October 2011

Cost £9.80

Research Review No. 74

Response of cereals to soil and fertilizer phosphorus

by

A. E. Johnston and P. R. Poulton

Department of Sustainable Soils and Grassland Systems,

Rothamsted Research, Harpenden AL5 2JQ

This review was undertaken as part of a four year project (RD-2008-3554) which started in April 2009. The review cost £7,000 and was part of an overall contract for £191,675 from HGCA with The Arable Group and Rothamsted Research.

CONTENTS

1. ABSTRACT

Data from 1969 to 2008 on the response of 102 cereal crops to plant-available soil phosphorus (Olsen P) in three contrasting soils, each with a wide range of Olsen P, have been summarised. For each crop, the response curve, relating grain yield to Olsen P, was fitted statistically, and from the curve was determined i) the maximum yield and ii) the critical Olsen P associated with 98% of the maximum yield.

On a well structured silty clay loam at Rothamsted (Herts), maximum yield of 16 crops of winter wheat and 7 of spring barley was achieved on soil with:

- 6 to 15 mg/kg Olsen P (top P Index 0 to Index 1) in 20 of the 23 crop years.
- 16 to 25 mg/kg Olsen P (P Index 2) in 2 years and P Index 3 in only 1 year.

On a poorly structured sandy clay loam at Saxmundham (Suffolk), maximum yield of 44 winter wheat crops and 23 of spring barley was achieved on soil with:

- 8 to 15 mg/kg Olsen P (top P Index 0 to 1) in 29 (43%) of the 67 crop years.
- 16 to 25 mg/kg Olsen P (P Index 2) in 24 (36%) of the years.
- 26 to 36 mg/kg Olsen P (P Index 3) in 14 (21%) of the years.
- larger concentrations of Olsen P were needed where little nitrogen was given.

On a poorly structured, heavy silty clay loam at Rothamsted on which it was difficult to get a good seedbed for early drilling, maximum yield of 8 spring barley crops was achieved on soil with:

- 10 to 25 mg/kg Olsen P (P Index 1 to 2) in 6 of the 8 crop years.
- 26 to 35 mg/kg Olsen P (P Index 3) in 2 of the 8 crop years.
- on the same soil, but with less SOM and a very poorly structure, 40-52 mg/kg Olsen P were needed to achieve maximum yield.

Year to year variation in maximum yield was due to weather, mainly rainfall, and the length of the grain filling period. Year to year variation in critical Olsen P on each soil type reflected differences in soil and seedbed conditions and the way they interacted with weather factors. These results highlight:

- the importance of maintaining a good soil structure and using appropriate, timely, cultivations such that roots can readily find nutrients within the soil to achieve maximum yield.
- until more data are available, most fields should be maintained at P Index 2 for cereals (i) to ensure that maximum yield is achieved in most years, (ii) to allow for in-field variation in Olsen P.

Changes in Olsen P reflect changes in the P balance.

- Where large crops were grown and no phosphate was applied, Olsen P declined rapidly; from the mid-point of P Index 2 to the bottom of Index 1 in six years.
- Large amounts of phosphate were required to build up Olsen P. To increase Olsen P from the mid-point of P Index 1 to the mid-point of Index 2 required 300-330 kg/ha P_2O_5 (670-750 kg/ha triple superphosphate).

2. SUMMARY

2.1. Introduction

General guidelines on phosphate fertilisation in the new Fertiliser Manual (RB209) (Defra, 2010) are to raise Olsen P in soils growing arable crops and grass to P Index 2 and then maintain this level by replacing the phosphorus removed in harvested crops. For potatoes and vegetables the guideline is P Index 3. In response to queries about the relevance of these guidelines for cereals grown on all soil types, HGCA commissioned The Arable Group (TAG) and Rothamsted Research (Rothamsted) to assess current phosphate recommendations for cereals and, if possible, oilseed rape, on a wider range of soil types than had been done already. A major part of the Rothamsted contribution to this project was to review existing data on the response of cereals to phosphate in relation to current recommendations. This report summarises the results of the review, together with an Appendix with additional background information.

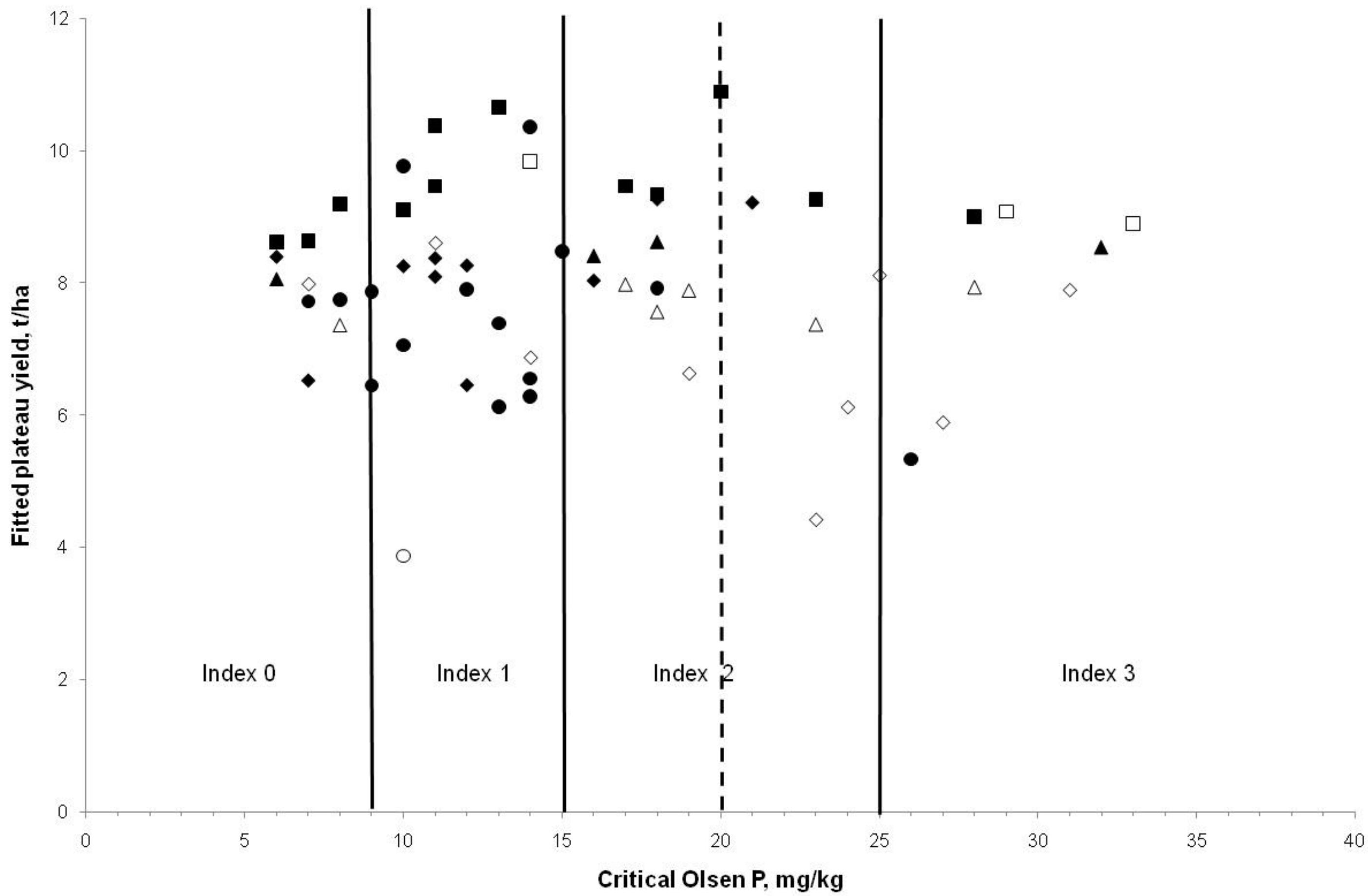
2.2. Methods

Data are available from three long-term field experiments each having plots with a range of established Olsen P which ensures that the various fractions of soil phosphorus, including Olsen P, were, as near as possible, in equilibrium when the experiments were made at different times between 1969 and 2008. The experiments were on the silty clay loam at Rothamsted (the Exhaustion Land and Agdell experiments) and the Rotation II experiment on the sandy clay loam at Saxmundham. For each crop, each year, a response curve relating yield and Olsen P was fitted statistically to determine maximum yield and the Olsen P level associated with 98% of the maximum yield. In this report we have divided the available data that fell within P Index 2 between two sub-groups, 15-20 and 21-25 mg/kg Olsen P.

2.3. Winter wheat – maximum yield and Olsen P

Data for 60 crop years of winter wheat are summarised in Summary Figure 1, which shows that i) the maximum grain yield, ranged from 4 to 11 t/ha, mean 8.03 t/ha, and ii) the Olsen P associated with 98% of the maximum yield ranged from 5 to 34 mg/kg, *i.e.* from the top of P Index 0 to the mid-point of P Index 3. Within this range:

- 55% of the maximum yields were on soils with 6 to 15 mg/kg Olsen P (P Index 0 and 1)
- about 30% of the maximum yields were on soils with 16 to 25 mg/kg Olsen P and mostly on soils with 16-20 mg P/kg (lower half of P Index 2)
- about 15% of the maximum yields were on soils with 26 to 35 mg/kg Olsen P (P Index 3) although most of these crops received only small amounts of nitrogen.
- there was no indication that a larger maximum yield necessarily needed a higher concentration of Olsen P



Summary Figure 1. Fitted plateau yields of winter wheat and the critical Olsen P associated with 98% of that yield. Saxmundham: 1st wheat, squares; 2nd wheat, triangles; 3rd/4th wheat, diamonds. Exhaustion Land: continuous wheat, circles. Filled symbols denote crops receiving sufficient N to achieve maximum yield; open symbols denote crops receiving insufficient N.

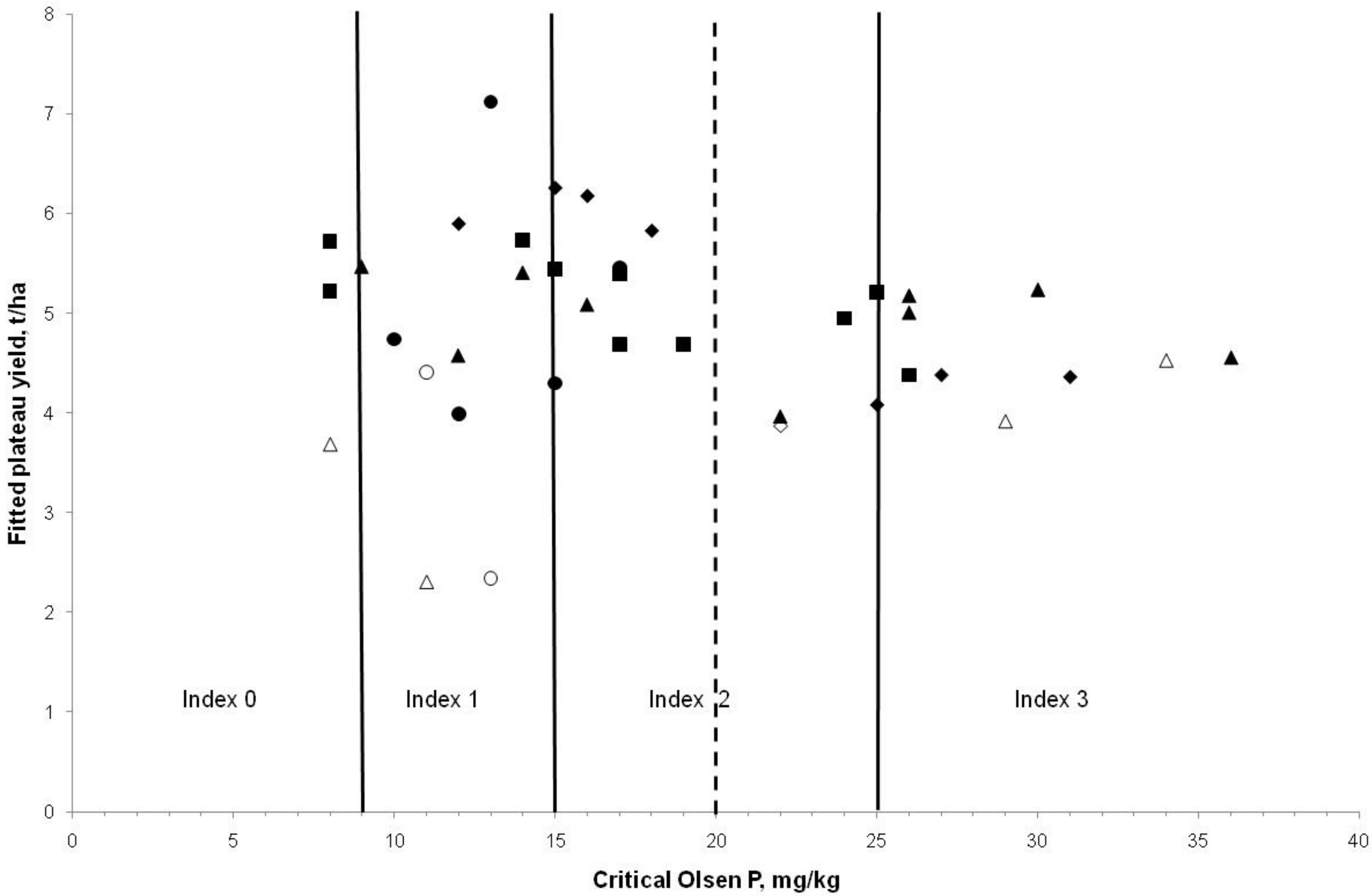
For wheat to have yielded well in some years with only 6 to 15 mg/kg Olsen P (top P Index 0 and P Index 1) suggests that seedbeds and soil conditions, especially for root growth and nutrient acquisition, were particularly favourable in those years. Conversely, however, about the same proportion of maximum yields were on soils with more than 16 mg/kg Olsen P (P Index 2 and above) suggests that seedbed and soil conditions were less favourable in those years.

Yields with open symbols are for crops given small amounts of nitrogen in experiments testing both nitrogen and Olsen P. For these crops, about 68% of maximum yields were on soils with more than 16 mg/kg Olsen P. Probably more Olsen P was required to encourage the production of sufficient roots to take up the small amount of nitrogen that was available. In practice however, it would be better to be more precise in the amount of nitrogen applied than to increase soil to, and then maintain it, above P Index 2 just to encourage root growth.

2.4. Spring barley – maximum yield and Olsen P

Data for 42 crop years of spring barley was assessed; 38 crop years are summarised in Summary Figure 2 which excludes data from four crops grown on soil with little SOM. The data show that i) the average maximum grain yield was only 4.76 t/ha, range 2.2 to 7.2 t/ha; however, most of the experiments were in the earlier years of the period 1969-2008 when the yield potential of the spring barley varieties then available was smaller than those of today, and ii) the Olsen P associated with 98% of the maximum yield ranged from 8 to 36 mg/kg. Within this range:

- one third of the maximum yields were on soils with 16 to 25 mg/kg Olsen P (top P Index 2) and another third on soils with 8 to 15 mg/kg Olsen P (top of P Index 0 and P Index 1)
- 26% of the maximum yields were on soils with 26 to 36 mg/kg Olsen P (P Index 3)
- for four crops grown on soils with little SOM and a very poor structure the range in Olsen P required was 40 to 55 mg/kg (data not shown in Summary Figure 2)
- there was no indication that larger maximum yields of spring barley necessarily needed a larger concentration of Olsen P, as with winter wheat



Summary Figure 2. Fitted plateau yields of spring barley and the critical Olsen P associated with 98% of that yield. Saxmundham: 1st barley, squares; 2nd/3rd/continuous cereal, triangles. Agdell, 1st barley on high SOM soil, diamonds. Exhaustion Land: continuous barley, circles. Filled symbols denote crops receiving sufficient N to achieve maximum yield; open symbols denote crops receiving insufficient N.

2.5. Effect of soil type on maximum yield and Olsen P

The effect of soil type on maximum yield and the Olsen P required to achieve 98% of the maximum yield can be assessed by combining the data for winter wheat and spring barley.

On a well structured silty clay loam at Rothamsted (Herts), maximum yield of 16 crops of winter wheat and 7 of spring barley was achieved on soil with:

- 6 to 15 mg/kg Olsen P (top P Index 0 to Index 1) in 20 of the 23 crop years
- 16 to 25 mg/kg Olsen P (P Index 2) in 2 years and P Index 3 in only 1 year

On a poorly structured sandy clay loam at Saxmundham (Suffolk), maximum yield of 44 winter wheat crops and 23 of spring barley was achieved on soil with:

- 8 to 15 mg/kg Olsen P (top P Index 0 to 1) in 29 (43%) of the 67 crop years
- 16 to 25 mg/kg Olsen P (P Index 2) in 24 (36%) of the 67 crop years
- 26 to 36 mg/kg Olsen P (P Index 3) in 14 (21%) of the 67 crop years
- larger concentrations of Olsen P were needed where little nitrogen was given

On a poorly structured, heavy silty clay loam at Rothamsted on which it was difficult to get a good seedbed for early drilling, maximum yield of 8 spring barley crops was achieved on soil with:

- 10 to 25 mg/kg Olsen P (P Index 1 to 2) in 6 of the 8 crop years
- 26 to 35 mg/kg Olsen P (P Index 3) in 2 of the 8 crop years
- on the same soil, but with less SOM and a very poor structure, 40-52mg/kg Olsen P were needed to achieve maximum yield

Year to year variation in maximum yield was due to weather, mainly rainfall, and the length of the grain filling period. Year to year variation in critical Olsen P on each soil type reflected differences in soil and seedbed conditions and the way they interacted with weather factors. These results highlight:

- the importance of maintaining a good soil structure and using appropriate, timely, cultivations such that roots can readily find nutrients within the soil to achieve maximum yield
- until more data are available, most fields should be maintained at P Index 2 for cereals (i) to ensure that maximum yield is achieved in most years, (ii) to allow for in-field variation in Olsen P

2.6. Conclusions

2.6.1. Cereal yields and Olsen P

Results presented here show that the maximum yield of both winter wheat (Summary Figure 1) and spring barley (Summary Figure 2) was achieved on soils with a wide range of Olsen P - from the top of P Index 0 to P Index 4.The variability in the maximum yield from year to year is mainly due to weather factors, especially rainfall, and the length of the grain filling period. For crops well supplied with nitrogen, the variability in critical Olsen P required to achieve 98% of the maximum yield probably reflects variation in soil conditions from year to year. Variability in soil structure and seedbed conditions will be related to timeliness of soil cultivations and weather. The wide range in Olsen P required to achieve 98% of the maximum yield within each of these three different soils suggests that it would be difficult to offer more specific advice about Olsen P for a particular soil type than is currently available.

Farmers have to decide at what level to maintain the Olsen P in their soils in relation to the financial viability of the farm. Data presented here in Summary Figure 1 for winter wheat and in Summary Figure 2 for spring barley grown on a sandy clay loam soil and two silty clay loams, on one of which there are more problems with soil structure, can be used to indicate the risk of not maintaining soils at P Index 2 and thus the opportunity to optimise the yield of cereals in most years. For example, for winter wheat, only 55% of the maximum grain yields were on soils at top P Index 0 and P Index 1, i.e. in about half of the years when winter wheat was grown on such soils optimum economic yields would not be achieved. For spring barley, only a third of the maximum yields were on soils at top P Index 0 and P Index 1, indicating an even greater risk than with winter wheat, of not achieving optimum economic yields if soils are not maintained at P Index 2.

2.6.2. Use of Olsen P for measuring readily plant-available soil phosphorus

For each fitted response curve relating yield to Olsen P the percent variance accounted was also calculated. This is a measure of how well Olsen P explained (accounted for) the variability in yield. A percent variance larger than 50% indicates that Olsen P was the major factor controlling yield, and thus Olsen P is a good indicator of the level of readily plant-available soil phosphorus. Summary Table 1 shows the number of response curves where the variance accounted for fell into one of three groups.

Summary Table 1. The number of response curves where the variance accounted for fell into one of three groups.

	Number of fitted response curves					
	Winter wheat			Spring barley		
	Variance accounted for, %			Variance accounted for, %		
	<50	50-79	≥80	<50	50-79	≥80
Exhaustion Land	-	1	16	-	1	5
Saxmundham	7	22	14	4	7	12
Agdell						
High SOM	nd[a]	nd	nd	3	5	-
Low SOM	nd	nd	nd	4	-	-

[a] not possible to fit a response curve

On the well structured, silty clay loam on the Exhaustion Land Olsen P accounted for more than 80% of the variance in the great majority of cases for both wheat and barley. On the less easy to cultivate sandy clay loam at Saxmundham more than 50% of the variance was accounted for by Olsen P in most cases. Where less than 50% was accounted for we believe that seedbed conditions and soil structure were less than ideal and root development and growth were impeded. Such soil conditions would also explain why, for spring barley grown on the poorly structured silty clay loam on Agdell, the variance accounted for was often less than 50%.

2.6.3. Effect of phosphorus balance on changes in Olsen P

Two frequently asked questions are: i) how much phosphate must be added to increase Olsen P, and ii) how quickly will Olsen P decline if no phosphate fertilizer is applied. A change in Olsen P depends on the phosphorus balance, which is the difference between the amount of phosphate applied and the amount removed in the harvested crops. Usually, Olsen P increases when the phosphorus balance is positive and declines when the balance is negative. The effect of a positive phosphorus balance on an increase in Olsen P has been determined in these experiments. It is quite small. A phosphorus balance of 23 kg P_2O_5/ha increased Olsen P by only 0.56 and 0.60 mg/kg on the silty clay loam (Rothamsted) and the sandy clay loam (Saxmundham) respectively. Thus, to increase Olsen P from the mid-point of P Index 1 (12 mg/kg) to the mid-point of P Index 2 (20 mg/kg) would require 327 and 304 kg P_2O_5/ha for the silty clay loam and sandy clay loam respectively (see Section 3.5.1). A decline in Olsen P will depend on the size of the negative phosphorus balance (see Section 3.5.2). On the silty clay loam (Rothamsted), soil at the mid-point of P Index 2 declined to the mid-point of P Index 1 over a six year period when no P was applied and with a total offtake of 120 kg P/ha. On the sandy clay loam (Saxmundham) soil at the mid-point of P Index 2 declined to the upper half of P Index 1 over a six year period with a total P offtake of 100 kg/ha.

3. TECHNICAL DETAIL

3.1. Introduction

The current recommendation for the phosphate fertilization of arable crops (other than potatoes) and grassland is to maintain the soil on which these crops are grown at P Index 2 (Defra, 2010). The basic premise is that plant-available phosphate in soils should be at, or a little above, an appropriate level (the critical level or “Target Index”) to achieve optimum yields for a rotation of crops, including, but not exclusively, cereals and oilseed rape. The recommendations also advise maintaining soils at the critical level by replacing the phosphate removed in the harvested crops. Part of the reason for setting the target index for phosphate at P Index 2 was because plant-available P (Olsen P) can, and frequently does, vary considerably within a field, often from P Index 0 or 1 to P Index 3. To some extent this variability would be allowed for by having a “field average” for Olsen P set at Index 2.

The recommendations are based on results from field experiments, mostly on a limited range of soil types, supported by observations on yields of crops in different locations. As fertilizer prices have increased, particularly those of phosphate and potash, many farmers have asked whether the recommendations are appropriate for all soil types and cropping systems. Specifically, farmers are asking whether they can maintain their soils at a lower P Index without the risk of losing yield. Additionally, these questions might have arisen because in the summary to HGCA Project Report No.OS58 (HGCA, 2002) there is the statement that 10 t/ha winter wheat was achieved on a soil with only 9 ppm (9 mg/kg) Olsen P, i.e. the top of P Index 0. Unfortunately this statement was not qualified by pointing out that this result was in a one-year experiment on a well structured, easy to cultivate soil.

While it must be emphasised that the recommendations in the new Fertiliser Manual (RB209) (Defra, 2010) can be varied under appropriate conditions, especially using less than the amount suggested, guidance is needed about when and where smaller amounts of phosphate fertilizer can be applied. In response to these questions, and as part of HGCA project (RD-2008-3554) the authors of this report have summarised data from existing experiments on the response of cereals to Olsen P. The results are presented here, together with some comments on the importance of soil structure and the interaction of applied nitrogen fertilizer with Olsen P.

Appendices to this Report present some background information on the phosphorus nutrition of crops and current concepts about the behaviour of phosphorus in soil, together with comments about maintaining Olsen P for crop rotations.

3.1.1. Olsen P and P Index

In England, Wales and Northern Ireland, readily plant-available phosphorus in soil is determined by one of two methods. The most widely used is to extract a representative soil sample with a dilute solution of sodium bicarbonate (0.5 M $NaHCO_3$) at pH 8.5, Olsen's Method (Olsen et al., 1954). Olsen's method is used at Rothamsted and throughout this report we refer to the P extracted as "Olsen P". Olsen's method is used by many commercial laboratories offering soil analytical services. The second method used to characterise plant-available soil P status is the "resin method" (resin P) developed by Levington Agriculture (Hislop and Cooke, 1968). The 7th edition of RB209 (MAFF, 2000) and the new Fertiliser Manual (RB209) (Defra, 2010) assign soil to a P Index based on the analytical data by either method. Most agricultural soils are in P Index 0-5 and the range of Olsen P and resin P values for P Index 0 to 5 are shown in Table 1.

Table 1. Olsen P and resin P values for P Index 0 to 5.

P Index	Olsen P	Resin P
	mg/L	
0	0-9	0-19
1	10-15	20-30
2	16-25	31-49
3	26-45	50-85
4	46-70	86-132
5	71-100	>132

From Fertiliser Manual (RB209) (Defra, 2010)

The P Index system is based on the relationship, shown in Figure 1, between the yield of a crop (vertical axis) and Olsen P (horizontal axis).

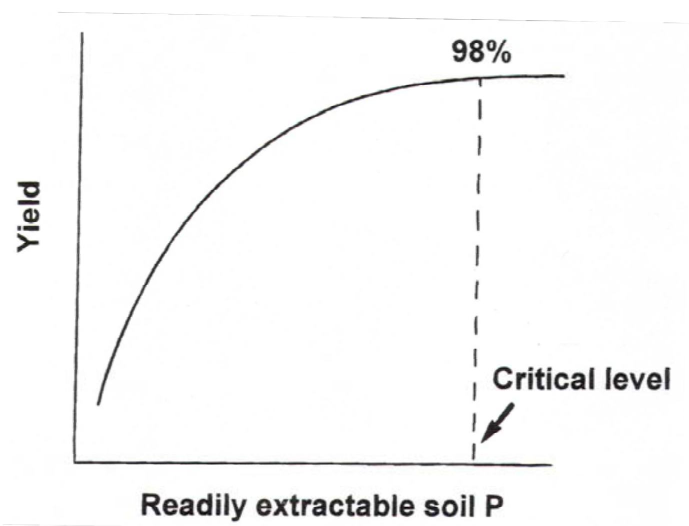


Figure 1. The theoretical relationship between crop yield and the level of readily available P in soil and the critical level at which 98% of the maximum yield is achieved.

As Olsen P increases from very low (acutely deficient) levels, yield increases, rapidly at first and then more slowly until maximum yield is reached. The level of Olsen P associated with the maximum yield (or more usually 95 or 98% of the maximum) can be considered the critical level of Olsen P for that crop grown on that soil in that farming system. When soil is below the critical level, yield is less than maximum and there is a risk of financial loss to the farmer. Equally, there is little justification in raising soil much above the critical level and maintaining it at that level, due to the cost of purchasing fertilizer from which there is no immediate benefit and where there is a potential environmental penalty if soil, excessively enriched with phosphorus, is eroded into water courses. Soils at P Index 0 are considered to be phosphorus deficient and crop yields will be increased by adding phosphate. Soils at P Index 1 are border-line deficient and crop yields will often be increased by applying phosphate fertiliser. Soils at P Index 2 are satisfactory for most arable crops and grass with the exception of potatoes and vegetables, which is why current advice is to first raise a soil to P Index 2 and then maintain it at this level. “Real life” examples of this relationship are in Figures 2, 3 and 4 in this report.

3.2. Conventions and methods adopted for this report

3.2.1. Phosphorus and phosphate

Phosphorus and phosphate are frequently used terms with phosphate probably used more widely in agriculture. Phosphorus (P) has a precise meaning; P is an element but it does not occur as such in nature, it is always found in combination with other elements in inorganic and organic compounds. Results for crop and soil analysis are always given in terms of phosphorus, e.g. %P in dry matter for crops, mg P/L or mg P/kg for soils. The Fertilisers Regulations (1991) require that the phosphorus concentration in a fertilizer is given in terms of phosphate (P_2O_5). Fertilizer recommendations are also given as P_2O_5 to aid calculating the amount of phosphate needed to replace that removed in a harvested crop. Typical removals of phosphorus by many crops, also expressed in terms of P_2O_5, are given in the Fertiliser Manual (Defra, 2010).

3.2.2. Crop data

For the experiments with cereals discussed here both grain and straw weights were measured and are presented as tonnes per hectare (t/ha) corrected to 85% dry matter. In all the experiments straw was removed and samples of grain and straw retained to determine their phosphorus content. The amount of phosphorus removed in the grain plus straw (P offtake) was calculated from the concentrations of P in grain and straw and yield of grain and straw and is expressed as kg P/ha. These data were used to calculate the phosphorus balance (phosphorus applied *minus* phosphorus removed) each year so that the overall balance in different periods could be calculated.

3.2.3. Soil data

Following cereal harvest the land was mouldboard ploughed, nominally to 20-23cm. Representative soil samples, 0-23cm, were taken from each plot either in autumn or spring but always before any phosphate fertilizer was applied for the coming season. The soils were air-dried, ground to pass a 2mm sieve and a subsample taken to determine Olsen P. The Fertiliser Manual (RB209) (Defra, 2010) gives soil phosphorus concentrations in each P Index as mg P/L, the method of presentation used by many laboratories doing routine soil analysis, because a volume of soil is taken for analysis rather than a weight. Many research laboratories present data as mg P/kg, and this is used here. For most mineral soils, the results, expressed as either mg P/L or mg P/kg, are closely similar because 10 ml of 2mm ground soil weighs about 10 g.

3.2.4. Statistical treatment of the yield/Olsen P relationship

The same statistical methodology has been used for all the experiments for which data are presented, except where noted. For each year, a response curve was fitted to the grain yield/Olsen P relationship for all plots using an asymptotic curve of the form:

$$Yield = a - b * r^{p}$$

Where *a* is the asymptotic yield in t/ha and *b* and *r* are range and rate parameters, respectively, which were estimated by maximum likelihood.

Two things were determined from this relationship: 1) the fitted asymptotic (maximum/plateau) grain yield and its standard error (s.e.) and the percentage variance accounted for, and 2) the concentration of Olsen P and its standard error (s.e.), associated with the yield at 98% of the maximum yield.

Values of Olsen P for which the yield was 0.98 of the asymptote were calculated by solving the following equation:

$$P = (\ln(0.02) + \ln(a) - \ln(b))/\ln(r)$$

The standard error of the fitted maximum yield and the standard error of the critical Olsen P at 98% of the maximum yield are related to how well the response curve “fits” the yield and Olsen P data. Where we consider that the standard error of the yield and/or Olsen P was unacceptably large, i.e. the relationship between yield and Olsen P was very poor, the values have been excluded from the discussion.

The percentage variance is the variability in yield that can be accounted for by Olsen P. A percentage variance of greater than 50% would indicate that Olsen P was the single most important soil factor affecting yield. In many of the cases discussed here the percentage variance accounted for was greater than 70% indicating that Olsen P had the greatest effect on yield.

Throughout this report the Olsen P needed to achieve 98% of the fitted maximum yield is referred to as the "critical Olsen P".

3.3. Determination of the critical level of Olsen P in field experiments

There are few field experiments in which soils with a range of Olsen P levels have been established for sufficient years to ensure that the phosphorus in the different pools of soil P are in equilibrium (see Appendix C). Only in such experiments can the critical level of Olsen P be determined with some degree of accuracy for crops grown continuously or in rotation. Among these experiments, two are at Rothamsted and one at Saxmundham and the results from these are summarised here. Results from two other experiments are given briefly in Appendix D.

All three experimental sites on which the experiments discussed here were made had one thing in common, a long history of known cropping and fertilising. This resulted in plots with different, well-established levels of Olsen P, and with the possibility of extending the range of Olsen P levels. There are, however, important differences between the soils on the three sites. On both the Exhaustion Land and Agdell the surface soil is a flinty silty clay loam but while that on the Exhaustion Land has 18-27% clay (Batcombe-Carstens Series) that on Agdell has 27-35% clay (Heavy Batcombe Series) (Avery and Catt, 1995). The Exhaustion Land is regarded as one of the easier soils on Rothamsted Farm to cultivate. Agdell, however, with its large clay content, is difficult to cultivate and prepare good seedbeds for early sown spring cereals, has a poor physical structure and the underlying Clay-with-flints is mottled suggesting poor natural drainage. The soil at Saxmundham is a sandy clay loam derived from chalky boulder clay (Beccles Series) with about 25% clay in the topsoil. The site is mole and tile drained and the soil can be plastic when wet and hard when dry (Hodge, 1972). It can be difficult to manage and there are problems with soil structure and soil cultivation (Cooke and Williams, 1972).

3.3.1. Exhaustion Land experiment, Rothamsted

The soil is a well-structured flinty silty clay loam over Clay-with-flints (Batcombe-Carstens Series) containing 18-27% clay. Johnston and Poulton (1977) detailed the history of the experiment before 1976 and results since then are being prepared for publication (Poulton and Johnston personal communication). The first experiment, in 1856-1874, was on winter wheat, followed by one on potatoes, 1876-1901; in the latter experiment there were ten main plots the dimensions of which have remained unchanged since then. Phosphorus, 33.5 kg P/ha applied annually as single superphosphate, was tested in both experiments, while farmyard manure (FYM), supplying about

40 kg P/ha, was applied annually, but only for potatoes. For both wheat and potatoes yields and phosphorus offtakes were small and large reserves of phosphorus accumulated in the soil. By 1903, Olsen P was 60-70 and 7-11 mg/kg on plots with and without added phosphorus, respectively. After 1901, no phosphorus was applied and, by 1951, Olsen P was 7 mg/kg in soils without P residues and had declined appreciably to, 24 and 26 mg/kg where superphosphate or FYM respectively had been applied (Johnston and Poulton, 1977). From 1949 spring barley was given 63 kg N/ha each year and by the 1970s the reserves of Olsen P accumulated from 1856 to 1901 more than doubled grain yields. In 1976, each of the ten main plots was divided into four to test the effect of the PK reserves at 0, 48, 96 and 144 kg N/ha. The yields of spring barley showed that the efficiency of nitrogen fertilizer use was very poor at low levels of Olsen P (see Section 3.6.). The yields also suggested that the largest Olsen P, 12 mg/kg in 1974, was not sufficient to give optimum yields and in 1986 it was decided to increase the range of Olsen P in the 20 sub-plots in the eastern half of the experiment.

Spring barley, 1986-1991

Between 1986 and 1992, seven applications of 0, 100, 200, 300 kg P_2O_5/ha, (rounded to 0, 44, 87,131 kg P/ha; P0, P1, P2, P3 respectively) were applied cumulatively to appropriate plots to increase Olsen P in the top 23cm soil – the plough layer. Each plot also received 144 kg N/ha and 100 kg K_2O/ha each year. For each treatment, average grain yields of spring barley grown from 1987 to 1991 and the Olsen P in 1989 – the middle of this period – are shown in Table 2. When yield was related to Olsen P (Table 3), the maximum (asymptotic) yield was reached at an Olsen P value well below the highest level in many plots, i.e. the range in Olsen P was sufficiently wide for the response of spring barley to Olsen P to be determined with confidence.

Winter wheat, 1992-1999

By 1992, soils with most Olsen P had nearly 50 mg/kg (the lower half of P Index 4) and it was decided to apply no more phosphate fertilizer. In 1992, winter wheat replaced spring barley. Each plot received 192 kg N/ha and 100 kg K_2O/ha each year. For each treatment, average annual grain yield of winter wheat grown without fresh phosphate fertilizer from 1993-1999 and the Olsen P in 1996 – the middle of this period – are shown in Table 2. Other than on soils to which most P had been added, Olsen P in 1996 was similar to that in 1989. The maximum yield was achieved on soils with an Olsen P well below the largest level.

Winter wheat, 2000-2008

In 2000 it was decided to test the validity of the advice given in RB209 (MAFF, 2000) and which continues in the new Fertiliser Manual (RB209) (Defra, 2010). This was to raise a soil to the critical P Index and maintain that level by replacing the P removed in the harvested crop, in this case in grain plus straw. In this experiment with grain yields ranging from 2 to nearly 8 t/ha it would have been logistically difficult to manage each plot separately. It was decided, therefore, to add 45 kg P_2O_5/ha (20 kg P/ha) to each plot after each harvest other than the five sub-plots that had not received phosphorus since at least 1901 – the P0 treatment. On plots with a small yield and phosphorus offtake, adding this amount of phosphate increased Olsen P slightly until 2008 (see Figure 5). Each year from 2004 to 2008, *cv* Xi-19 was grown with 150 kg K_2O/ha and a total of 300 kg N/ha split between three applications: 50, 200, 50 kg N/ha. For each treatment, average grain yields of winter wheat grown in this period and the Olsen P are in Table 2.

Table 2. Average Olsen P, average annual grain yields and P offtakes in three periods[a], Exhaustion Land experiment, Rothamsted.

Plot and P treatment 1986-92[f]		1987-91, spring barley			1993-99, winter wheat			2004-08, winter wheat		
		Olsen P[b] mg/kg	Grain t/ha	P offtake[e] kg/ha	Olsen P[b] mg/kg	Grain t/ha	P offtake[e] kg/ha	Olsen P[b] mg/kg	Grain t/ha	P offtake[e] kg/ha
11	P3	22	4.71	14.0	22	7.01	20.3	19	6.96	16.2
12	P2	16	4.57	13.4	13	6.92	19.6	13	7.15	16.2
13	P1	10	4.25	12.0	5	6.08	14.7	8	6.46	13.6
14	P0	3	2.26	5.2	2	2.25	3.7	3	2.26	3.5
31	P3	38	4.76	14.8	41	7.27	23.8	32	7.41	18.5
32	P2	27	4.92	15.2	27	7.39	22.9	16	7.38	18.4
33	P1	13	4.76	14.2	13	7.07	20.7	15	7.29	16.6
34	P0	7	3.85	10.2	4	5.78	12.2	5	4.49	8.5
51	P3	17	4.75	13.8	24	6.98	21.1	21	6.94	15.0
52	P2	14	4.79	13.8	15	7.04	20.6	16	7.57	16.6
53	P1	7	4.28	11.6	7	6.43	16.0	9	6.62	12.9
54	P0	2	2.00	4.4	3	2.62	4.6	3	2.08	3.1
71	P3	30	4.84	15.0	33	7.20	22.1	30	7.54	17.9
72	P2	23	4.91	14.7	23	7.08	22.4	23	7.10	17.6
73	P1	15	4.46	12.7	10	6.59	18.7	15	6.83	15.0
74	P0	4	3.30	8.1	4	4.94	10.8	5	3.74	6.6
91	P3	35	4.75	15.1	41	7.29	23.2	32	7.30	17.7
92	P2	26	4.82	15.3	26	7.54	23.0	25	7.76	18.5
93	P1	14	4.62	14.1	11	7.07	19.3	14	7.34	15.7
94	P0	5	3.47	9.0	4	5.26	11.3	4	4.55	8.2

[a] 1987-91, P added each year, spring barley cv Triumph; 1998-99, no P added, winter wheat cv Mercia or Hereward; 2004-08, replacement P added each year, winter wheat cv Xi-19

[b] Olsen P in 1989; [c] Olsen P in 1996; [d] Olsen P mean 2004/06/08

[e] P offtake in grain plus straw

[f] First digit, plot number from 1876; second digit, number added for plot made in 1976 by dividing the original plot into four; for P treatment since 1986 see 3.3.1.

Fitted response curves to the yield/Olsen P relationship

For each of the 23 crops grown between 1986 and 2008, grain yield was plotted against Olsen P and a response curve fitted statistically as described above (Section 3.2.4). The fitted maximum grain yield and the Olsen P in the top 23cm soil needed to achieve 98% of the maximum yield for each year are in Table 3, together with the standard error of both yield and Olsen P and the percent variance accounted for. With two exceptions, percent variance accounted for varied from 83 to 97%, i.e. there was a strong relationship between yield and Olsen P.

Table 3. Fitted maximum grain yield and Olsen P in 0-23cm soil needed to achieve 98% of the maximum yield, Exhaustion Land, Rothamsted.

Crop	Harvest year	Fitted maximum yield and its standard error		Olsen P at 98% max. Yield and its s.e.		Variance accounted for, %
		t/ha	s.e.	mg/kg	s.e.	
Spring barley	1986[a]	4.41	0.164	11	2.1	83
	1987	4.74	0.102	10	1.7	84
	1988	7.12	0.082	13	0.9	97
	1989	2.34	0.075	13	2.8	77
	1990	4.30	0.066	15	2.3	92
	1991	5.46	0.062	17	2.2	96
Winter wheat	1992	7.90	0.092	12	1.1	96
	1993	6.12	0.192	13	3.3	72
	1994	7.87	0.081	9	0.6	97
	1995	6.28	0.112	14	2.0	92
	1996	7.74	0.133	8	0.9	87
	1997	7.39	0.110	13	1.0	97
	1998	7.72	0.109	7	0.7	91
	1999	7.06	0.178	10	1.2	91
	2000	3.87	0.099	10	1.2	91
Spring wheat	2001[b]	3.99	0.124	12	2.3	85
Winter wheat	2002	6.55	0.245	14	2.9	84
	2003	6.45	0.115	9	1.2	90
	2004	7.92	0.219	18	2.4	94
	2005	9.77	0.169	10	1.6	88
	2006	8.48	0.226	15	2.4	91
	2007	5.33	0.241	26	6.2	86
	2008	10.36	0.135	14	1.2	97

[a] Spring barley drilled very late (2nd May), immediately after application of phosphate fertilizer

[b] Winter wheat failed; replaced by spring wheat

To illustrate the relationship between yield and Olsen P, years with a similar maximum yield were grouped together (note: not all years are used in these illustrations).

For each group of years, a response curve was then fitted, as described above, to the average yield and average Olsen P. Figures 2, 3 and 4 show these relationships: Figure 2 for spring barley when phosphate fertilizer was being applied, Figure 4 for winter wheat when no phosphate was applied, and Figure 4 for winter wheat when replacement phosphate was applied.

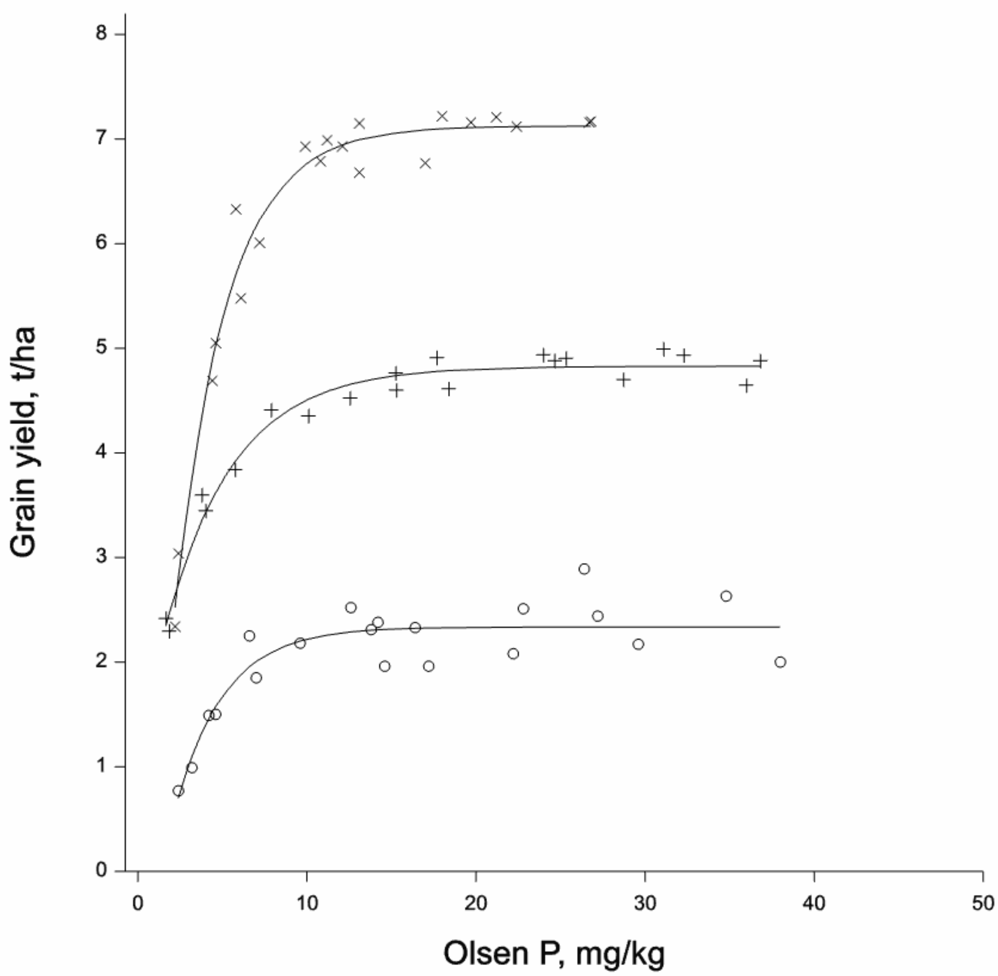


Figure 2. Asymptotic regression of barley grain yield on Olsen P in soil averaged over years with similar maximum yield: 1988 (x); 1987, 1990 & 1991 (+); 1989 (o). Exhaustion Land.

The response curves in the three figures show that there was little change in the critical level of Olsen P although there were large differences in maximum yield.

- From the three response curves for spring barley (Figure 2) the maximum yields were 2.35, 4.83 and 7.12 t/ha and the critical Olsen P levels were 12.6, 14.9 and 12.8 mg/kg, respectively. For an almost three-fold difference in yield the largest difference in Olsen P was only 2.3 mg/kg.
- From the three response curves for winter wheat when no phosphorus was added (Figure 3) the maximum yields were 3.87, 6.59 and 7.79 t/ha and the critical Olsen P levels were 10.3, 11.9 and 8.5 mg/kg, respectively; a 2-fold difference in yield but only a 3.4 mg/kg difference in Olsen P.

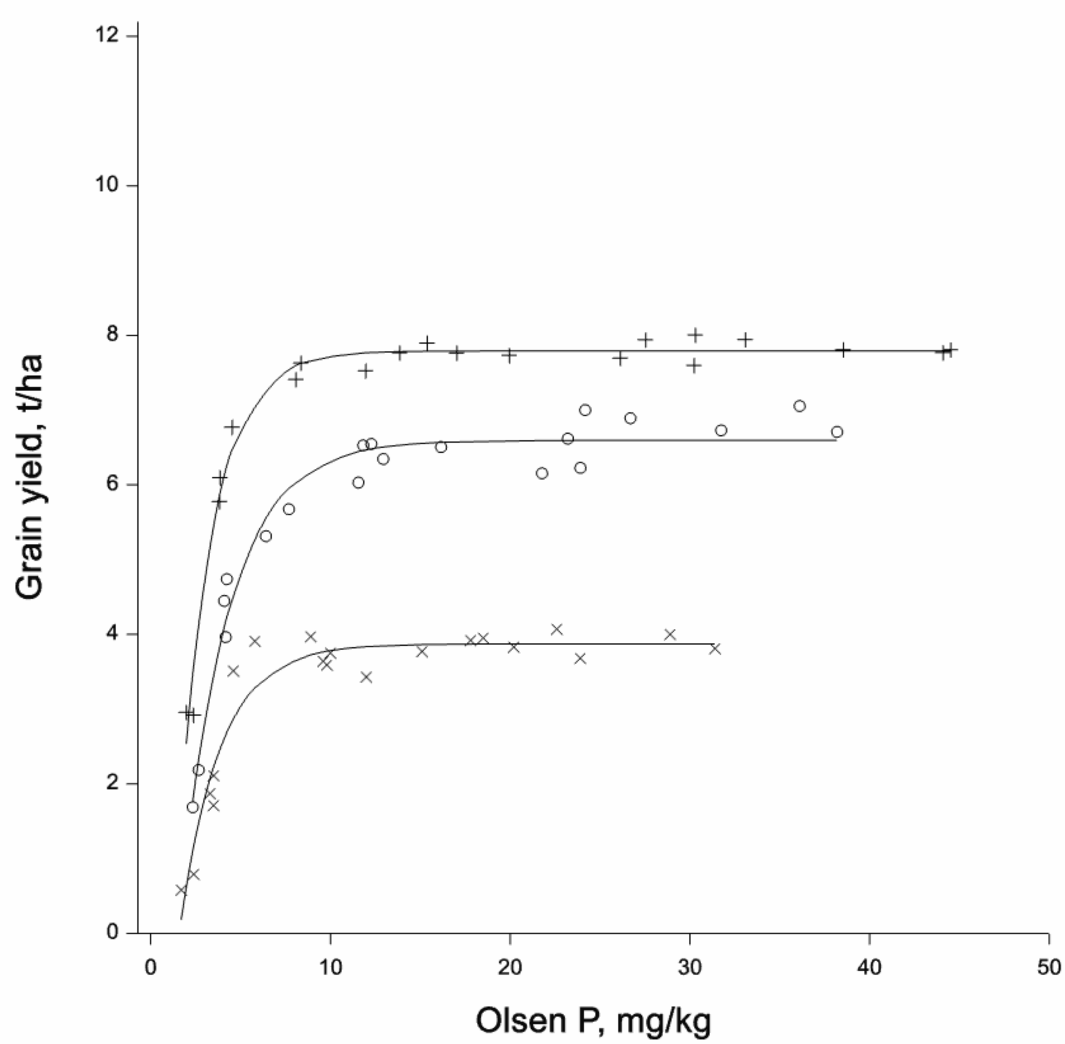


Figure 3. Asymptotic regression of wheat grain yield on Olsen P in soil averaged over years with similar maximum yield: no fresh P added: 2000 (x); 1992, 1994, 1996 & 1998 (+); 1993, 1995, 1997 & 1999 (o). Exhaustion Land.

- From the three response curves for winter wheat when the phosphorus removed in the harvested crop was replaced (Figure 4), the maximum yields were 5.33, 8.18, and 10.02 t/ha and the critical Olsen P levels were 26.3, 16.7 and 11.4 mg/kg, respectively. In this case a large Olsen P was associated with the smallest yield and some other factor, which we cannot identify, appears to have affected root growth so that the limited root system required a large Olsen P to find sufficient phosphorus for even a small yield.

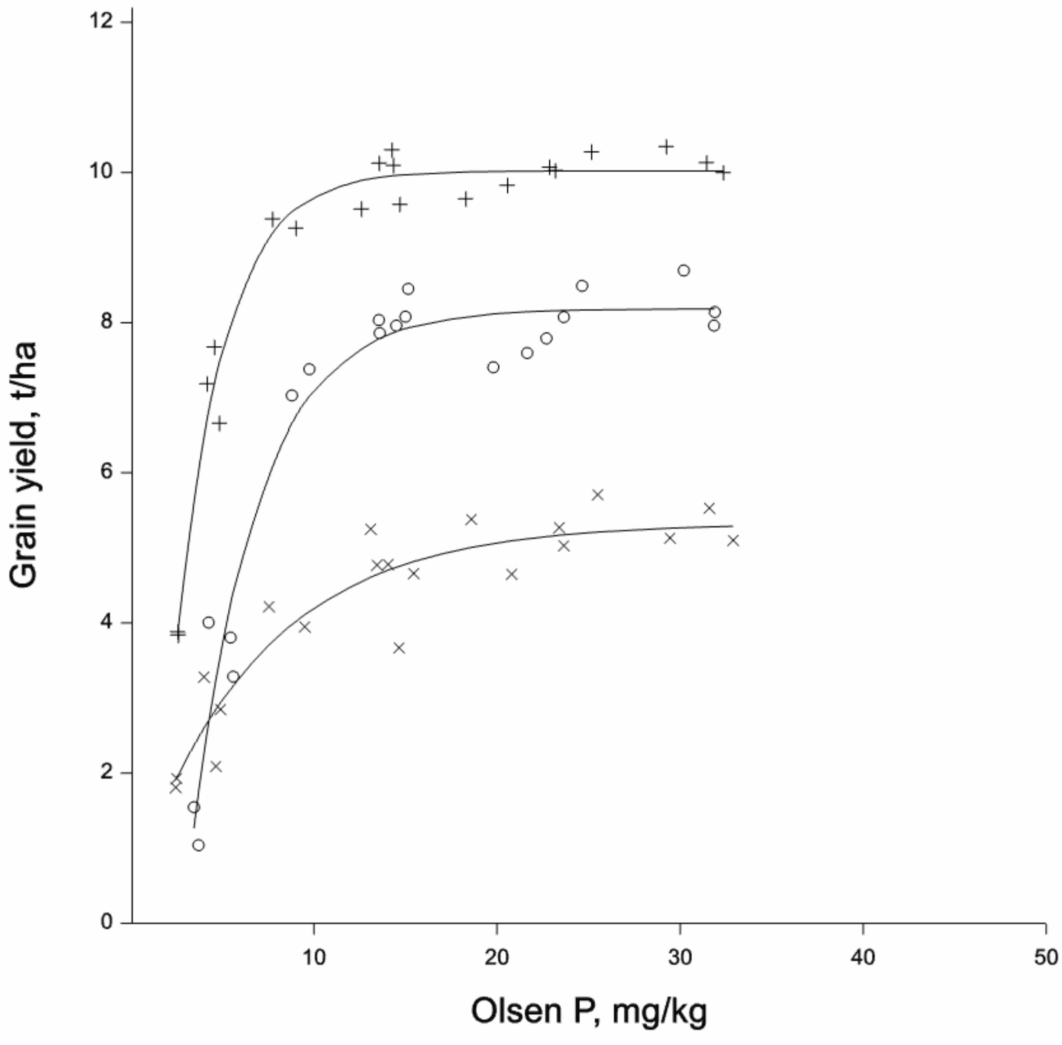


Figure 4. Asymptotic regression of wheat grain yield on Olsen P in soil averaged over years with similar maximum yield: maintenance P added: 2007 (x); 2005 & 2008 (+); 2004 & 2006 (o). Exhaustion Land.

3.3.2. Agdell experiment, Rothamsted

The soil is a flinty silty clay loam over mottled Clay-with-flints (Heavy Batcombe Series) containing 27-35% clay. It has a poor physical structure and is difficult to cultivate, especially to prepare good seedbeds for spring sown cereals. Started in 1848, this long-term experiment had six main treatments: 3 fertilizer treatments x 2 rotations (Warren, 1958). The treatments were no fertilizer, NPK and PK; the fertilizers were applied only for the first crop, turnips, of the four grown in rotation so nutrient inputs were small. The soil became acid where nitrogen (N) was applied as ammonium sulphate and this encouraged the spread of the fungus *Plasmodiophora sp.,* which so severely decreased the yield of turnips that the original experiment ceased in 1951. Acidity was corrected before starting to evaluate the reserves of P that had accumulated in soil (Johnston & Penny, 1971). In 1958, the six large plots of the original experiment were halved. On one half, the "arable plots", the P residues were evaluated for potatoes, sugar beet and spring barley from 1959 to 1962 (Johnston & Warren, 1970); from 1963 to 1969 these half plots were fallowed. The other six half plots were sown to grass in 1958 and remained in grass until 1969, the "grass plots". The range of Olsen P on both grass and arable half plots was increased in 1964 on four subplots (Johnston & Penny, 1971). Growing grass for 12 years increased the level of soil organic matter (SOM) and, by 1969, the grass and arable soils contained 2.4 and 1.5% SOM, respectively, and both grass and arable soils had 24 plots with Olsen P ranging from 3 to 69 mg/kg.

Spring barley, potatoes and sugar beet, 1970-1972

The grass and arable plots were ploughed in autumn 1969 to grow spring barley, potatoes and sugar beet in rotation. Two crops were grown each year so that, using the 2-year average yield of barley grain, potato tubers and sugar (from sugar beet) the relationship between yield and Olsen P was determined. Each crop was grown twice in the three years, and using the 2-year average yield of barley grain, potato tubers and sugar (from sugar beet) the relationship between yield and Olsen P was determined. For all three crops, the shape of the response curve on the soils with more SOM was significantly different from that on the soil with less SOM. The effect was mostly due to improved soil structure on soil with more SOM (see Appendix D1.1). For spring barley, maximum grain yields were 5.26 and 4.69 t/ha on soils containing 2.4 and 1.5 %SOM respectively; the critical levels of Olsen P needed to achieve 95% of those yields were 16 and 45 mg/kg respectively. Thus, on the soil with better structure the critical level of Olsen P was in the lower half of P Index 2, but on the poorly structured soil, the soil had to be in the upper half of P Index 3.

Spring barley, 1973-1976

Spring barley was grown in this period when no phosphate was applied but two levels of nitrogen (N) were tested at each level of Olsen P and grain yield was related to Olsen P as described previously. Some yields and their corresponding Olsen P values have been excluded from Table 4 because the standard errors were too large.

Table 4. Effect of soil organic matter on the fitted maximum yield of spring barley grain and Olsen P in 0-23cm soil needed to achieve 98% of the maximum yield. Agdell, Rothamsted, 1973-1976.

	N applied kg/ha	Fitted maximum yield and its standard error		Olsen P at 98% max. Yield and its s.e.		Variance accounted for, %
		t/ha	s.e.	mg/kg	s.e.	
1.5% SOM						
1973	63	-[a]	-	-	-	-
1974	63	--	-	-	-	-
1973	94	6.19	0.642	-	-	-
1974	94	5.94	0.260	-	-	-
1975	63	4.00	0.243	51	23.6	30
1976	63	3.82	0.150	47	27.3	28
1975	94	4.29	0.261	52	24.2	31
1976	94	4.08	0.176	40	17.4	27
2.4% SOM						
1973	63	6.26	0.096	15	3.4	45
1974	63	5.83	0.086	18	3.8	49
1973	94	5.90	0.088	12	2.9	29
1974	94	6.18	0.063	16	2.3	63
1975	63	3.87	0.120	22	4.2	59
1976	63	4.08	0.093	25	3.1	7.9
1975	94	4.38	0.126	27	5.1	65
1976	94	4.36	0.110	31	4.8	77

[a] Excluded – the standard error of the yield and/or Olsen P was unacceptably large

Optimum grain yields in 1973-74 were acceptable for the cultivar Julia but were much less in 1975-76, two very dry years. The exclusion of data for the low SOM plots in the more favourable years was because of the large standard errors when crops were grown on poorly structured soils. In each 2-year period, there was little response to N and the maximum yield for all treatments was very similar. However, to achieve similar maximum yields required much more Olsen P, 40-52 mg/kg, on soil with less SOM compared with 12-18 mg/kg in the years with larger yields and 22-31 mg/kg in the years with smaller yields. Again, these results demonstrate the importance of maintaining a good soil structure to optimise the use of soil phosphorus by crops, especially in dry years.

Winter wheat, 1980-1984

Grass was grown in 1977-78. In 1979, it was decided to halve the experimental site and grow winter field beans and winter wheat alternately with both crops present each year. In autumn before the beans were sown, phosphate was applied at 150 kg P_2O_5/ha (65 kg P/ha) to those subplots that had had P in 1970-72. Thus, there was some time for the phosphate to equilibrate with the existing Olsen P before winter wheat was grown. It was not possible to statistically fit a response curve to the grain yield/Olsen P relationship because the yields on the very small plots were too variable. Instead, each year, the yield on each plot was assigned to one of five groups according to the Olsen P on the plot: 0-9, 10-15, 16-20, 21-25 and 26-45 mg/kg Olsen P. Initially, yields for soils with different levels of SOM were kept separate but surprisingly, there was no consistent difference between them during this period and the average is given here for each Olsen P group. Yields for individual years were then averaged for 1980-81 and for 1982-84, because yields in the first two years were smaller than those in 1982-84. Table 5 shows, for the five Olsen P groups, yields of wheat, with and without fresh P applied the previous year.

Table 5. Average yield of winter wheat grain, t/ha, at each P Index. Agdell, Rothamsted.

P Index[a]	Olsen P mg/kg	Mean yield, 1980-81		Mean yield, 1982-84	
		no fresh P	with fresh P	no fresh P	with fresh P
0	0-9	3.85	-	7.12	7.84
1	10-15	5.23	5.61	7.54	8.56
2A	16-20	5.18	5.47	7.78	7.82
2B	21-25	5.69	6.18	7.48	8.59
3	26-45	5.66	5.74	8.25	8.16
4+	46+	-	5.63	-	8.76

[a] For the purpose of this report P Index 2 has been divided into 2A and 2B as shown.

Maximum grain yield where no fresh P was applied was on soil with 21-25 and 26-45 mg P/kg in 1980-81 and 1982-84 respectively and there was a very small and variable response to fresh P applied one year previously. The lack of a consistent response to fresh P indicates that it is better to maintain soil P at an appropriate level rather than rely on getting optimum yield with a fresh application of P, especially when the soil has a poor physical structure and is difficult to cultivate.

3.3.3. Saxmundham experiment, Suffolk

The soil is a sandy clay loam derived from chalky boulder clay (Beccles Series). The original purpose of the Rotation II experiment, started in 1899, at Saxmundham, Suffolk, was described by Boyd & Trist (1966) while later modifications were described by Mattingly *et al.* (1970). In 1965, the experiment comprised four blocks, each containing eight plots but there were only four levels of Olsen P. To expand the range of Olsen P it was decided to add further amounts of phosphorus as fertilizer and/or farmyard manure (FYM) to four of the plots in each block and this was done between 1965 and 1968 (Mattingly *et al*., 1970). Consequently, by spring 1969 the eight plots in each block had a different level of Olsen P ranging from 4 to 65 mg/kg. In spring 1969, each plot was divided into five subplots to compare no further P addition (two replicates) with three amounts of freshly applied phosphate fertilizer to potatoes and sugar beet with the intermediate crop of spring barley testing the residue of the phosphorus applied to the root crop. Having four blocks allowed replication of each crop over a 2-year period; for details of treatments and yields between 1969 and 1977 see Johnston *et al.* (1986a). Here the yields of five arable crops grown between 1969 and 1984 are related to Olsen P and, in some cases, to freshly applied phosphate.

Potatoes and sugar beet, 1969-1974

Potatoes, spring barley, sugar beet and spring barley were grown in rotation. Fresh phosphate fertilizer was applied only for the root crops and the soil was sampled before the phosphate was applied to determine Olsen P. Each year the yield/Olsen P relationship was fitted statistically for both potatoes and sugar beet grown with and without fresh phosphate and the maximum yield and the critical Olsen P associated with 98% of the maximum yield determined. The results are summarised in Johnston *et al.* (1986a, Tables 7 and 11). The determination of the standard errors in the original (1986) statistical analyses was slightly different to that used for the experimental results presented in this review. Consequently, the standard errors for the potatoes and sugar beet have been recalculated to be consistent with other data presented here. The data, given in Appendix Table 3 (Appendix D), show the need to consider the soil fertility required to maintain optimum yields of all crops grown in a rotation and not just cereals. The fitted maximum yield for potato tubers and sugar (from sugar beet) and the critical Olsen P varied from year to year as seasonal factors, mainly rainfall, affected crop growth. In all but one of the 12 crop years, the variance accounted for by Olsen P ranged from 61 to 99%, i.e. of all the soil factors that could have affected crop growth, Olsen P was the most important.

Spring barley, 1970-1977

Spring barley, grown between 1970 and 1975, followed either potatoes or sugar beet. The yields, which measured the response to the existing “established” levels of Olsen P and the effects of the 1-year old residues of phosphate applied for potatoes and sugar beet, are tabulated in Johnston *et al.* (1986a, Tables 9, 15 and 16). For this report the maximum yield and the critical Olsen P has been determined from the yield/Olsen P relationship for the barley grown on plots without added P to the root crops (Table 6). Yields were acceptable for the cultivar, Julia, grown in this period. The amount of N applied during the 6-year period was decreased because the larger amounts given initially caused some lodging and loss of yield. Two years are excluded in Table 6 because of the large standard error associated with the yield and/or critical Olsen P.

- The Olsen P associated with 98% of the maximum yield ranged from 8 to 26 mg/kg, i.e. from the top of P Index 0 to the top of P Index 2 (Table 6). For the ten yields given in Table 6, the variance accounted for by Olsen P ranged from 79 to 97% (excluding one value at 48%) indicating that Olsen P was the most important soil factor affecting yield.

Table 6. Fitted maximum spring barley grain yield and critical Olsen P in 0-23cm soil at 98% maximum yield, Saxmundham, Suffolk.

Harvest year	N applied kg/ha	Fitted maximum yield and its standard error		Olsen P at 98% max yield and its s.e.		Variance accounted for, %
		t/ha	s.e.	mg/kg	s.e.	
Spring barley after potatoes						
1970	125	4.69	0.068	17	3.5	88
1971	125	4.95	0.083	24	3.9	93
1972	100	5.72	0.113	8	1.6	79
1973	100	4.27	0.504	excluded*		
1974	80	5.44	0.201	15	13.6	48
1975	80	5.39	0.074	17	3.8	95
Spring barley after sugar beet						
1970	125	4.38	0.086	26	5.5	91
1971	125	4.69	0.090	19	2.5	93
1972	100	5.73	0.1056	14	3.4	83
1973	100	5.22	0.068	8	1.0	95
1974	80	5.21	0.097	25	4.5	97
1975	8080	excluded*				

* excluded – the standard error of the yield and/or Olsen P was unacceptably large.

After it was decided to stop growing potatoes and sugar beet, the phasing-in of the cropping at Saxmundham allowed a second crop of spring barley to be grown both in 1975 and 1976, after spring barley the preceding year, and a third successive barley in 1976 and 1977. For these crops too, the maximum yield and the critical Olsen P were determined statistically from the yield/Olsen P relationship. These data are not shown here but are included in Summary Figure 2. Grain yields in 1975 and 1976 were small in these two very dry years, especially in 1976.

- Yields ranged from 3.9 to 5.2 t/ha and critical Olsen P ranged from 16 to 36 mg P/kg, i.e. the bottom of P Index 2 to the mid-point P Index 3. The highest level for Olsen P needed for maximum yield was in 1976, the driest year.

Spring barley, 1978-1979

Spring barley, grown in these two years, followed winter wheat in 1977 and 1978. Four amounts of nitrogen, 30, 60, 90 and 120 kg N/ha, were tested. Table 7 shows the maximum yield and the critical Olsen P determined from the yield/Olsen P relationship. Yields increased up to 90 kg N/ha in 1978 and 120 kg N/ha in 1979 with a larger response to nitrogen in 1979 than in 1978 (Table 7).

- Critical Olsen P varied from 8 to 34 mg P/kg, i.e. from the top of P Index 0 to the mid-point of P Index 3 as it had for the spring barley crops grown from 1975 to 1977. The percentage variance accounted for ranged from 42 to 76% with one exception at only 10%.

Table 7. Fitted maximum spring barley grain yield and Olsen P in 0-23cm soil at 98% maximum yield, Saxmundham, Suffolk, 1978-79.

Harvest year	N applied kg/ha	Fitted maximum yield and its standard error		Olsen P at 98% max yield and its s.e.		Variance accounted for, %
		t/ha	s.e.	mg/kg	s.e.	
1978	30	4.53	0.175	34	11.6	75
	60	5.24	0.200	30	11.9	64
	90	5.41	0.103	14	2.5	76
	120	5.47	0.132	9	1.8	60
1979	30	2.31	0.103	11	7.6	10
	60	3.69	0.107	8	2.5	49
	90	4.58	0.136	12	3.0	63
	120	5.01	0.224	26	13.8	42

Winter wheat, 1978-1980

Winter wheat grown in these three years followed spring barley. Four amounts of nitrogen, 40, 80, 120 and 160 kg N/ha were tested, and in general yield increased as the amount of N applied increased. Critical Olsen P was determined as before and the results are in Table 8. The data for 80 kg N/ha in 1980 is excluded because the standard error was very large. The percentage variance accounted for ranged from 34 to 84%; in most cases Olsen P was the major soil factor controlling yield.

- Critical Olsen P varied from 7 to 27 mg P/kg, i.e. from the top of P Index 0 to the top of P Index 2.

Table 8. Fitted maximum winter wheat grain yield and critical Olsen P in 0-23cm soil at 98% maximum yield, Saxmundham, Suffolk, 1978-80.

Harvest year	N applied kg/ha	Fitted maximum yield and its standard error		Olsen P at 98% max yield and its s.e.		Variance accounted for, %
		t/ha	s.e.	mg/kg	s.e.	
1978	40	6.63	0.176	19	3.6	64
	80	8.04	0.138	16	2.4	84
	120	8.10	0.125	11	1.5	80
	160	8.27	0.175	12	3.7	44
1979	40	4.42	0.182	23	12.8	42
	80	5.89	0.266	27	14.7	44
	120	6.46	2.520	12	2.0	76
	160	6.53	0.111	7	0.7	71
1980	40	6.12	0.288	24	12.7	34
	80	8.85	2.140	excluded*		
	120	7.98	0.175	7	2.0	56
	160	9.22	0.278	21	6.4	64

* excluded – the standard error of the yield and/or Olsen P was unacceptably large.

Winter wheat, 1981-1986

The objective in this period was to relate the yield of a 1st, 2nd and 3rd winter wheat to Olsen P; the 1st wheat having followed winter beans. Nitrogen was tested at 80, 120, 160 and 200 kg N/ha in the first three years but was increased to 120, 160, 200 and 240 kg N/ha for the 1st wheat grown in 1985. The critical Olsen P was determined as before and the results are in Table 9; four of the 36 results are excluded because the standard error associated with the yield and/or the critical Olsen P was unacceptably large. In the majority of cases the variance accounted for was greater than 50%. In the four years when a 1st wheat followed beans, grain yields were good, ranging from 8.6 to 10.9 t/ha. In 1981-82 maximum yield was achieved with 160 kg N/ha; in 1985-86 it was with 160 or 200 kg N/ha.

- The critical Olsen P ranged from 7 to 33 mg/kg and there was an indication that as the amount of nitrogen applied increased critical Olsen P decreased.
- Grain yields of the 2nd and 3rd wheat crops were less than those of the 1st, ranging from 6.7 to 9.3 t/ha. There was no indication that the 2nd wheat required more Olsen P to achieve maximum yield; critical Olsen P ranged from 6 to 32 mg/kg. Similarly for the 3rd wheat, critical Olsen P ranged from 6 to 31 mg/kg.

Summary of spring barley and winter wheat data from Saxmundham, 1970-1986

There were 65 crop years in this period when the yield/Olsen P relationship could be fitted statistically and the critical Olsen P associated with 98% of the maximum yield estimated. For spring barley grown between 1970 and 1979 (23 crop years), the critical Olsen P ranged from 8 to 36 mg/kg. For winter wheat grown between 1978 and 1986 (42 crop years), the critical Olsen P ranged from 6 and 33 mg/kg. Perhaps surprisingly, there was little difference in the range of Olsen P for both spring barley and winter wheat. The latter, with its longer growing season, might have been expected to acquire the phosphorus it required from a smaller amount of Olsen P in soil. For both spring barley and winter wheat, the variance accounted for was ≥ 50% in most cases, and ≥ 70% in half of the cases, indicating that Olsen P had the greatest influence on yield.

Table 9. Fitted maximum winter wheat grain yield and Olsen P in 0-23cm soil at 98% maximum yield, Saxmundham, Suffolk, 1981-86.

Harvest year	N applied kg/ha	Fitted maximum yield and its standard error		Olsen P at 98% max yield and its s.e.		Variance accounted for, %
		t/ha	s.e.	mg/kg	s.e.	
1st wheat						
1981	80	8.90	0.407	33	23.0	54
	120	9.08	0.665	excluded*		
	160	9.46	0.144	11	2.9	63
	200	9.46	0.279	17	9.8	42
1982	80	9.84	0.115	14	1.5	84
	120	10.38	0.122	11	1.5	80
	160	10.89	0.163	20	3.4	88
	200	10.65	0.148	13	3.0	73
1985	120	9.00	0.457	28	20.5	41
	160	9.34	0.208	18	3.9	72
	200	8.62	0.133	6	1.5	70
	240	8.63	0.118	7	2.6	40
1986	120	9.26	0.123	23	3.5	88
	160	excluded*		excluded*		
	200	9.19	0.152	8	1.5	75
	240	9.10	0.145	10	3.0	65
2nd wheat						
1982	80	7.37	0.244	23	6.5	82
	120	7.56	0.256	18	4.1	70
	160	8.41	0.187	16	2.6	88
	200	8.62	0.186	18	2.7	92
1983	80	7.36	0.095	8	2.1	75
	120	excluded*		excluded*		
	160	8.06	0.117	6	1.4	69
	200	excluded*		excluded*		
1986	120	7.93	0.416	28	10.5	70
	160	7.97	0.130	17	1.9	91
	200	7.88	0.087	19	4.0	80
	240	8.54	0.106	32	5.3	92
3rd wheat						
1983	80	7.89	0.406	31	21.2	50
	120	8.26	0.130	10	2.9	66
	160	8.40	0.087	6	1.1	82
	200	8.38	0.106	11	3.6	64
1984	80	6.87	0.194	14	3.6	66
	120	8.11	0.429	25	12.4	55
	160	8.60	0.145	11	1.5	90
	200	9.27	0.216	18	4.7	77

* excluded – the standard error of the yield and/or Olsen P was unacceptably large.

3.4. Maintaining Olsen P by replacing phosphorus taken off in the harvested crop

In autumn 1977, a first, simple test of whether Olsen P could be maintained by the application of a “maintenance dressing” of phosphorus was started at Saxmundham. Plots growing winter wheat that year had been sampled in spring and then, in autumn, 120 kg P_2O_5/ha (52.4 kg P/ha) was applied to the stubble and ploughed in. In autumn 1978, this phosphate application was repeated on the plots growing winter wheat that year. The soil sampling and phosphate application in alternate years was repeated three times. During the 6-year period winter wheat, spring barley, winter wheat, winter beans, winter wheat, and winter wheat were grown in rotation.

For five soils with increasing levels of Olsen P, the total phosphorus applied and removed, and the phosphorus balance are shown in Table 10. On soils with least Olsen P in 1977/78, yields were small and there was a large positive phosphorus balance which increased Olsen P. On the two soils with most Olsen P the smaller positive phosphorus balance during the 6-year period maintained Olsen P (Table 10).

Table 10. Change in Olsen P when “maintenance” phosphorus was given to replace the phosphorus removed in six arable crops, Saxmundham RII, 1977/78 to 1982/83.

	Olsen P, mg/kg, in 1977/78[a]				
	7	10	18	24	35
Total phosphorus applied, kg P/ha[b]	157	157	157	157	157
Total phosphorus removed, kg P/ha	86	94	107	110	115
Phosphorus balance, kg P/ha	71	63	50	47	42
Olen P, mg/kg, in 1983/84[a]	9	14	23	23	34
P use efficiency % (balance method)	55	60	68	70	73

[a] Olsen P in spring prior to phosphorus application in autumn

[b] Three applications of 52.4 kg P/ha in alternate years

A more rigorous test of replacing phosphorus removed in grain plus straw was started on the Exhaustion Land in 2000 on the 15 sub-plots testing fresh applications of phosphorus from 1986-1992. These plots had a wide range of Olsen P and consequently yields and phosphorus offtake varied greatly. Logistically it would have been difficult to determine and replace the phosphorus removed from each plot in the short period between harvest and drilling the next crop of wheat. Consequently, it was decided to apply 45 kg P_2O_5/ha (20 kg P/ha) to all 15 plots; unfortunately, due to an error, three times the intended amount of phosphorus was applied in the first autumn, 1999. Between 2000 and 2004 yields, and consequently phosphorus offtake, were less than expected. There was a positive phosphorus balance on all plots and Olsen P increased a little (not shown). Yields were much larger between 2005 and 2008 and the P balance was much smaller but nevertheless Olsen P was maintained (Table 11, Fig. 6). The principle of replacing phosphorus removed in the harvested crop did maintain Olsen P.

Table 11. Maintaining Olsen P in soil by replacing the phosphorus removed in four winter wheat crops[a], Exhaustion Land, Rothamsted, 2005-2008.

	Olsen P, mg/kg, in 2004[b]				
	9	14	20	23	31
Average annual grain yield, t/ha	7.6	8.3	8.1	8.5	8.5
Total phosphorus applied, kg P/ha[c]	80	80	80	80	80
Total phosphorus removed, kg P/ha	56	68	66	77	75
Phosphorus balance, kg P/ha	24	12	14	3	5
Olen P, mg/kg, in 2008[b]	8	13	18	24	31
P use efficiency % (balance method)	70	85	82	96	94

a Winter wheat grown continuously

b Olsen P in autumn

c Phosphorus, 20kg P/ha, applied in autumn

The data in Tables 10 and 11 illustrate an important point about phosphorus use efficiency. When phosphorus use efficiency has been measured by the difference method the values are often in the range 10-15% and rarely exceed 25%. Syers *et al.* (2008) present reasons for replacing the difference method with a “Balance method” which more nearly estimates the total efficiency with which phosphorus is used in agriculture. When the balance method was used with the data in Tables 10 and 11 phosphorus use efficiency increased as the phosphorus applied more nearly balanced phosphorus removed indicating that phosphorus use efficiency can exceed 90% when the phosphorus applied is about equal to that in a harvested crop.

3.4.1. Importance of regular soil analysis for Olsen P

Figure 5 shows the change in Olsen P from 1981 to 2008 in the Exhaustion Land experiment. From 1986 to 1992, 0, 44, 87 and 131 kg P/ha were applied each year (P0, P1, P2 and P3) and Olsen P increased, except on the soil receiving no fresh P (P0). Olsen P then declined when no phosphate was applied between 1993 and 1999. This period of decline was followed by a small increase in Olsen P after the application of “replacement” phosphorus started in 2000. These changes show the benefits of regular soil sampling and analysis to indicate the effect of changes in phosphorus inputs, and hence phosphorus balance on Olsen P.

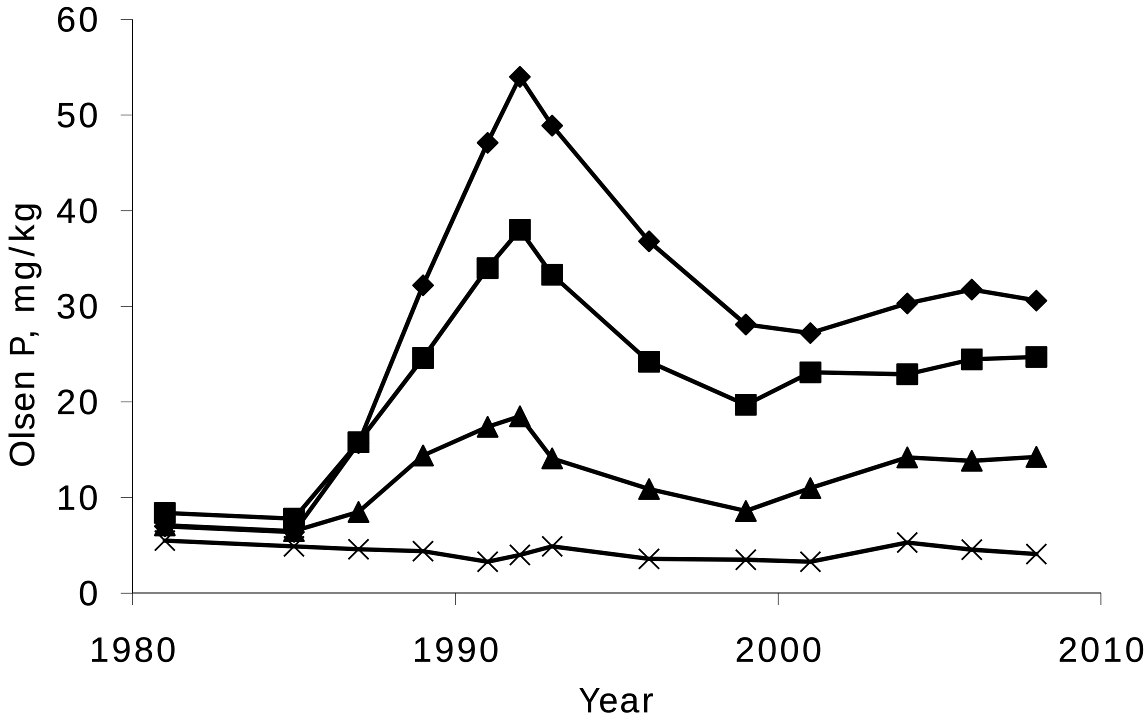


Figure 5. Olsen P in soils given no fresh P since 1901 (x). Treatments from 1986-1992 were: 44 kg P/ha/yr (▲), 87 kg P/ha/yr (■) 131 kg P/ha/yr (♦): no P was applied from 1993-1999: 61.5 kg P/ha was applied in 2000, followed by 20 kg P/ha/yr since 2001. Exhaustion Land.

3.5. Effect of phosphorus budgets on changes in Olsen P

Two frequently asked questions are, (i) how much phosphorus must be added to increase Olsen P; and (ii) how quickly will Olsen P decline if no phosphate fertilizer is applied. These questions are not easy to answer because of the continual, and often rapid, transfer of phosphorus between the readily plant-available and less readily plant-available pool of soil phosphorus shown in Appendix Figure 1 (Appendix C). A more detailed discussion of the implications arising from this transfer of phosphorus between the different pools of soil phosphorus is given in Appendix C. The phosphorus balance is the difference between the amount of phosphorus applied and that removed in the harvested crop. The balance is positive when the amount applied exceeds that removed and negative when removal exceeds the amount applied. A phosphorus balance can be prepared at a range of scales from the field to a country. At the farm scale a phosphorus balance indicates whether enough phosphate is being purchased to match removals. At the field scale the phosphorus balance can be related to the change in Olsen P as a result of phosphate management for that field. A positive phosphorus balance would usually, but not always increase Olsen P, while Olsen P will usually decline when the phosphorus balance is negative. Such changes can be monitored over the short- or long-term. At the field scale the change in Olsen P, expressed as kg P/ha, will usually be less than the phosphorus balance, in kg P/ha, because of the transfer of phosphorus between the readily available pool of soil P and the less readily available pool as discussed in Appendix C. Nevertheless field experiments show that phosphorus in the less readily available pool becomes available to crops when required (Johnston, 2001; Johnston *et al.* 2001).

Here we give an indication of changes in Olsen P over periods up to six years using data from the experiment on the Exhaustion Land and that at Saxmundham.

3.5.1. Adding phosphate fertilizer to increase Olsen P

Table 12 shows that, for both the silty clay loam on the Exhaustion Land and the sandy clay loam at Saxmundham, the increase in Olsen P, in kg/ha, was less than the positive P balance, in kg/ha.

Table 12. Effect of a positive phosphorus balance on Olsen P.

Exhaustion Land[a], phosphorus added 1986 to 1991						
Total P added, kg/ha	Olsen P in		Change in Olsen P kg/ha	P offtake kg/ha	P balance kg/ha	Change in Olsen P as % of P balance
	1985 mg/kg	1991 mg/kg				
262	7	18	33	80	182	18
524	8	38	90	87	437	20
786	7	48	124	86	700	18
Saxmundham[b], phosphorus added 1965 to 1967						
Total P added, kg/ha	Olsen P in		Change in Olsen P kg/ha	P offtake kg/ha	P balance kg/ha	Change in Olsen P as % of P balance
	1964 mg/kg	1969 mg/kg				
231	36	39	10	66	165	6
247	34	44	34	65	182	19
478	32	54	74	68	410	18
493	37	67	101	67	426	24

[a] Based on a soil weight of 3030 t/ha

[b] Based on a soil weight of 3370 t/ha

Because this phosphorus remains in the soil it can be considered as a phosphorus input and is used in this sense in Figure 6. The relationship between the increase in Olsen P and phosphorus input was fitted with a straight line, constrained to go through the origin (Figure 6). From these figures, the increase in Olsen P, mg/kg, for a phosphorus input of 10 kg P/ha (23 kg P_2O_5/ha) was calculated. On the Exhaustion Land and at Saxmundham the increase in Olsen P was 0.56 and 0.60 mg/kg, respectively.

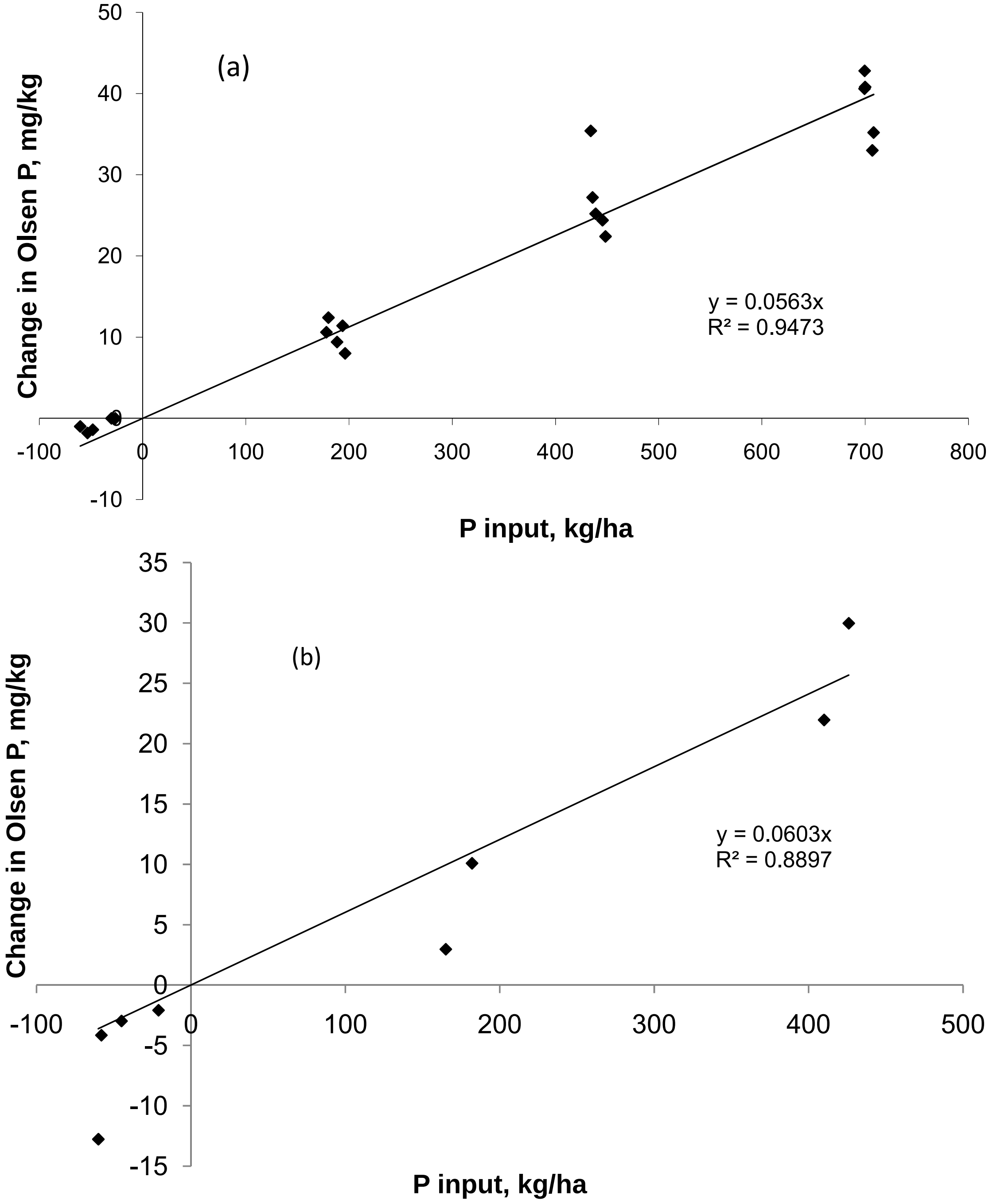


Figure 6. Change in Olsen P, in kg/ha, in relation to the P input: a) Exhaustion Land, 1986-1991; b) Saxmundham, 1964-1968.

Using these data the amount of phosphorus required to increase Olsen P from the mid-point of P Index 0, 1 and 2 to the mid-point of P Index 1, 2 and 3, respectively, can be calculated. Table 13 shows just how much phosphate must be added to build up Olsen P from the mid-point of P Index 0 to the mid-point of P Index 1 and also for a similar change from P Index 1 to 2. The amounts range from 286 to 327 kg P_2O_5/ha.

Table 13. The amount of phosphorus required to increase Olsen P from the mid-point of one P Index to the mid-point of the P Index above.

P Index	Mid-point of P Index mg P/kg	Required increase in Olsen P mg/kg	Exhaustion Land[a]		Saxmundham[b]	
			kg P/ha	kg P_2O_5/ha	kg P/ha	kg P_2O_5/ha
0	4.5					
		7.5	134	307	125	286
1	12					
		8	143	327	133	304
2	20					
		15	268	613	250	572
3	35					

[a] Based on an addition of 10 kg P/ha increasing Olsen P by 0.56 mg/kg (see text) and soil weight (0-23cm) of 3030 t/ha.

[b] Based on an addition of 10 kg P/ha increasing Olsen P by 0.60 mg/kg (see text) and soil weight (0-23cm) of 3370 t/ha.

3.5.2. Decline in Olsen P when no phosphate is applied

Table 14 shows that the decline in Olsen P, in kg/ha, was less than the negative phosphorus balance, in kg/ha. The decline in Olsen P over a number of years when soils are cropped without adding phosphorus can be related to the initial Olsen P in the soil. But, even for a soil with most Olsen P, the decrease accounted for less than 50% of the phosphorus removed from the soil in the harvested crops. In other words, much of the phosphorus removed by the crop was coming from phosphorus moving from the less readily available pool to the readily available pool during the growing season.

Table 14. Effect of a negative phosphorus balance on Olsen P.

Olsen P in		Change in Olsen P kg/ha	P offtake kg/ha	P balance kg/ha	Change in Olsen P as % of P balance
Exhaustion Land[a], no phosphorus added 1994 to 1999					
1993 mg/kg	1999 mg/kg				
49	28	-64	140	-140	46
33	19	-42	139	-139	30
15	8	-21	119	-119	18
Saxmundham[b], no phosphorus added 1969/70 to 1983/84					
Olsen P in		Change in Olsen P kg/ha	P offtake kg/ha	P balance kg/ha	Change in Olsen P as % of P balance
1969/70 mg/kg	1983/84 mg/kg				
45	20	-84	263	-263	32
27	12	-50	237	-237	21
8	5	-10	153	-153	6

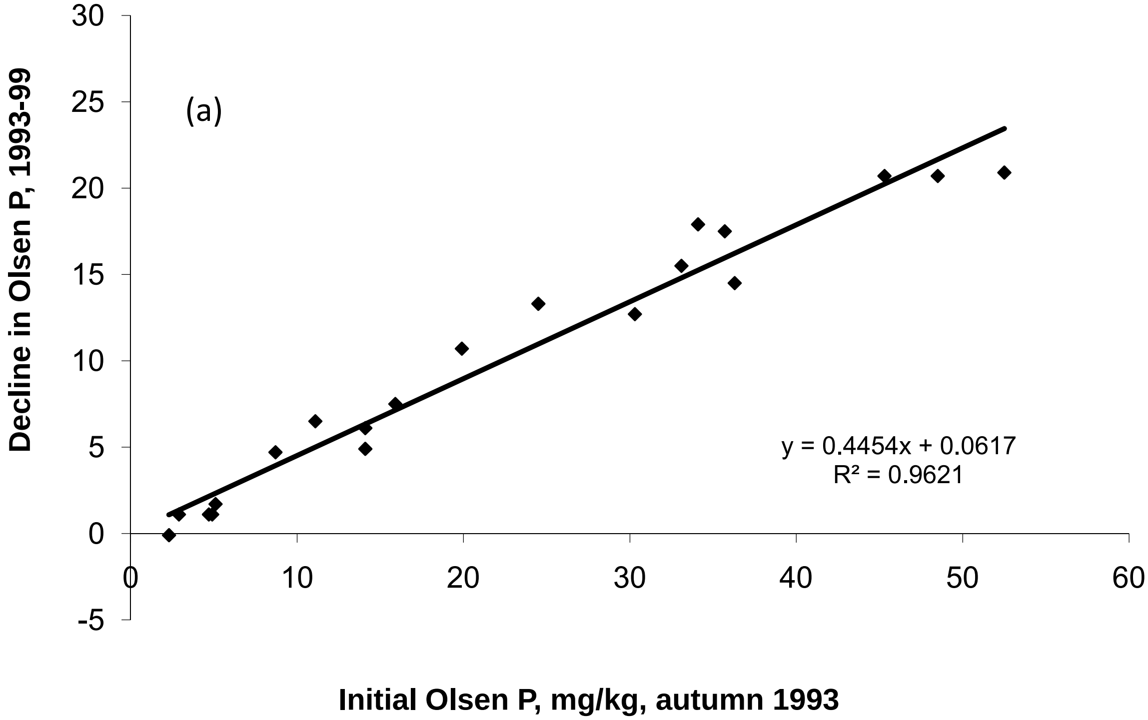
[a] Based on a soil weight of 3030 t/ha

[b] Based on a soil weight of 3370 t/ha

For both the Exhaustion Land and Saxmundham experiments a linear relationship was fitted between the decline in Olsen P and initial Olsen P (Figure 7). From these relationships the level to which Olsen P would decline for a given phosphorus offtake was estimated for each soil (Table 15). In six years, soil at the mid-point of P Index 3, 35 mg Olsen P/kg, would decline to mid-point P Index 2 on the Exhaustion Land and the top half of P Index 2 at Saxmundham. Soil at the mid-point of P Index 2 would decline to the bottom of P Index 1 on the Exhaustion Land and the top half of P Index1 at Saxmundham. Soil at the mid-point of P Index 1 would decline to the top of P Index 1 on both the Exhaustion Land and at Saxmundham. At this level of Olsen P there would be a serious risk of less than optimum yields in most years.

Table 15. Decline in Olsen P when no phosphate is applied.

P Index	Olsen P at P Index mid-point mg/kg	Exhaustion Land		Saxmundham	
		P offtake kg/ha	Olsen P declined to mg/kg	P offtake kg/ha	Olsen P declined to mg/kg
3	35	130	19	116	22
2	20	120	11	100	13
1	12	90	7	76	9



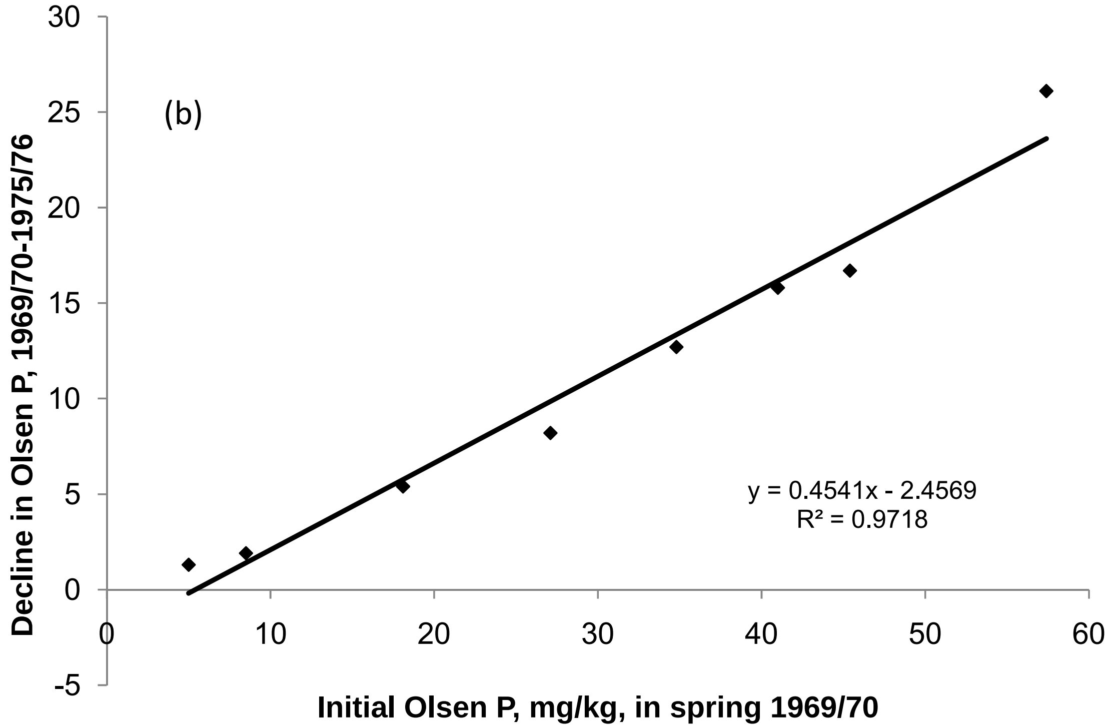


Figure 7. Decline in Olsen P when no fresh P is applied, relative to the initial Olsen P: a) Exhaustion Land; b) Saxmundham.

The decline in Olsen P will depend on both the amount of phosphorus removed in the harvested crops and the rate at which phosphorus is released from the less readily-available pool of soil phosphorus. When comparing a low input farming system where phosphorus offtake is only 15-20 kg P/ha each year, with a high input system with an annual phosphorus offtake of 25-30 kg P/ha on the same soil type, Olsen P will decline more slowly with the smaller offtake. We know from field experiments discussed in this report that phosphorus is released from the less readily-available pool when there is a demand to replace phosphorus in the soil solution as it is taken up by crops.

The effect of the phosphorus balance on the change in Olsen P can vary from soil to soil and can occur over a few years. What we do not know is the extent to which the rate of change in Olsen P varies from soil to soil in relation to the phosphorus balance. Consequently, farmers are recommended to have field soils sampled and analysed every 3-5 years, or possibly every 2-3 years if they are close to the critical value for Olsen P, to ensure that the appropriate level for their soil is being maintained.

Data from the Saxmundham experiment showed that, in the longer term, the decline in Olsen P was curvilinear rather than linear (Johnston *et al*., 1986b). Data on the longer term decline in Olsen P on the other experiments reported here is being prepared for publication.

3.6. Soil phosphorus and nitrogen fertilizer use efficiency

An important reason for maintaining soil at, or just above, the critical level of Olsen P for the soil, crop and farming system is that this ensures that a crop has the potential to achieve the economic optimum yield each year. This also ensures that other inputs, like nutrients and agro-chemicals are used efficiently. This applies especially to the use of nitrogen fertilizers.

The most accurate way of assessing nitrogen use efficiency is using a ^{15}N-labelled nitrogen fertilizer. Winter wheat grown on Broadbalk at Rothamsted recovered 62% of 96 kg N/ha on soil well supplied with phosphorus but only 42% on soil with too little phosphorus (Powlson *et al*., 1986). Similarly, spring barley on Hoosfield given 144 kg N/ha recovered 53 and 42% of the applied nitrogen on soil containing sufficient and too little Olsen P, respectively (Glendining *et al*., 1997). The fate of the additional nitrogen not accounted for on soil with too little Olsen P is not known but at least it is a financial loss to the farmer.

On the Exhaustion Land, average grain yields, 1976-1985, showed that at each rate of nitrogen tested yield increased as Olsen P increased from 2 to 10 mg/kg. On soil with only 2 mg/kg Olsen P it was not justified to apply more than 48 kg N/ha, while with 10 mg/kg Olsen P not more than 96 kg N/ha could be justified (Johnston and Poulton, 2009). Even so, when the best yield in this experiment was compared with that in the adjacent Hoosfield Barley experiment it was clear that in soil with only 10 mg/kg Olsen P there was too little plant-available phosphorus to give maximum yield.

Another example is the response to nitrogen by spring barley (Figure 8a) and winter wheat (Figure 8b) in experiments on the sandy clay loam at Saxmundham. For both crops, optimum yield was on P Index 2 soils; the reason for the small increase in yield of barley on P Index 3 soils is unclear. For barley it was not justified to apply more than 60 kg N/ha on P Index 0 soil and optimum yield on P Index 2 soil required only 90 kg N/ha. For winter wheat it was not justified to apply more than 80 kg N/ha on P Index 0 soil but 160 kg N/ha gave optimum yield on P Index 2 soil.

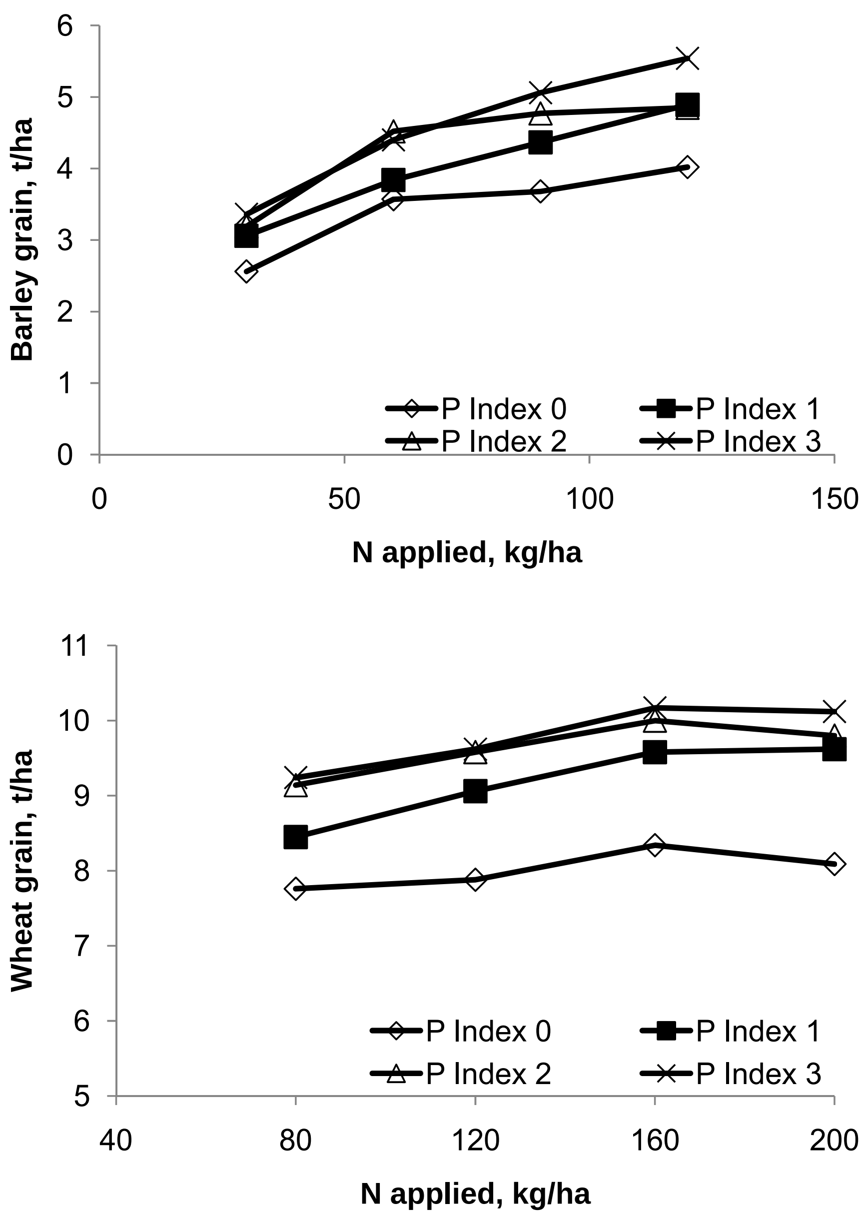


Figure 8. Yields of barley and wheat grown on soil with a range of Olsen P values and given different amounts of fertilizer nitrogen; a) spring barley, 1978-79; b) winter wheat after beans, 1981-82. Rotation II, Saxmundham.

3.7. Response of cereals to fresh fertilizer phosphorus on soils with different levels of Olsen P

In recent years, some farmers have responded to increases in the price of phosphate and potash fertilizers by not applying them every year. Interestingly, data in the British Survey of Fertiliser Practice (Defra, 2011) show that where phosphate fertilizer was applied to a cereal crop, the amount was that recommended in RB209. However, in any one year recently, some 50% of fields growing cereals received no phosphate. Not applying phosphate may be acceptable on some soils and in some situations but needs to be tested. Even on soils where experimental evidence suggests that not applying phosphate may be acceptable for a time, the soil should be sampled and analysed every 3-4 years to check that Olsen P is not declining below the critical level. There should be concern about not applying phosphate to those soils well below the critical level. Experiments show that taking remedial measures to correct phosphorus deficiency by applying recommended amounts of phosphate does not increase yields to those on soils well supplied with Olsen P, at least for a number of years. This is because it will require several cultivations to mix even a large application of phosphate fertilizer, supplying say 200 kg P_2O_5/ha into the topsoil, which, to 15cm, may weigh 2,000,000 kg/ha. The following examples, for spring barley (Table 16) and winter wheat (Table 17) at Saxmundham, show that fresh applications of phosphate fertilizer, or residues from a number of applications added to a soil with little Olsen P did not increase yield to that on a soil well supplied with P.

Table 16. Effect of fresh P on the yields of spring barley grain, t/ha, grown as first (1974-5) or second (1975-6) cereals after a root crop, Saxmundham.

Olsen P[a] mg/kg	After potatoes		After sugar beet	
	No fresh P	With fresh P[b]	No fresh P	With fresh P[b]
1st crop after roots				
5	4.29	5.19	3.07	3.78
16	5.33	5.36	4.30	5.03
24	5.52	5.45	4.60	4.98
30	5.24	5.57	5.07	4.80
2nd crop after roots				
5	2.55	3.64	2.59	3.73
16	4.16	4.41	4.10	4.43
24	4.67	4.80	4.73	4.80
30	4.57	4.75	4.57	4.90

[a] Mean Olsen P in 1975-6 on soils that received no fresh P during 1969-76

[b] 27 kg P/ha applied to each barley crop and to the preceding root crop

Table 17. Effects of recent P residues on the yield of winter wheat grain, t/ha, 1977, Saxmundham.

Olsen P[a] mg/kg	No fresh P	Recent P residues[b]
3	4.08	5.05
5	5.00	5.63
11	6.06	6.38
17	6.55	6.42
27	6.34	6.59

[a] Mean Olsen P on soils which received no fresh P during 1969-77

[b] Residues of P applied between 1969-76, totalling, on average, 165 kg P/ha

Similar data for potatoes and sugar beet from the Saxmundham experiment showed that applying fresh phosphate fertilizer to soil with little Olsen P did not increase yields to that on soil with adequate Olsen P (Johnston *et al*., 1986a).

3.8. Conclusions

The critical level of plant-available phosphorus in soil (Olsen P) needed to achieve 98% of the maximum yield of winter wheat and spring barley, has been determined on two silty clay loams (Rothamsted, Hertfordshire) and a sandy clay loam (Saxmundham, Suffolk). All three soils had a wide range of well-established levels of Olsen P so that all the different fractions of soil phosphorus were in equilibrium. Each year a response curve relating grain yield to Olsen P was fitted statistically to determine the maximum yield, which varied from year to year and was achieved on soils ranging from the top of P Index 0 to P Index 4. The critical Olsen P associated with 98% of the maximum yield also varied greatly from year to year.

For all 60 response curves for winter wheat the average maximum grain yield was 8.03 t/ha; 55% of the maximum yields were on soils at top P Index 0 and P Index 1, and about 30% and 15% on P Index 2 and 3 soils, respectively. About two-thirds of the results for P Index 2 soils were on soils with 16-20 mg/kg Olsen P. There was a difference between the soil types in the percentage of maximum yields achieved on soils with smaller amounts of Olsen P. On the better structured silty clay loam and the poorer structured sandy clay loam, 87 and 58% of the maximum yields were on soils with 8 to 15 mg/kg Olsen P (top P Index 0 and P Index 1), respectively.

For the 42 response curves for spring barley there were differences between the soils. On the better structured silty clay loam, all 7 of the maximum yields that were determined were on soils at P Index 1 and the lower half of P Index 2. The other 35 maximum yields were on soils with a poorer soil structure and only 40% of these were on soils at P Index 1 and the lower half of P Index 2, while 42% were on soils with 21-35 mg/kg Olsen P (mid- point P Index 2 to mid-point P Index 3).

The year to year variability in maximum yield was mainly due to weather, especially rainfall and the length of the grain filling period. The variability in the critical level of Olsen P reflects differences in soil conditions and highlights the importance of soil structure for roots to find nutrients for crops to achieve maximum yield. Based on these results there is a considerable risk of cereals not achieving maximum yield in some years if soils are not maintained at P Index 2. The wide range in Olsen P associated with 98% of the maximum yield on each of the three soil types suggests that it would be very difficult to offer more specific advice on Olsen P for a particular soil type than is currently available.

Olsen P changes with the phosphorus balance (P applied minus P removed). An application of 300-330 kg P_2O_5/ha was required to increase Olsen P from 12 to 20 mg P/kg. When no phosphorus was applied for six years the removal of 120-100 kg P/ha caused a decline in Olsen P from 20 mg P/kg to 11-13 mg P/kg, respectively.

3.9. Acknowledgements

We thank Rodger White for fitting the response curves. This review was funded by HGCA using facilities funded by the Biotechnology and Biological Sciences Research Council (BBSRC).

3.10. References

Avery B W, Catt J A. 1995. The soil at Rothamsted, Lawes Agricultural Trust, Harpenden, 44pp.

Boyd D A, Trist P J O. 1966. The Saxmundham rotation experiments: Rotation II 1899-1952. *Journal of Agricultural Science, Cambridge* 66, 337-339.

Cooke G W, Williams R J B. 1972. Problems with cultivations and soil structure at Saxmundham. *Rothamsted Experimental Station Report for 1971,* Part 2, 122-142.

Defra. 2010. Fertiliser Manual (RB209). Department of the Environment, Food and Rural Affairs, TSO (The Stationary Office). 252pp.

Defra. 2011. British Survey of Fertiliser Practice. Fertiliser Use on Farm Crops for Crop Year 2010, Department of the Environment, Food and Rural Affairs, 88pp.

Glendining M, Poulton P R, Powlson D S, Jenkinson D S. 1997. Fate of ^{15}N-labelled fertilizer applied to spring barley grown on soils of contrasting nutrient status. *Plant and Soil* 195, 83-98.

HGCA. 2002. Plant and soil testing to assess the adequacy of phosphorus supply to winter oilseed rape. Home Grown Cereals Authority Project Report No. OS58.

Hislop J, Cooke I J. 1968. Anion exchange resin as a means of assessing soil phosphate status: a laboratory technique. *Soil Science* 105, 8-11.

Fertiliser Regulations. 1991. http://www.legislation.gov.uk.uksi/1991/2197

Hodge C A H. 1972. The soils at Saxmundham Experimental Station. *Rothamsted Experimental Station Report for 1971,* Part 2, 143-148.

Johnston A E. 2001. Principles of crop nutrition for sustainable food production. Proceedings 459. *International Fertiliser Society*, York, UK. pp 1-40.

Johnston A E, Warren R G. 1970. The value of residues from long-period manuring at Rothamsted and Woburn. III. The experiments made from 1957 to 1962; the soils and histories of the sites on which they were made. *Rothamsted Experimental Station Report for 1969,* Part 2, pp 22-38.

Johnston A E, Penny A. 1971. The Agdell experiment, 1848-1970. *Rothamsted Experimental Station Report for 1970,* Part 2, 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. 2009. Nitrogen in agriculture: an overview and definitions of nitrogen use efficiency. Proceedings 651. *International Fertiliser Society*, York, UK. pp 2-48.

Johnston A E, Lane P W, Mattingly G E G, Poulton P R, Hewitt M V. 1986a. The effects of soil and fertilizer P on yields of potatoes, sugar beet, barley and winter wheat on a sandy clay loam soil at Saxmundham, Suffolk. *Journal of Agricultural Science, Cambridge* 106, 155-167.

Johnston A E, Poulton PR and Lane P. 1986b. Modelling the Long-term Residual Effects of Phosphorus residues in Soil. *Journal of Science, Food and Agriculture,* 37, 8.

Johnston A E, Poulton P R, Syers J K. 2001. Phosphorus, potassium and sulphur cycles in agricultural soils. Proceedings 465. *International Fertiliser Society*, York, UK. pp 2-44.

MAFF. 2000. *Fertilizer Recommendations for Agricultural and Horticultural Crops* RB 209, 6^{h} ed. HMSO, London. 178pp. ISBN 0 11 243058 9.

Mattingly G E G, Johnston A E, Chater M. 1970. The residual value of farmyard manure and superphosphate in the Saxmundham Rotation II Experiment, 1899-1968. *Rothamsted Experimental Station Report for 1969*, Part 2, 91-112.

Olsen S R, Cole C V, Watanabe F S, Dean L A. 1954. Estimation of available phosphorus in soils by extraction with sodium bicarbonate. *United States Department of Agriculture*, Circular No. 939. 19 pp.

Powlson D S, Pruden G, Johnston A E, Jenkinson D S. 1986. The nitrogen cycle in the Broadbalk Wheat experiment: recovery and losses of ^{15}N-labelled fertilizer applied in spring and inputs of nitrogen from the atmosphere. *Journal of Agricultural Science, Cambridge* 107, 591-609.

Syers J K, Johnston A E, Curtin D. 2008. *Efficiency of Soil and Fertilizer Phosphorus.* FAO Fertilizer and Plant Nutrition Bulletin 18. Food and Agriculture Organization of the United Nations. 107pp.

Warren R G. 1958. The residual effects of manuring and cropping treatments in the Agdell rotation experiment. *Rothamsted Experimental Station Report for 1957*, 252-260.

APPENDIX A: DEVELOPMENT AND USE OF SOIL ANALYSIS

In England and Wales before World War Two, much soil analysis was done at county agricultural colleges and they often used different reagents. Following the setting up of the National Agricultural Advisory Service (N.A.A.S.) in 1945, regional laboratories were established for plant and soil analysis. The same extractant, 0.5 M ammonium acetate/0.5 M acetic acid at pH 4.8 (Morgan's reagent) was used for both "available" P and K in soil. Then, in the late 1960s, there was much discussion about the most suitable soil extractants and extraction techniques. Olsen's method, first introduced in England and Wales in the early 1950s, was tested rigorously. This method satisfactorily characterised the plant-available phosphorus status of the majority of soils in this country both in terms of the response of a wide range of crops to an application of phosphate fertilizer and to the yield of crops when related to the concentration of Olsen P in the soil. The outcome was that the Agricultural Development and Advisory Service (A.D.A.S.) decided to make a change from 1 January 1971. At that time the first edition of what became RB209, Fertilizer Recommendations for Agricultural and Horticultural Crops was being prepared (MAFF, 1973). Plant-available soil phosphorus would be determined by extracting soil with 0.5 M sodium bicarbonate at pH 8.5 (Olsen's reagent; Olsen *et al*., 1954). This fraction of plant-available phosphorus is now simply referred to as Olsen P. Available potassium and magnesium in soil would be extracted using M ammonium nitrate. Apportioning the analytical data for phosphorus, potassium and magnesium to an "Index" has remained unchanged, see Section 3.1.1 for phosphorus. Later editions of RB209 also related the amount of phosphorus extracted using an anion exchange resin to the P Index (Resin P) (Hislop and Cooke, 1968). The 1st edition of RB209 gave tables with fertilizer recommendations for individual crops, arable, grassland and horticultural crops, similar to those in the current edition of the new Fertiliser Manual (Defra, 2010).

As RB209 progressed through its various editions the concept of defining and reaching a critical level of plant-available phosphorus in soil, the Target P Index - for a crop and farming system was developed (see Section 3.1.1.). Based on much experimental data (but from a limited range of soil types) it was agreed to set the critical level for Olsen P for most arable crops and grassland at P Index 2 and for potatoes and vegetable crops at P Index 3, as shown in the new Fertiliser Manual (RB209).

Also, the recommendation has been to consider the phosphorus requirement for a rotation of crops and not just an individual crop and, on this basis, to raise soil to the appropriate P Index for all the crops grown in rotation and then maintain it at that level by replacing the phosphorus removed in the harvested crop. The recommendation to raise soils to P Index 2 was based, in part, on the fact that the Olsen P level can, and in most cases does, vary considerably within a field, often from P Index 0 and/or 1 to P Index 3. To some extent this variability would be allowed for by having a "field average” for Olsen P set at P Index 2. To maintain a soil at P Index 2 it is recommended to replace the amount of P removed in the harvested crop (see Section 3.4.).

APPENDIX B: PHOSPHORUS AND CROP NUTRITION

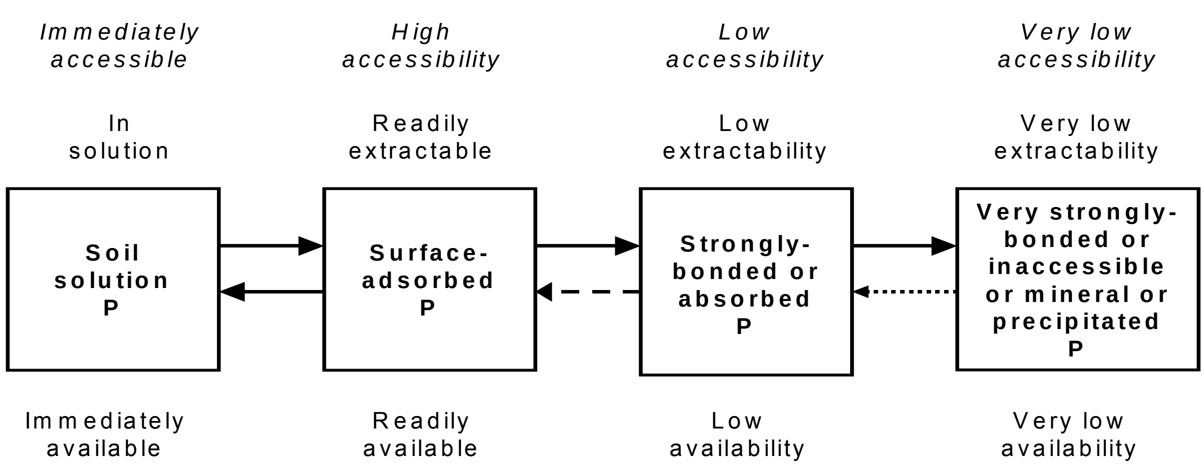
Phosphorus is an essential element for all living organisms. It has a vital role in many essential processes occurring in plants and animals and in these roles it cannot be replaced by any other element. Consequently there must be an adequate supply of plant-available phosphorus in soil if crops are to produce economically viable yields whether the crop is required for food, feed, fuel, fibre or bioenergy. Plant roots take up phosphorus from the soil solution as an orthophosphate ion, principally $H_2PO_4^-$ and to a lesser extent HPO_4^{2-}. The concentration of phosphorus in the soil solution is very small. A soil well supplied with phosphorus and containing 6 cm of water in the top 30cm will have less than 0.2 kg P/ha in the soil solution to that depth. If the crop uses 37cm of water during its growth there will only be about 1 kg P/ha dissolved in the soil solution, yet, to give an acceptable yield the crop will have to acquire 20-40 kg P/ha. Thus, the soil must contain a supply of phosphorus that readily replenishes the phosphorus in the soil solution. The Olsen and resin methods adequately quantify this source of phosphorus (see Appendix A).

A number of other factors, however, can have a major impact on the availability of soil phosphorus for its uptake by roots. Principle among these factors is soil structure. Maintaining a good soil structure has many benefits in terms of nutrient and water availability (see Appendix D). Plant roots take up nutrients from the soil solution. Thus, there has to be a continuous film of water on soil particles through which nutrients can move to reach roots and/or roots have to move towards nutrients. Phosphorus ions, $H_2PO_4^-$ and HPO_4^{2-}, move only very slowly in the soil solution; estimates suggest that $H_2PO_4^-$ ions move only about 0.13mm a day. This movement is driven by the root taking up phosphorus, lowering its concentration at the root surface and a fresh supply of phosphorus then moving towards the root from a source where the concentration is higher. The slow rate of movement of phosphate ions has two consequences. First, roots have to move towards a source of this nutrient, hence the need for a good soil structure. Second, there needs to be a sufficient supply of plant-available phosphorus throughout much of the topsoil being explored by roots; estimates suggest that annual crops rarely explore more than 25% of the top soil in any growing season to find the nutrients they require. Hence the need to maintain a good soil structure and soil at an appropriate P Index.

APPENDIX C: CURRENT CONCEPTS ABOUT THE BEHAVIOUR OF PHOSPHORUS IN SOIL

For a long time it was considered that any residue of phosphorus added to soil in a fertilizer or manure was irreversibly fixed in soil and was unavailable for uptake by subsequent crops. This view is no longer tenable. Syers *et al*. (2008) reconciled recent changes in understanding about the behaviour of phosphorus in soil with the response of crops to soil and fertilizer phosphorus. These authors further developed a concept proposed by Johnston (2001) and Johnston *et al*. (2001) in which soil phosphorus is defined in relation to its availability for uptake by crops and its extractability by reagents used for routine soil analysis. This concept operationally defines inorganic phosphorus in soil as existing in four pools (Appendix Figure 1). Phosphorus in the soil solution and the readily available pool is the phosphorus immediately available for uptake by plant roots and is the phosphorus determined by routine soil analysis. Phosphorus in the third, less readily available pool is not immediately available for uptake but can become available as crop demand for phosphorus increases. The fourth pool of phosphorus is only very slowly available and can be discounted for practical purposes.

The concept of soil phosphorus behaviour discussed here envisages that most of the plant-available phosphorus in the second and third pools is held by adsorption reactions on soil particles and soil organic matter and by absorption within soil constituents. The strength of the bonding between the negatively charged phosphorus ion and positively charged sites on soil constituents varies. Consequently, different reagents used in routine soil analysis will extract different amounts of phosphorus depending on “the energy they exert” to break the bond holding a phosphorus ion to a soil constituent. However, this does not matter provided that the amount of phosphorus extracted satisfactorily characterises the plant-available phosphorus status of a soil. In England, Wales and Northern Ireland, Olsen’s method does this satisfactorily.



Appendix Figure 1. Conceptual diagram for the forms of inorganic P in soils categorized in terms of accessibility, extractability and plant availability.

The important feature illustrated in Appendix Figure 1 is the reversible transfer of phosphorus, particularly between the first three pools and this is a major change in understanding the behaviour of soil phosphorus. Evidence from field experiments for the reversible transfer of phosphorus between the first three pools is given in Section 3.5 and further evidence was given by Johnston (2001), Johnston *et al*. (2001) and Syers *et al.* (2008). Much of the phosphorus added to soil in water-soluble phosphate fertilizers and the water-soluble fraction of phosphorus in organic manures transfers rapidly to the less readily available pool.

APPENDIX D: IMPORTANCE OF SOIL STRUCTURE AND MAINTAINING OLSEN P FOR A ROTATION OF ARABLE CROPS

Importance of soil structure

For a crop to achieve its optimum yield it has to take up adequate amounts of nutrients and water from the soil. The combination of good soil structure and adequate water supply is crucial to producing optimum crop yields. To acquire nutrients and water the roots of annual arable crops have to explore the largest possible volume of soil in the shortest possible time, especially spring sown crops. At best, roots may explore little more than 25% of the topsoil in one growing season and for them to do this effectively the soil must have a good structure. When the volume of soil that can be explored by roots is restricted because of poor structure, especially when the soil is compacted, the opportunity for roots to take up nutrients and water is limited. Soils that have a poor structure must contain more Olsen P to achieve satisfactory yields.

In the Agdell experiment on the silty clay loam at Rothamsted modifications to the treatments gave, by 1969, two groups of soils with 1.5 and 2.4% SOM, respectively, and a wide range of Olsen P at both levels of SOM (see 3.3.2.). In 1970-72, spring barley, potatoes and sugar beet were each grown twice and the 2-year mean yield of barley grain, potato tubers and sugar (from sugar beet) was related to Olsen P and the yield at 95% of the maximum and its associated Olsen P were determined. Barley yield on the soil with less SOM was about 0.5 t/ha less than on soil with more SOM but tuber and sugar yields were about the same on both soils (Appendix Table 1). However, very much less Olsen P was required to achieve 95% of the maximum yield on the soil with more SOM (Appendix Table 2). The soils were sampled in 1972 and after grinding to 5mm, they were each cropped with ryegrass under uniform conditions in the glasshouse. The grass was harvested four times and the total yield of dry grass related to Olsen P. The maximum yield from the fitted response curve was the same on both soils and the Olsen P needed to achieve this yield was the same (Appendix Table 1). Thus, when the constraints to growth experienced by the crop growing in the field on soil with too little SOM were removed then the response by grass to Olsen P was the same (Johnston and Poulton, 1992).

Three other experiments which show benefits from extra organic matter in soil can be mentioned. On the silty clay loam on the Hoosfield Continuous Barley experiment average grain yields of c.v. Cooper given 144 kg N/ha annually were 4.61 and 7.35 t/ha on soils with 1.7 and 6.3 % SOM, respectively, in 2004-2007 (Johnston *et al*., 2009).

Data from two experiments on the sandy loam soil at Woburn (Appendix Table 2) can be combined to show the benefit of SOM in the presence of adequate Olsen P (Johnston and Poulton, 1992).

Appendix Table 1. The effect of soil organic matter on yield responses to Olsen P, Agdell, Rothamsted.

Crop	Soil organic matter %	Maximum fitted yield t/ha	Olsen P associated with 95% max. Yield mg/kg	Variance accounted for, %
	Field experiment			
Spring barley grain, t/ha	2.4	5.26	16	83
	1.5	4.69	45	46
Potatoes tubers, t/ha	2.4	47.1	17	89
	1.5	46.5	61	72
Sugar beet sugar, t/ha	2.4	6.92	18	87
	1.5	6.91	32	61
	Pot experiment			
Grass, dry matter, g/pot	2.4	6.80*	23	96
	1.5	6.85	25	82

* The response curves at the two levels of SOM were not visually different.

Appendix Table 2. Effect of soil organic matter on the yields of spring barley, potato tubers and sugar (from sugar beet) on sandy loam soil at Woburn.

	SOM, %			
	1.18	1.87	2.49	3.15
Spring barley, grain, t/ha	3.72	4.93	5.15	5.23
Potato tubers, t/ha	38.7	45.0	51.4	58.2
Sugar, t/ha	6.00	6.72	8.24	8.15

Maintaining Olsen P for a rotation of crops

Appendix Table 1 shows that on a soil with 2.4% SOM, and thus an acceptable structure for this soil type, the critical Olsen P associated with 95% of the maximum yield was no different for spring barley than it was for potatoes and sugar beet, namely 16-18 mg/kg. These three crops were also grown for six years in the Saxmundham experiment (Johnston *et al*., 1986). For all crops the maximum yield was determined from the yield/Olsen P relationship together with the Olsen P associated with 98% of the maximum yield (Appendix Table 3). Both yield and associated Olsen P varied from year to year but there was no direct relationship between the two; i.e. large yields were not associated with high levels of Olsen P and *vice versa.* Seemingly, yield varied more with rainfall in the growing season and perhaps also with the quality of the seedbed prepared in spring.

Appendix Table 3 shows that to achieve 98% of the maximum yield the range in Olsen P was 8-26 mg/kg for spring barley and 14-30 mg/kg for sugar from sugar beet. For potatoes it was 11-19 mg/kg in four out of the six years and 46 and 53 mg/kg in the other two years.

These results on these soils confirm the view that spring barley requires the same level of Olsen P as potatoes and sugar beet to ensure optimum yields in all years.

Appendix Table 3. Fitted maximum yields of three arable crops and the associated critical Olsen P at 98% maximum yield, Saxmundham, Suffolk.

Harvest year	N applied kg/ha	Fitted maximum yield and its standard error		Olsen P at 98% maximum yield and its s.e.		Variance accounted for
		t/ha	s.e.	mg/kg	s.e.	%
Potato tubers, t/ha						
1969	250	39.6	0.70	11	1.8	84
1970	250	29.4	1.35	46	9.7	92
1971	250	51.6	1.42	19	6.2	81
1972	250	42.3	0.88	14	3.5	81
1973	250	41.3	1.67	13	7.8	66
1974	250	54.7	2.87	53	11.8	97
Sugar, from sugar beet, t/ha						
1969	190	8.93	0.137	20	1.8	97
1970	190	4.02	0.335	30	13.7	61
1971	190	7.59	0.155	19	3.9	90
1972	190	6.38	0.173	28	5.9	91
1973	190	8.39	0.128	14	1.2	99
1974	190	4.79	0.856	excluded*		
Barley after potatoes, grain, t/ha						
1970	125	4.69	0.068	17	3.5	88
1971	125	4.95	0.083	24	3.9	93
1972	100	5.72	0.113	8	1.6	79
1973	100	4.27	0.504	excluded*		
1974	80	5.44	0.201	15	13.6	48
1975	80	5.39	0.074	17	3.8	95
Barley after sugar beet, grain, t/ha						
1970	125	4.38	0.086	26	5.5	91
1971	125	4.69	0.090	19	2.5	93
1972	100	5.73	0.106	14	3.4	83
1973	100	5.22	0.068	8	1.0	95
1974	80	5.21	0.097	25	4.5	97
1975	80	excluded*				

* excluded – the standard error of the yield and/or Olsen P was unacceptably large.