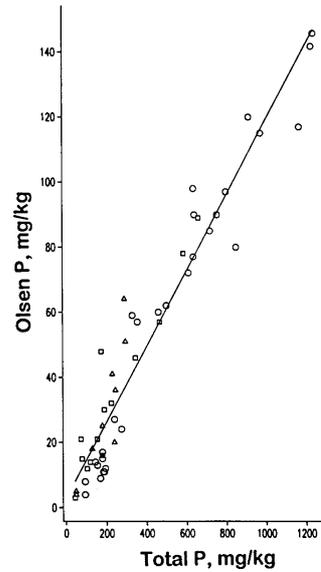


Table 9. Effect of residual P in soil and freshly applied P fertilizer on the yields of three arable crops. (Adapted from Higgs et al., 2000).

Crop	P applied kg/ha	Experiment* and Olsen P, mg/kg							
		Agdell		Exhaustion land		Woburn		Saxmundham	
		4	13	4	12	18	42	4	26
		Yield, t/ha							
Spring barley	0	1.54	3.41	2.03	3.11	2.62	3.34	3.28	4.83
(grain)	56	2.89	3.88	3.49	3.48	2.86	3.61	4.89	4.81
Potato tubers	0	12.1	29.9	12.8	21.1	35.1	40.7	21.2	43.3
	56	25.4	38.2	32.6	32.6	38.2	43.4	33.6	44.7
Sugar	0	3.38	5.77	3.84	5.67	5.17	5.90	1.85	6.79
(from beet)	56	4.79	6.00	5.72	6.00	5.15	6.15	5.44	6.41

* For each experiment the soil with the lower level of Olsen P had received no P fertilizer since the start (Agdell 1848; Exhaustion Land, 1852; Woburn, 1876; Saxmundham, 1899).

Such results pose two interrelated questions:

- To what extent should soil phosphorus reserves be increased?
- How much fertilizer should be recommended on soils with different levels of reserves?

READILY AVAILABLE SOIL PHOSPHORUS AND FERTILIZER RECOMMENDATIONS

Soil analysis for readily available phosphorus

Only a small proportion of the total soil phosphorus is readily available and much effort has been devoted to find methods of soil analysis which would reliably predict the amount. Most methods estimate the quantity in the soil solution and the readily available pool. Many methods used currently involve extracting soil with a chemical reagent or using an anion exchange resin. In most countries the chosen methods adequately characterise soils in relation to their responsiveness to applications of phosphatic fertilizer. In England and Wales, Olsen's method is widely used to determine readily available P (Olsen P) and the illustrations in this publication all use Olsen P expressed as mg P/kg of soil.

Fertilizer recommendations

Ideally fertilizer recommendations are based on the results of field experiments in which yield is measured at increasing amounts of applied P. From the response curve relating yield to P applied, the optimum application of P is determined. Field experiments, however, are expensive and cannot be done for all the crops grown in different farming systems on all soil types. Thus the fertilizer P application associated with the optimum yield is, in turn, related to the readily available P determined by soil analysis. The recommendation for this soil analysis value is then used for other soils of the same type with the same or similar analytical value. Thus from a limited, but on-going, number of field experiments reliable fertilizer recommendations can be established.

Desired readily available soil phosphorus levels

The acknowledged value of soil P reserves discussed previously and their estimation by soil analysis now allows another approach to fertilizer recommendations. In field experiments, instead of relating yield to increasing amounts of added P in fertilizer, yield is related to levels of readily available P in soil. If all factors affecting growth are optimum except readily available P, then as this factor increases, yield will increase rapidly at first, then more slowly until a plateau yield is reached (Figure 5). The value of readily soluble P at which yield closely approaches the plateau yield can be considered the critical P level for that crop and soil.

Figure 5. A schematic representation of the relationship between crop yield and readily available phosphorus in soil.

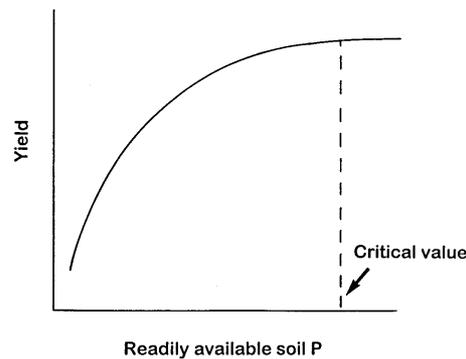


Figure 6 shows recent examples of the relationship between yield and Olsen P from three field experiments. In each experiment, although there were large differences in the asymptote yield, the critical soil P value was very similar. The yields of potatoes (Figure 6a) and of spring barley (Figure 6b) differed between years due to differences in rainfall. Figure 6c shows that although applying different amounts of nitrogen to winter wheat gave different maximum yields the critical Olsen P value was independent of the final grain yield.

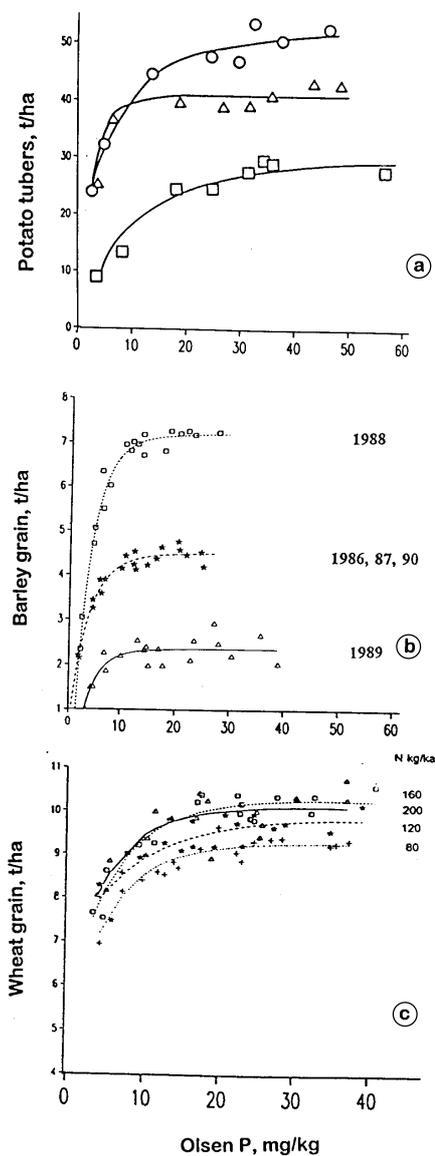
Statistical analysis of the data in Figure 6 showed that much of the variance in yield could be accounted for by Olsen P: 87% for barley, 84% for potatoes and 68% for winter wheat. This suggests that there is little wrong with the Olsen method for determining readily available P as a method for predicting probable yield responses with reasonable accuracy when all other factors affecting growth

Figure 6. The relationship between the yields of three arable crops and Olsen P.

Figure 6a. Potatoes grown on a sandy clay loam.

Figure 6b. Spring barley grown on a silty clay loam.

Figure 6c. Winter wheat grown on a sandy clay loam.



are controlled, e.g. nitrogen supply or disease incidence, or are the same like soil texture, cultivations and weather. When there is a poor relationship between yield and Olsen P then the interference from other factors should be assessed to determine whether they are affecting yield.

Below the critical level, yield is severely decreased and this is a large financial loss to the farmer. If the soil is much above the critical value there is no increase in yield and so there is no financial justification for the farmer to buy and apply more P fertilizer. The rationale for P manuring should be to build up and then maintain soils just above the critical value. At this level the simplest fertilizer recommendation will be to replace the P removed from the field in the harvested crop. The concept of replacement or maintenance applications of P fertilizers is becoming established.

Farmers, however, are unlikely to even consider using the concept of P replacement if it is difficult or time consuming to calculate the amount of P which has been removed in the harvested crop. In most cases the farmer will have a reasonable estimate of the yield for each field and this can be multiplied by the average P content (in kg P or P_2O_5) per tonne of fresh produce, taken from "Look up" tables, to estimate the total amount of P or P_2O_5 removed in the harvested crop (see for example PDA, 1997). This will be the amount of P to be applied in fertilizer. The degree of accuracy from using estimated yields and the P content from look up tables is sufficient. Periodic soil analysis can be used to check that the soil is not moving too far away from the critical value set for that soil and farming system.

The importance of maintaining the critical readily available soil phosphorus level

All factors affecting crop growth and yield need to be optimum to ensure that the best economic yield is obtained. Often factors that affect growth without obvious visual symptoms are ignored when planning the nutrient management strategy for the farm. Among such factors are soil P (and K) levels. When the P level is not seriously below the critical value other inputs are often used inefficiently. This is especially so for nitrogen (N). When applied to P deficient soils, N often does not increase yield as much as it does on soils with an adequate supply of P. This results in only small recoveries of the added N which, in turn, leaves a large residue of nitrate in the soil at risk to loss by leaching or denitrification.

Applying nitrogen to crops grown on soils with only small amounts of phosphorus

Table 10 shows the yields of spring barley grown on soils with different, but only small amounts of Olsen P, and given increasing amounts of fertilizer N. On the soil with least Olsen P it was not justified in terms of yield to apply more than 48 kg/ha N while on the two soils with more, but still too little Olsen P, 96 kg/ha N was optimum for yield. Table 10 also shows how much of each application of N was not accounted for. With the 96 and 144 kg/ha N applications the amounts of N not accounted for were large, 63 to 84 kg N when 96 kg/ha of N was applied and 107 to 127 kg/ha N when 144 kg/ha was applied. Such large quantities are a financial cost to the farmer and could have had an appreciable adverse environmental impact if the N not accounted for was nitrate which could be lost by leaching or denitrification.

Table 10. Yields of spring barley grain, nitrogen in grain plus straw and nitrogen not accounted for when the barley was grown on soils with low levels of Olsen P and given different amounts of fertilizer nitrogen. Ten year average 1976-85.

Plot	Olsen P, mg/kg	N applied, kg/ha			
		0	48	96	144
Grain yield, t/ha					
1	2	0.86	1.20	1.32	1.49
2	7	1.65	2.33	2.87	2.96
3	10	2.19	3.28	3.79	3.61
Nitrogen in grain plus straw, kg/ha					
1		16	24	28	33
2		29	44	56	62
3		38	55	71	75
Fertilizer nitrogen, kg/ha, unaccounted for*					
1			40	84	127
2			33	69	111
3			31	63	107

* Based on the difference method

Applying nitrogen to soils with declining levels of Olsen P

The data in Table 5 show that P can be released from the less readily available soil P reserves to provide P for plant growth. This release can continue for many years on some soils depending on the initial level of readily available P. But as the rate of release of these P reserves declines, the response by crops to N and the efficiency with which the N is used decreases. Table 11 shows how the yields of spring barley have changed over a 30 year period on a soil on which P fertilizer applications ceased and where the Olsen P was 12 mg/kg in 1970. As for the soil with most Olsen P in Table 10, it was never justified to apply more than 96 kg/ha fertilizer N in any of the three periods. Although the Olsen P in the soil had declined only a little by 1999, as the net result of P being removed in the crop and released from P reserves, the average annual yield of barley nevertheless declined by about 1 t/ha grain in the 30 year period.

Table 11. Effect of stopping the application of phosphorus and continuing to supply fertilizer nitrogen on the yields of spring barley.

Period	N applied, kg/ha		
	48	96	144
	Grain yield, t/ha		
1970-73	3.21	5.27	4.94
1984-87	3.76	4.81	5.05
1996-99	3.18	4.21	3.88

THE EFFICIENT USE OF PHOSPHORUS FERTILIZERS

The efficiency with which plant nutrients are used is of considerable interest. A standard way of doing this is to determine the percentage recovery of an added plant nutrient by the difference method. In field experiments, different plots are, or are not, given the nutrient under test, yields are measured and the nutrient content is determined. Percentage recovery is then calculated as the difference in the amount of nutrient in the crops with and without the nutrient, divided by the amount of nutrient applied and multiplied by 100 as shown for N in Table 10.

Estimated in this way the percentage recovery (or efficiency) of P is very low, often only 10 to 15% and rarely exceeding 25%.

Efficiency can also be estimated when the P in the applied fertilizer can be uniquely identified. This can be done by labelling the fertilizer P with its heavy isotope ^{32}P . Analytical techniques exist to determine the amount of ^{32}P in samples of crops grown on soils to which the labelled fertilizer has been added. Thus the proportion of the P in the crop which has been taken up from the fertilizer can be calculated. This more detailed, but very expensive method, gives data for arable crops which are similar to the difference method, that is recovery does not exceed 25%. (See Mattingly & Widdowson, 1958, 1959 and references therein).

Another, quite different, approach to looking at the effectiveness of P fertilizer use is to relate the amount of P in the crop with the amount which was applied. This is a useful method for P because little of the applied P is taken up by the crop and nearly all of the residue remains in the surface soil. For example, in the experiment on winter wheat on Broadbalk at Rothamsted, the average annual grain yield was 2.70 t/ha in 1852-71 and the grain plus straw contained 11 kg P/ha, a third of the 33 kg P/ha applied as superphosphate. By 1991-92 the yield was 8.35 t/ha grain the grain plus straw contained 32 kg P/ha, almost the same amount as the 35 kg P/ha now applied in superphosphate. This is not an increased efficiency in use because much of the P in the crop will have come from soil reserves. But this amount of P taken off in the crop must be returned if soil P reserves are not to be depleted (Johnston, 1997).

MINERAL PHOSPHORUS FERTILIZERS

A wide range of phosphatic fertilizers are now available and farmers have to make choices. The first criterion must be whether the fertilizer will benefit the growth and yield of the crops they wish to grow on their soil. The second criterion will be cost. The criterion of suitability comes from experience and advice but there is also a need for a guide about quality.

Chemical evaluation of phosphorus fertilizers

When superphosphate was first produced the reaction between the insoluble calcium phosphates in the bones and the acid went to completion if the acid strength and the ratio of acid to bones was right. Under these conditions the P was completely converted to water soluble monocalcium phosphate. When applied to the very P deficient soils on most farms at that time, the superphosphate greatly increased the growth and yield of crops. These benefits were linked to the water solubility of the P and water solubility became a criterion for judging the quality of superphosphate offered for sale. A high water solubility was a guarantee that sufficient acid had been used to solubilise most of the P to make it plant available and that a good quality product had not been adulterated with an inert, worthless additive. In Britain, The Fertiliser and Feeding Stuffs Act first passed in 1893 required manufacturers to state the percentage water solubility of the phosphorus in superphosphate.

The intrinsic, large (in excess of 95%) water solubility of P in superphosphate made from bones was because they consisted of very pure calcium phosphates. As bones were replaced by mined phosphate rocks, water solubility declined when some rocks were used. It is now realised that this was due to the presence in the rocks of aluminium and iron compounds. In the presence of these impurities, the phosphorus is converted to water insoluble phosphates which carry through to the final product, single or triple superphosphate. However, there are strong indications from recent tests that, in some circumstances, these water insoluble phosphates can supply plant available P in the immediate/short term. What is clear is that iron and aluminium phosphates are not contaminants when added to soil because there are already large quantities of harmless aluminium and iron phosphates in soil.

As other products containing P became available they were tested as fertilizers. Many were very effective in supplying plant available P although many contained P compounds which were not water soluble. It was found that the agronomic effectiveness could be related to the solubility of the P in chemical reagents other than water. Different reagents are now used for different products.

The principal phosphorus fertilizers used in agriculture

Some of the more important phosphate fertilizers and the reagent in which their solubility is normally measured are:

- Single (or normal) superphosphate is made by reacting phosphate rock with sulphuric acid. Water soluble monocalcium phosphate is the active ingredient. The accompanying co-product calcium sulphate (gypsum) is a useful source of sulphur. Solubility in neutral ammonium citrate and the proportion of this which is soluble in water.
- Triple superphosphate is made by reacting phosphate rock with phosphoric acid. Water soluble monocalcium phosphate is the principal ingredient. Solubility as for single superphosphate.
- Mono- and di-ammonium phosphates are made by reacting phosphoric acid with ammonia to produce water soluble mono- and di-ammonium phosphate. Solubility as for superphosphates.
- Nitrophosphates. These are a range of products produced by reacting phosphate rock with nitric acid to produce a mixture of water soluble monocalcium phosphate and calcium nitrate. The latter takes up water and has to be removed. There is a range of water solubilities depending on the amount of monocalcium phosphate which is converted to dicalcium phosphate.
- Finely ground phosphate rocks. These can only be used on acidic soils where soil acidity slowly releases plant available P. These finely ground materials are difficult to handle. In the humid tropics they have proven beneficial effects on plantation crops grown on acid soils. The more suitable phosphate rocks are those which are classified as "reactive". Their chemical composition allows rapid dissolution in the soil. (See papers in Johnston & Syers, 1998).
- Compound fertilizers. Mono- and di-ammonium phosphates are examples of a fertilizer containing two plant nutrients. Fertilizers containing two or more nutrients contained in one granule are called compound fertilizers. Manufacturers often produce a range of such fertilizers containing various proportions of nitrogen, phosphorus and potassium.
- Blended fertilizers. Provided single or multi-nutrient fertilizers have granules/crystals of about the same size and weight they can be mixed together (blended) to give an almost infinite range of ratios of N to P to K. The physical characteristics of the individual components are important to prevent separation during transport, handling and spreading.

Changes in phosphorus fertilizer consumption

The International Fertilizer Industry Association (IFA) maintains a database on global fertilizer use. This is continuously updated and is available on their web site: <http://www.fertilizer.org>

In relation to global food production it is interesting to note that in 1984 the developed countries used almost twice as much phosphatic fertilizer as did the developing countries but by 1995 this had changed dramatically. Between 1984 and 1995 phosphate fertilizer use in the developing countries increased from 12.1 to 19.0 Mt P_2O_5 . This overall increase in the developing countries is especially welcome because it recognises the need to raise the phosphorus status of their soils. If continued, this increasing demand will begin to redress the mining of soil phosphorus reserves by the imbalanced use of nitrogen fertilizers. However, it must be recognised that this increased use in the developing countries is a global overview. There is still far too little P used in some developing countries notably in sub-Saharan Africa.

In the developed countries where soil phosphorus status has been raised to satisfactory levels, future use should at least replace the offtake in the harvested crops with allowance made for the return of phosphorus in animal manures and slurries.

PHOSPHORUS AND ENVIRONMENTAL ISSUES

Phosphorus and the aquatic environment

The biological balance in aquatic ecosystems

Within many aquatic ecosystems there is a very complex, finely balanced, ecological structure often of great biodiversity. Not only productivity but the balance between species frequently depends on the availability of nutrients. In turn, many other species of fish, mammals and birds rely for their food supply not only on the productivity of the plants but also on the presence of specific species.

Since the early 1970s there have been an increasing number of reports of undesirable changes in many aquatic ecosystems. Declining fish stocks and illness and even death of animals drinking the water are examples. These undesirable effects have often been related to drastic changes within the ecological structure in the lake/river. Often an early visual symptom has been a rapid increase in the growth of the microscopic algal communities - phytoplankton - which live suspended in the upper layers of water in a lake. If algae grow rapidly to create an algal bloom this prevents sufficient light reaching the plant communities at the bottom of the lake and they die. During active growth of a bloom, the algae use up a lot of the oxygen in the water. When they die and then decompose in oxygen deficient water (anaerobic conditions) toxins can be produced which can cause illness and sometimes death when animals drink the water. Often such changes have been associated with increasing concentrations of nutrients within the water - a process called eutrophication.

Eutrophication

The proper use of the term eutrophication is for the increase in the rate of addition of nutrients to water bodies. Frequently, however, eutrophication is being used more loosely to describe the problematic consequences of the nutrient additions.

The functioning of lake and river systems

Water entering a river or lake can come directly from rainfall which can carry nutrients, especially nitrogen and sulphur. Of much greater significance is the water coming from the land which comprises the catchment area of the lake. This water can come via various routes.

- Surface runoff - water which has run over the surface of the land
- Drainage from piped systems intended to remove excess water quickly from farmed land. Such drains are usually quite shallow (70-100 cm) and water passes to them quite quickly
- Water percolating through land without an artificial drainage system can meet an impermeable layer and move along the layer's surface to discharge as a spring which often forms a stream.

The amount and quality of the water flowing into a river or lake depends on many factors. Amongst the many variables are the geology, meteorology, hydrology, topography and land use - urban, agriculture or natural vegetation.

In largely agricultural catchments the nature and intensity of the farming systems are important.

Nutrients and aquatic ecosystems

Just as phosphorus is essential for plants and animals on land so it is essential for plants and animals living in fresh and marine waters. The plants in aquatic ecosystems all photosynthesise to fix carbon to produce a crop and like their terrestrial counterparts, they require a supply of mineral nutrients and nitrogen. The phytoplankton living suspended in water acquire their nutrients from those dissolved in the water. Many of the larger plants (macrophytes), which have anchorage in lake sediments, can acquire nutrients from the sediments.

Nutrients in aquatic systems mainly come from the land via various routes:

- In eroded soil which forms the sediment
- In surface runoff which can carry soil or nutrients in solution
- In water which has percolated through the soil (drainage or leachate) before being discharged to eventually reach lakes or the oceans.

Nutrients and the productivity of aquatic ecosystems

Frequently the two most important nutrients controlling the productivity of a lake are nitrogen and phosphorus. Little of either nutrient is lost to water from land under natural vegetation but with the increasing intensity of land use there has come an increasing risk of larger amounts of both nutrients being lost to rivers and lakes.

Most nitrogen is lost from land as readily soluble nitrate. Little of this nitrate comes directly from the use of nitrogen fertilizers provided they are applied in the correct amount at the most appropriate time. Most nitrate in soil at risk to loss when leaching starts in autumn comes from the microbiological breakdown of soil organic matter and organic residues in soil.

Explaining the sources of phosphorus has not been easy. For a long time it was considered that point sources, like sewage treatment works, were the most important. Water soluble inorganic phosphorus compounds, from detergents and the microbial decomposition of the organic phosphorus molecules in human sewage, were discharged to rivers in the effluent leaving the works.

To limit P discharges, larger sewage treatment works were required to remove the P before discharging the effluent. Often removing or limiting the discharge of P from point sources decreased the total load of P in lakes but this did not have the desired effect of restoring the biological balance in many of them. This focused attention on the loss of P from agriculture. Although the amount lost had probably not increased, the proportion of the total input to a lake coming from agriculture had increased.

Losses of phosphorus from land to water

Losses of phosphorus from agriculture can come from both point and diffuse sources. Point sources include farmyard waste water from cleaning to achieve acceptable animal welfare and hygiene standards. Diffuse sources can be considered as individual fields.

Losses from individual fields can be by three main routes:

- Soil erosion. Heavy raindrops can detach both mineral and organic particles from the main body of the soil. If the volume of rainfall is sufficient for the excess to run off over the surface then the detached particles are carried in the flowing water and can eventually reach lakes. The particles carry with them any associated nutrients which can then enrich the water in the lake. Soil erosion is more severe in regions with intense rainfall, and where the soil on sloping land is not protected by a permanent cover of vegetation.
- Surface runoff. A number of factors conspire to increase the risk of losses of P in surface runoff from agricultural land. Where topography and climate are suitable for agriculture but not for arable crops, animal husbandry predominates. Such systems are frequently found on sloping land in high rainfall areas. In the past, the faeces and urine, produced in the period when the animals were housed, was retained and stored in solid farmyard manure. This has now been replaced by liquid slurry kept in tanks which do not always have sufficient capacity. Often lack of storage and weather result in slurry being applied to soils already saturated with water. Because further rain cannot percolate into the soil it runs off over the surface carrying with it both soluble nutrients, including P, and particulate organic matter containing phosphorus.
- Leaching. Water percolating through soil can carry soluble nutrients to add to the amount in lakes. Much of the nitrate in lakes comes via this route but there is much less certainty about how much P can be transported. There is evidence that the concentration of P in drainage water from soils which have

been over enriched with P is larger than that from soils with just sufficient P to give acceptable yields of agricultural crops.

The amount of phosphorus which might be lost by leaching is likely to be much smaller than that which can be lost by soil erosion and by surface runoff. But besides the total amount, the bioavailability of the phosphorus which is lost from land to water is important.

The bioavailability of phosphorus

A very simple classification of the global P resource is as bioavailable and non-bioavailable. Bioavailable P can be defined as that which can be taken up and incorporated into plant or animal tissue. For algae living suspended in water and for plants in both aquatic and terrestrial ecosystems the immediately bioavailable P must be in solution. The implication that sewage treatment works were largely responsible for eutrophication was because they discharged water soluble P compounds into the rivers. The effects of P lost from agriculture must be considered relative to its bioavailability. Phosphorus lost in drainage water would be soluble but the amount would be small. Soluble forms of P lost in surface runoff would be bioavailable and where the amounts are large they could make an appreciable contribution to the bioavailable P in lakes. The immediate bioavailability of P associated with soil particles lost by erosion could well be small. In the longer term, however, the environmental conditions within the sediment, where much of the eroded soil will reside, could result in its slow release.

Minimising losses of phosphorus to the aquatic environment

Improving the efficiency of use of P in agriculture must be a priority. Measures like adding phytase rather than inorganic phosphorus compounds to animal feeds will decrease the amount of P in faeces going into slurry. Encouraging farmers to follow published Codes of Good Agricultural Practice in all aspects of husbandry will be helpful. Invariably this requires greater management skill and input. One way to minimise losses by any of the three routes described above will be to ensure that soils are not over enriched with P. An important step forward will be to identify the critical soil P levels for a range of soils and cropping systems and ensure that soil P levels are not allowed to greatly exceed the appropriate value. Losses of P from land to water, its consequences and possible

control methods have been the topic of two recent conferences, see Tunney et al., 1997, and papers in the *Journal of Environmental Quality* Vol 29 No 1 (2000).

The greatest risk of phosphorus losses is associated with intensive livestock production where animal waste becomes a disposal problem rather than one of recycling nutrients to the benefit of following crops. Satisfactory solutions to this waste disposal problem would almost certainly depend on a restructuring of the livestock industry. This would imply modifications to the infrastructure which supports on-farm animal production. Often whole rural communities owe their very existence to this web of different but interrelated enterprises.

Changing the biological balance in aquatic ecosystems

Attention became focused on the loss of P from agricultural soils because the decreased input of P from some point sources did not have immediate benefit in restoring the desired biological balance in many lakes. However, as limnologists (those who study freshwater systems) learn more about river and lake systems their complexity suggests that there may be no simple solution. Even different parts of the same lake may behave differently. An important point appears to be the different responses to eutrophication in large, deep lakes and shallow lakes and wetlands. The former are often set within spectacular scenery, are a much admired part of the landscape, and often have considerable amenity value. Shallow lakes and wetlands on the other hand are much more important habitats than deep lakes. They are host to parts of the food chain for a great diversity of species.

Water entering lakes is generally richer in N than in P. This is because there is much more N than P in agricultural systems, nitrate is very soluble and soils have no mechanisms for holding nitrate as they have for holding phosphorus. Thus the ratio of total N : total P in waters entering lakes tends to be much greater than the ratio of 7-10:1 required by algae.

The view that lessening the amount of bioavailable P entering lakes would lessen the risk of algal blooms arose from an initial consideration of deep lakes where the suspended phytoplankton in the upper water layers take up nutrients directly from the water. Nitrate is usually present in excess so available P determines the potential maximum growth. Little of this P will come from the sediments, which are at depth. Thus lessening the input of bioavailable P entering the lake should lessen algal growth.

When the concept of just lowering the P loading was applied to shallow lake restoration programmes, the results were invariably disappointing. Frequently, neither the concentration of P in the water nor the algal population declined. Waters did not clear and plant communities did not return. Occasionally, the reverse of what had been predicted occurred; increasing the nutrient supply in waters with well developed plant communities caused them to flourish not die.

The effects of eutrophication in shallow lakes are now being reconsidered. Without doubt, at very low (less than 20 $\mu\text{g P/l}$) concentrations of phosphorus and a nitrogen:phosphorus ratio exceeding 10:1 plants anchored in the sediment dominate. The plants derive their P from both the water and the sediment and lowering the P concentration by the macrophytes in the water will limit the growth of algae.

As nutrient concentrations increase both plant and phytoplankton algal communities can exist but with a risk of a sudden change (a "flip") from one community to another. A flip from plants to algae tends to occur more easily at higher nutrient concentrations. A possible mechanism would be that actively growing plants lower the oxygen concentration at and near the sediment surface. The oxygen deficient conditions induce the release of P from the sediment and also cause the microbial breakdown of nitrate to nitrogen gas. Phosphorus concentrations increase, nitrate concentrations decrease. The latter favours an increase in blue green algae living near the surface because they have the ability to meet their N need by fixing nitrogen gas dissolved in the water. Lack of nitrate and shading by the algal bloom kills the plants at the bottom of the lake.

Once established, algal communities are difficult to dislodge. To re-establish a plant community may well involve changing a number of factors including the restructuring of the fish community, a process called biomanipulation. Introducing, therefore, by whatever means, measures simply aimed at decreasing the amount of P lost from agricultural soils in the hope of maintaining or rapidly re-establishing a desirable biological balance in shallow lakes and wetlands appears to have little chance of success without increased management of the system. (For a more detailed account of biomanipulation in shallow lakes see Moss, 1998).

Phosphorus fertilizers and the terrestrial environment

Cadmium in phosphorus fertilizers

Phosphate rocks contain very variable amounts of cadmium (Cd), from less than 10 to more than 50 mg/kg of rock. The average Cd content of sedimentary rocks is appreciably greater than that of igneous rocks (Van Kauwenbergh, 1997). Some of the Cd in the rock carries through into the processed fertilizer. Traces of Cd are very toxic to humans and, therefore, the possibility of Cd accumulating in soil as a result of applying P fertilizers is of concern because plant based foodstuffs are the largest source of dietary Cd (Johnston & Jones, 1995 and the references therein).

Analyses of soils archived from the 1850s onwards, from the long-term experiments at Rothamsted, have shown that atmospheric deposition of Cd has been a significant source as it may well have been in other industrialised countries in Europe. However, within Europe atmospheric emissions have declined appreciably since the mid-1960s. This suggests that P fertilizers may become a more significant source of soil Cd as they already are in countries where atmospheric deposition is already small. Thus controls on the amount of Cd in P fertilizers are already in place, being proposed or being considered in a number of European countries.

The uptake of Cd by crops, i.e. the availability of soil Cd, is related to soil pH. Availability is increased in acid soils with pH (in water) below 6.5. This can result in something of a dilemma. As noted earlier, the most cost effective way of adding P to soils for resource-poor farmers working on acid soils is to apply phosphate rock to increase yields. But there is then the risk that any Cd in the rock will be available for uptake by crops because the soil is acid. So there is a need to balance two risks; one is to only have a small, poor quality diet reasonably free from Cd, the other is to have a better diet with perhaps more Cd.

Total dietary intake of Cd is related to both the amount of a foodstuff consumed and the concentration of Cd in it. In the developed countries most people have sufficient food and a wide range of foodstuffs to choose from. So decreasing the dietary intake of Cd requires either a change of foodstuffs or decreasing the Cd concentration in the foodstuffs generally. Factors controlling plant Cd levels include: 1) direct aerial deposits if these are adsorbed through the leaves; there is evidence for this but atmospheric concentrations are declining.

2) dilution effects when the rate of Cd uptake is less than the rate of dry matter accumulation as a result of photosynthesis. 3) plant control over the transport and storage of Cd within the plant; there is evidence that translocation into cereal grain is controlled. 4) the addition of P fertilizers, these encourage root growth and this may increase Cd uptake; the Cd in fertilizers may be more plant available than that in soil until it has reacted with soil constituents that can decrease its availability.

The issues about Cd and human health are complex and their resolution requires much more understanding of the soil-plant-animal-human Cd cycle. It is important to understand that it is not possible to just put an overall limit on the amount of Cd which can be added to soil or on the Cd concentration in soils because the concentration can vary over a wide range naturally. For example, in UK soils the range is from less than 0.5 to more than 1.7 mg/kg. Rather it is important to construct Cd balances for a range of soils and cropping systems. These must include measurements of aerial and fertilizer inputs, leaching losses, changing soil Cd availability and crop uptake. Such balances are essential to determine the effectiveness of government policies and industry and farming practices on the changing levels of Cd in soils and crops and in plant based foodstuffs.

Radioactivity and phosphate fertilizers

Radioactive elements, like uranium (U) and radium (Ra), are normal constituents of the earth's crust (Scholten & Timmermans, 1996). In some cases, the concentration of these elements has been increased in phosphate rocks by geological processes and a proportion of these elements is carried through into processed P fertilizers. For some people the use of such fertilizers in agriculture has become an issue because the radioactive elements they contain will be added to the soils on which crops are grown. Their concern is that these radioactive elements will be taken up by crops and pass into the food chain. Equally there is concern about the environmental impacts of the co-product phosphogypsum which will also contain a proportion of the radioactive elements present in the original rock (Rutherford et al., 1994).

Soils from the long-term experiments, started between 1843 and 1856 at Rothamsted, were sampled in 1976 and analysed for uranium. The superphosphate applied annually added 33 kg P and 15 g U/ha giving a total of about 1300 g/ha U in more than 120 years. The soil is a silty clay loam and in

1976 most of the added U was found in the plough layer (23 cm) where arable crops have been grown each year or in the organic surface layer of permanent grassland. In New Zealand, most of the 330 g/ha U added in superphosphate to permanent grassland was found also in the surface layer. There is evidence that U (like P) can be lost by leaching from very sandy soils or can be transported to rivers and lakes with eroded soil (Rothbaum et al., 1979).

In these long-term experiments there is no evidence of increased U uptake by cereals even where 1300 g/ha U has been applied in superphosphate during the more than 120 years that the experiments have been continued (Smith, 1960). This supports the generally accepted view that there is little transfer of radionuclides from soil to vegetation (Rutherford et al., 1994).

CONCLUDING REMARKS

From all points of view, agricultural, environmental and resource conservation, improving the efficiency of phosphorus use in agriculture and minimising its loss from soil to water has much to offer not only to farmers but to society as a whole. A number of approaches are discussed in this booklet and some are summarised here.

The need to solubilise the P in phosphate rock has been accepted for more than 150 years. But in recent decades P fertilizers with less water soluble P than in superphosphates have been effective in increasing yields on many soils. The requirement for water solubility needs to be reassessed. This is especially so for P amendments for use on acid soils. There can be financial benefits for resource poor farmers growing annual arable crops on acid soils in tropical and subtropical climates but these benefits need to be quantified. The uniform application of finely ground phosphate rock is not easy and the possible availability, crop uptake and transfer of cadmium to the food chain must be considered.

Integrated plant nutrient management is a part of the developing concept of integrated crop management which seeks to carefully consider the need for inputs required to achieve optimum economic yields. The aim is to use inputs efficiently and minimise any adverse environmental impact from them or their residues. When applied to the P nutrition of crops the concept implies that each farmer considers all available sources of P on the farm when deciding the P fertilizing

policy. This would include soil P, organic manures produced on the farm as well as purchased manures and P fertilizers. The idea of integrated phosphate management fits well with the idea of maintaining a soil at about the critical readily available P level. This is because the immediate availability of the P in those P amendments available to the farmer is of less importance than their ability to maintain the critical level of soil P which has been set for that soil from the results of field experiments.

For each soil and cropping system, the relationship between yield and readily available soil P indicates that yield reaches a plateau or asymptotic yield at a level of soil P which can be considered the critical level. Below the critical level, the loss of yield can be a severe financial penalty for a farmer but maintaining soils much above the critical value can be an unnecessary financial burden. The rationale for P manuring should be to build up and then maintain soils just above the critical level. Maintaining the critical level of available soil P implies at least returning to the soil as much P as that which has been removed in the harvested crop. That is the P balance (P applied minus P removed) should be about zero for a crop rotation. Phosphorus balances need to be determined on a field basis. At this level the effectiveness of replacing P offtake can be checked by periodic soil analysis. At the field level, P balances give the farmer a reasonable estimate of the amount of fertilizer to purchase. In addition individual farm nutrient balances can be aggregated to national balances. These can inform governments of the need to set up supply and distribution chains and the need for educational and advisory services.

Soil analysis, using well proven methods, is an important management tool for maintaining the fertility of soil and its productive capacity. In field experiments where other factors controlling yield are kept near optimum, soil analysis for readily available P can account for as much as 85% of the variance in yield of a range of arable crops. This suggests that appropriate methods of analysis can be used with advantage to ascertain the P status of soils and on which P fertilizer recommendations can be based. Where soil analysis has apparently been unsatisfactory, it is essential to check that all other factors which could have affected crop growth and yield have in fact been at or near optimum.

In many countries where agriculture is well developed the concept of precision farming is being developed and practised. The comparative ease with which yield maps for individual fields can now be generated makes it possible to ascertain the possible causes of yield variation. Soil variability within fields has long been recognised but soil sampling, especially on a whole field basis, has not allowed

for this variability. Now, however, the yield map and GPS allows good and poor areas of growth within a field to be not only identified but returned to with precision for in situ soil examination and sampling for laboratory analysis. The data then allow critical appraisal of the possible causes of yield variation, which will allow remedial action to be taken. Using such a system will allow variable application of P fertilizer to remedy within-field differences in readily available soil P status and thereby improve the efficiency with which phosphate fertilizers are used in agriculture.

REFERENCES AND FURTHER READING

References

Benckroun, A. (1995) Prospects for phosphate fertilizer demand and available supply by the year 2000. Proceedings No. 363. The International Fertiliser Society, York, UK.

Blake, L., Johnston, A.E., Poulton, P.R. & Goulding, K.W.T. (1997) The determination of soil phosphate reserves. A report submitted to IMPHOS. Casablanca, Morocco.

Chater, M. & Mattingly, G.E.G. (1980) Changes in organic phosphorus contents of soils from long continued experiments at Rothamsted and Saxmundham. Rothamsted Experimental Station Report for 1979, Part 2, 41-61.

Crowther, E.M. (1945) Fertilizers during the war and after. Pamphlet No. 13. Bath and West and Southern Counties Society, Bath, 59 pp.

Higgs, B., Johnston, A.E., Salter, J.L. & Dawson, C.J. (2000) Some aspects of achieving sustainable phosphorus use in agriculture. *Journal of Environmental Quality* 29, 80-87.

Johnston, A.E. (1994) The Rothamsted Classical Experiments. In: (eds) R.A. Leigh & A.E. Johnston. *Long-term Experiments in Agricultural and Ecological Sciences*. CAB International, Wallingford, pp. 9-37.

Johnston, A.E. (1997) Fertilisers and agriculture: fifty years of developments and challenges. The Francis New Memorial Lecture, The International Fertiliser Society, York, U.K., pp. 19-48.

- Johnston, A.E. & Jones, K.C. (1995) The origin and fate of cadmium in soil. Proceedings No. 366, The International Fertiliser Society, York, U.K., pp. 2-40.
- Johnston, A.E. & Penny, A. (1972) The Agdell Experiment, 1848-1970. Rothamsted Experimental Station Report for 1971, Part 1, 38-67.
- Johnston, A.E. & Poulton, P.R. (1977) Yields on the Exhaustion Land and changes in the NPK contents of the soils due to cropping and manuring, 1852-1975. Rothamsted Experimental Station Report for 1976, Part 2, 53-85.
- Johnston, A.E. & Poulton, P.R. (1992) The role of phosphorus in crop production and soil fertility: 150 years of field experiments at Rothamsted, United Kingdom. In: (ed) J.J. Schulz. Phosphate Fertilizers and the Environment. International Fertilizer Development Center, Muscle Shoals, USA, pp. 45-64.
- Johnston, A.E. & Syers, J.K. (1998) Nutrient Management for Sustainable Crop Production in Asia. CAB International, Wallingford, UK, 394 pp.
- Johnston, A.E., Barraclough, P.B., Poulton, P.R. & Dawson, C.J. (1998) Assessment of some spatially variable soil factors limiting crop yields. Proceedings No.419, The International Fertiliser Society, York, U.K., pp.3-48.
- Leigh, R.A. & Johnston, A.E. (1986). An investigation of the usefulness of phosphorus concentrations in tissue water as indicators of the phosphorus status of field grown spring barley. *Journal of Agricultural Science, Cambridge*, 107, 329-333.
- Marschner, H. (1995) *Mineral Nutrition of Higher Plants*, second edition. Academic Press, London, New York.
- Mattingly, G.E.G., Chater, M. & Johnston, A.E. (1975) Experiments made on Stackyard Field, Woburn, 1876-1974. III. Effects of NPK fertilisers and farmyard manure on soil carbon, nitrogen and organic phosphorus. Rothamsted Experimental Station Report for 1974, Part 2, 61-77.
- Mattingly, G.E.G. & Widdowson, F.V. (1958, 1959) Uptake of phosphorus from ³²P labelled superphosphate by field crops. *Plant and Soil* Pt 1 1958, 9, 286-303. Pt 2 1959, 10, 161-175.
- Moss, B. (1998) Shallow lakes biomanipulation and eutrophication. SCOPE Newsletter No. 29, CEEP/CEFIC Brussels, 45 pp.
- PDA (1997) Phosphate and Potash Removal by Crops. The Potash Development Association. Langharne, Carmarthen, U.K., 4 pp.

- Rothbaum, H.P., McGaveston, D.A., Wall, T., Johnston, A.E. & Mattingly, G.E.G. (1979) Uranium accumulation in soils from long-continued applications of superphosphate. *Journal of Soil Science* 30, 147-153.
- Rutherford, P.J., Dudas, M.J. & Samek, R.A. (1994) Environmental impacts of phosphogypsum. *The Science of the Total Environment* 149, 1-38.
- Scholten, L.C. & Timmermans, C.W.M. (1996) Natural radioactivity in phosphate fertilizers. *Fertilizer Research* 43, 103-107.
- Smith, G.H. (1960) Uranium in crops dressed frequently with superphosphate. Rothamsted Experimental Station Report for 1959, 58.
- Syers, J.K. & Curtin, D. (1988) Inorganic reactions controlling phosphorus cycling. In: H. Tiessen (ed) *Phosphorus Cycles in Terrestrial and Aquatic Ecosystems*. I. Europe. SCOPE, UNDP. Saskatchewan Institute of Pedology, Saskatoon, Canada.
- Tunney, H., Carton, O.T., Brookes, P.C. & Johnston, A.E. (eds.) (1997) *Phosphorus Loss from Soil to Water*. CAB International, Wallingford, U.K., 467 pp.
- Van Kauwenbergh, S.J. (1997) Cadmium and other minor elements in world resources of phosphate rock. *Proceedings No. 400, The International Fertiliser Society*, York, UK, 40 pp.

Further Reading

(Books etc devoted wholly or in part to phosphorus)

The Control of Soil Fertility. G.W. Cooke (1967). Crosby Lockwood & Son Ltd, London, 526 pp.

The Role of Phosphorus in Agriculture. F.E. Khasawneh, E.C. Sample and E.J. Kamprath (eds). ASA, CSSA, SSSA, Madison, Wisconsin, 910 pp.

Agriculture, Fertilizers and the Environment. M. Læg Reid, O.C. Bøckman and O. Kaarstad (eds.). CAB International, Wallingford, UK, 294 pp.

Mineral Nutrition of Higher Plants. 2nd edition 1995. H. Marschner. Academic Press, London, New York.

Principles of Plant Nutrition. 4th edition 1987. K. Mengel and E.A. Kirkby. International Potash Institute, Basel, 687 pp.

Fertilizer Manual. IFDC and UNIDO (1998). Kluwer Academic Publishers, Dordrecht, the Netherlands. 615 pp.



International Fertilizer Industry Association

International Fertilizer Industry Association

28, rue Marbeuf

75008 Paris, France

Tel: +33 153 930 500

Fax: +33 153 930 545 /546 /547

Email: publications@fertilizer.org

Web: www.fertilizer.org