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Identification of critical soil phosphate (P) levels for cereal and oilseed rape crops on a range of soil types

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1. Abstract

Current advice for arable crop rotations is to maintain soils at P Index 2 (16–25 mg/l Olsen P) (Defra, 2010). This is considered the level of plant-available soil P needed to achieve optimum yields of arable crops in most years and to ensure that other agronomic inputs, especially nitrogen (N), are used effectively. This recommendation is based on results of many field experiments conducted by many organisations (see for example HGCA Research Review 18). Where soils are maintained at below the critical level, yield potential will be reduced with a risk of lower profitability and nitrogen fertiliser use efficiency. Previous research has indicated that even a large amount of fresh P fertiliser added to a P-deficient soil will not give yields equal to those on a P-sufficient soil. Where soils are maintained above the critical level, there will be little yield benefit and there is a potential environmental cost. Rising phosphate fertiliser prices and concerns about scarcity of supply have led some growers to question whether or not current recommendations are appropriate for all soil types, arable rotations and crop conditions, and many have asked if arable soils can be maintained at a P Index of less than 2 without risk of yield loss.

This project was in two parts. 1. A review of field experiments from 1969 to 2008 on specific silty clay loam and sandy clay loam soils (HGCA Research Review 74). 2. A series of new experiments on six sites with low Olsen P levels, representing soil types on which cereals and oilseed rape are widely grown, but for which critical P levels had not been determined specifically. The soils chosen were deep clays, loams and shallow soils over limestone or chalk. Field experiments were established at each site in autumn 2009 and continued in the same place for four cropping years. Winter wheat, oilseed rape or spring barley were grown following the host farmer's rotation. Large plots were created and varying rates of phosphate fertiliser applied to create a range of Olsen P levels from P Index 0 to P Index 3. No further P fertiliser was applied to any plot in the first two years. Measured grain or seed yields were related to Olsen P levels. For the third and fourth years, each large plot was split into three sub plots, two of which continued to receive no P fertiliser. The third sub plot received fresh P fertiliser prior to cultivation and sowing in the autumns of 2011 and 2012 to test the response of the crop grown to fresh P at each level of Olsen P.

Results over four cropping years generally supported current advice, namely to maintain soils growing cereals and oilseed rape at P Index 2. In the few cases where 98% of maximum yield was only achieved on soils with more than 25 mg/kg Olsen P, it would not be justified economically to increase Olsen P above 25 mg/kg to achieve these yields. There were differences between sites and crops or years in the responsiveness of yield to Olsen P, but these could not obviously be related to soil conditions or other factors. Extremes of weather experienced during the project mean that further cropping years are required before more robust advice can be given about maintaining a certain level of Olsen P on a specific soil type. Three of the sites are now continuing within a new HGCA project that will provide more information on year to year variation. At Index 0,

even a large application of fresh P fertiliser did not raise wheat yields to those achieved at Index 2. However, at P Index 1 a large application of P did increase yields to those achieved at P Index 2. This suggests that there may be the potential to manage annual P applications to achieve optimum yield where soil is at P Index 1 but further work is needed to determine the amount and method of applying the P that is needed. The amount of P fertiliser required to increase Olsen P by a given amount varied between sites, however, on average, the proportion (17%) of applied P that remained as Olsen P was similar to that (13-15%) found in other experiments. The proportion was highest on the heavy clay at Peldon and lowest on the shallow limestone soil at Cirencester. The Cirencester site required three times as much P fertiliser as Peldon in order to raise the soil P level by one Index, and at this site it was not possible to consistently maintain the soil at P Index 2 as recommended for arable rotations. An alternative approach could be to use an organic P source, although the likely effectiveness would require further investigation.

2. Introduction

2.1. Background

Over the five year period from 2008 to 2012, overall annual use of phosphate fertiliser (P_2O_5) on winter wheat, spring barley and oilseed rape averaged 25, 33 and 26 kg P_2O_5/ha, respectively (Defra, 2013); a substantial decline from comparable data for the period 1983–1987 when the applications to winter wheat, spring barley and oilseed rape were 55, 42 and 61 kg P_2O_5/ha, respectively. Overall, phosphate use on wheat, barley and oilseed rape in 2009 was the lowest ever recorded by the British Survey of Fertiliser Practice (an average of 22 kg/ha). This decrease was largely the result of a decline in the proportion of crops being treated rather than a reduction in the amount of phosphate applied to fields receiving phosphate, which over the period from 2008 to 2012 averaged 59, 49 and 58 kg/ha for winter wheat, spring barley and oilseed rape, respectively. Considering only the quantities of inorganic phosphate fertilisers applied to arable crops there has been a negative phosphorus (P) balance since 1995. Recent surveys of soil samples tested indicate that some soils are well supplied with P, whereas others have too little.

Crop yields increase, rapidly at first and then more slowly, as the amount of plant-available P in soil increases from a very low level (highly deficient) to a level at which a maximum yield is reached (Figure 1). The level of readily plant-available P required to achieve near maximum yield represents the 'critical level' for that crop grown on that soil in that cropping system. In England, Wales and Northern Ireland the main test used to determine plant-available P is Olsen's method (Olsen *et al.*, 1954); an alternative, especially in Scotland, is Resin P (Hislop and Cooke, 1968). For these experiments Olsen P was determined at Rothamsted where each batch of samples analysed included an internal standard containing 11.6 mg P/kg with a standard error of +/- 0.58 mg/kg.

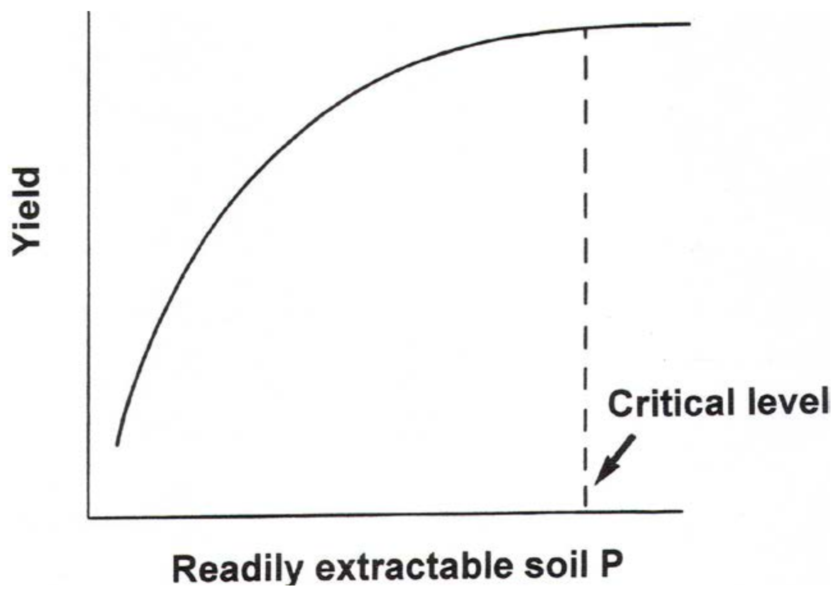

Figure 1. Relationship between readily extractable (plant-available) soil P and crop yield

Current advice for arable and forage crop rotations in the 8th Edition of the Fertiliser Manual 'RB209' (Defra, 2010) is to maintain soils at a target P Index of 2, or 16–25 mg/litre Olsen P (see Appendix 1). This is considered to be the level of plant-available soil P needed to achieve optimum yields of most arable crops, including cereals and oilseeds, grown in rotation in most years. A larger application of phosphate is recommended for soils at P Index 0 than at P Index 1 to increase yields and also raise the level of soil P towards P Index 2. RB209 also recommends that soil is maintained at P Index 2 by replacing the P removed in the harvested crop.

The current target P Index for arable and forage crop rotations indicated in RB209 is based on the results of field experiments, many of which were reviewed in HGCA Research Review 16 (Arnold and Shepherd, 1990). It indicates the range of Olsen P levels at which crop yield approaches the maximum (Figure 1). In their recent review of past and current field experiments as part of this project (see section 2.3), Johnston and Poulton (2011) identified the critical level of Olsen P associated with obtaining 98% of maximum yield.

Where soils are maintained at below the critical level of soil P, yield potential will be reduced and there is a risk of lower profitability and nitrogen (N) fertiliser use efficiency. Previous research has indicated that even a large amount of fresh P fertiliser added to a P-deficient soil will typically not give yields equal to those on a P-sufficient soil in the short-term. This is because it is not possible to uniformly mix added P fertiliser in soil, and the phosphate ion, $H_2PO_4^-$, the form of P added in water-soluble P fertilisers and taken up by plant roots, only moves about 0.13mm per day by diffusion through the soil. Thus the root has to grow to find the freshly added P which is poorly distributed within the soil volume explored by roots. Equally, where soils are maintained above the critical level, there will be little or no yield benefit to justify the cost of the fertiliser, and there is a potential environmental cost if soil that is high in P is eroded into water courses.

Many of the field experiments on which the phosphate recommendations are based were on a limited range of soil types, mostly silty clay loam and sandy clay loam soils, whereas cereals and oilseeds are grown over a wider range of soil textures and depths. Although, for a given Olsen P value, the crop availability of P per unit volume of soil should be the same regardless of the crop and soil type (except perhaps on acid soils or for permanent grassland), critical P values can vary between soils and years, depending on weather and soil factors such as soil structure, moisture, bulk density, porosity and stone content. Critical P values will also depend on the crop grown, on root growth or architecture and the rate of P uptake needed for maximum yield. To date there have not been sufficient data available to warrant changing the recommendations. However, rising phosphate fertiliser prices and concerns about scarcity of supply have led some growers to question whether or not current recommendations are appropriate for all soil types, arable rotations and crop conditions. In particular, many have asked if arable soils can be maintained at a P Index of less than 2 (below 16–25 mg/kg) without risk of yield loss.

2.2. Aim and objectives

2.2.1. Aim

Identify critical soil P levels for cereal and oilseed rape crops on different soils.

2.2.2. Objectives

1) Review existing knowledge on critical soil P levels for cereals and oilseed rape and thus identify soil types and crop situations where data are lacking.
2) Determine critical soil P levels for cereals and oilseed rape on soils where data are not currently available.
3) Examine the influence of soil and crop factors on critical soil P levels and on crop responses to P fertiliser at different soil P levels.

The outputs from the project will be used to update phosphate recommendations for cereals and oilseed rape in future editions of the Fertiliser Manual 'RB209'.

2.3. Review of existing knowledge

Findings from the review of existing knowledge on the response of cereal crops to soil and fertiliser P were reported in HGCA Research Review 74 (Johnston and Poulton, 2011). There was insufficient information available to include oilseed rape. Data were reviewed on the response of winter wheat and spring barley to Olsen P by 102 crops from 1969 to 2008 grown on three contrasting soils, each with a wide range of Olsen P levels. From the yield / Olsen P response curve, the maximum yield of cereal grown each year and the critical P level associated with 98% of maximum yield were determined. Maximum yield varied greatly from year to year and was achieved on soils with Olsen P levels ranging from P Index 0 to P Index 4.

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 of 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 of 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 very poor structure, 40–52 mg/kg Olsen P was needed to achieve maximum yield.

Year to year variation in maximum yield was attributed to weather, mainly rainfall, and the length of the grain fill period. Year to year variation in critical Olsen P on each soil was considered to reflect differences in soil and seedbed conditions and the way they interacted with weather factors. The results highlight the importance of maintaining a good soil structure and using appropriate, timely, cultivations such that roots can readily access soil nutrients to achieve maximum yield. For both cereals the wide range in Olsen P levels at which maximum yield was reached on all three soil types underline the difficulties in providing Olsen P recommendations that are specific to soil type. When the average Olsen P level at which maximum yield was achieved was calculated the result confirmed the existing recommendation that most fields should be maintained at P Index 2 for cereals to ensure that maximum yield is achieved in most years and to allow for in-field variation in Olsen P.

The review also considered two frequently asked questions: i) how much phosphate fertiliser must be added to increase Olsen P, and ii) how quickly will Olsen P decline if no phosphate fertiliser is applied. The former depends on the difference between the amount of phosphate applied and the amount removed in harvested crops. When the ‘P balance’ is positive, Olsen P increases, and when the ‘P balance’ is negative it decreases. Large amounts of phosphate were required to build up Olsen P. To increase Olsen P from the mid-point of P Index 1 (12 mg/kg) to the mid-point of Index 2 (20 mg/kg) required 300–330 kg/ha P_2O_5 (as 670–750 kg/ha triple superphosphate, TSP). Similarly, decline in Olsen P will depend on the size of the negative P balance. Where large crops were grown and no phosphate fertiliser was applied, Olsen P declined rapidly; from the mid-point of P Index 2 to Index 1 in six years.

3. Materials and methods for new field experiments

3.1. Overview

To augment the results of the review six sites with low Olsen P levels (15 mg/l or less, Index 0 or 1) were identified, representing soil types on which cereals and oilseed rape are widely grown but for which critical Olsen P levels had not been determined specifically. The six sites were on deep clay soils, loams and shallow soils over limestone or chalk. Field experiments were established on each site in autumn 2009 and were continued on the same plots for four successive cropping years (2009/10, 2010/11, 2011/12 and 2012/13). A range of combinable crops (mainly winter wheat, oilseed rape and spring barley) were grown following the farmer's normal rotation. In autumn 2009, 18 large plots were established and varying amounts of triple superphosphate (TSP) were applied to some of these to create a range of Olsen P levels in each experiment. The target range of Olsen P levels, once the Olsen P levels had equilibrated, was from Index 0 or low Index 1 (10 mg/l or less) to Index 3 (26–45 mg/l). No further P fertiliser was applied to any plots in the first two cropping years, and grain or seed yields were related to Olsen P measured in that year. For the third and fourth years, each large plot was split into three sub plots, two of which continued to receive no P fertiliser. The third sub plot received fresh P fertiliser prior to cultivation and sowing in autumn 2011 and again in autumn 2012 to measure the response of the crop grown to the freshly applied P, and maintain the Olsen P level.

3.2. Site details, cultivation method, cropping and agronomy

Soil series and texture, cropping, primary cultivation method and depth and sowing date for each of the six experiments are shown in Tables 1 to 6. Soil pH, % organic matter and extractable calcium (Ca) content were measured on soil samples sent to a commercial laboratory, and tested by potentiometric titration, loss on ignition and atomic absorption spectrophotometry respectively.

Previous cropping and manure history are recorded in Appendix 2, Table 2. Soil potash (K) and magnesium (Mg) levels are recorded in Appendix 2, Table 3. Experiments were positioned in an area of uniform soil type, previous management and yield potential. Plots had to be located precisely every time, following primary cultivations and drilling of each new crop. The position and orientation of the experiment areas were accurately recorded relative to field edges and other suitable reference points, with permanent maker posts located on the field edge to enable boundaries and corners to be checked and remarked following cultivation and drilling. With the exception of P fertiliser, crop inputs were managed by the host farmer following best local practice for the crop. This included a comprehensive crop protection programme to minimise yield losses due to pests, weeds or diseases and prevention of lodging, plus normal nitrogen (N) and (where necessary) K or Mg fertiliser treatments. Signs were placed by the experiments to remind farm operators that no P-containing fertilisers were to be applied. Sites were closely monitored and any site or agronomic factors (*e.g.* crop damage, pest, weed or disease problems, waterlogging, erosion, lodging or uneven N application) that may have adversely affected yields were recorded.

Site 1: Peldon, Essex

Soil series: Windsor　　　　　　　　Soil texture: Deep clay

Table 1. Cropping, primary cultivation method and depth, sowing date, soil pH and % organic matter content for the Peldon site (2008/09 = prior year, 2009/10 to 2012/13 = experiment years)

Crop year	2008/09	2009/10	2010/11	2011/12	2012/13
Cropping	Cont. wheat	Cont. wheat	Cont. wheat	Cont. wheat	Cont. Wheat
Primary cultivation	Plough	Plough	Plough	Non-inversion	Plough
Cultivation depth	25 cm	25 cm	25 cm	20 cm	25 cm
Date sown	-	22/09/09	12/10/10	24/09/11	15/10/12
Soil pH	7.4	-	7.3	7.2	-
Extractable Ca mg/l	-	-	3018	-	-
Organic Matter %	-	-	-	3.9	-

Site 2: Weston, Suffolk

Soil series: Ragdale　　　　　　　　Soil texture: Chalky clay loam

Table 2. Cropping, primary cultivation method and depth, sowing date, soil pH and % organic matter content for the Weston site (2008/09 = prior year, 2009/10 to 2012/13 = experiment years)

Crop year	2008/09	2009/10	2010/11	2011/12	2012/13
Cropping	Spring Beans	First wheat	Spring Beans	First wheat	Oilseed rape
Primary cultivation	Non-inversion	Non-inversion	Non-inversion	Non-inversion	Non-inversion
Cultivation depth	15 cm	15 cm	15 cm	15 cm	15 cm
Date sown	-	29/09/09	18/03/11	07/09/11	25/08/12
Soil pH	7.5	-	7.4	7.3	-
Extractable Ca mg/l	-	-	2392	-	-
Organic Matter %		-	-	3.0	-

Site 3: Great Carlton, Lincolnshire

Soil series: Holderness   Soil texture: Fine loam

Table 3. Cropping, primary cultivation method and depth, sowing date, soil pH and % organic matter content for the Great Carlton site (2008/09 = prior year, 2009/10 to 2012/13 = experiment years)

Crop Year	2008/09	2009/10	2010/11	2011/12	2012/13
Cropping	First wheat	Oilseed rape	First wheat	Second wheat	Fallow*
Primary cultivation	Plough	Plough	Plough	Plough	Non-inversion
Cultivation depth	22 cm	22 cm	22 cm	22 cm	22 cm
Date sown	-	05/09/09	04/10/10	26/09/11	13/09/12
Soil pH	6.9	-	-	6.2	6.2
Extractable Ca mg/l	-	-	-	-	2368
Organic Matter %	-	-	-	1.6	-

* Winter oilseed rape crop failed due to adverse weather conditions.

Site 4: Caythorpe, Lincolnshire

Soil series: Quorndon (Blackwood assoc.)   Soil texture: Sandy loam

Table 4. Cropping, primary cultivation method and depth, sowing date, soil pH and % organic matter content for the Caythorpe site (2008/09 = prior year, 2009/10 to 2012/13 = experiment years)

Crop year	2008/09	2009/10	2010/11	2011/12	2012/13
Cropping	First wheat	Second wheat	Third wheat	Fourth wheat	Spring barley
Primary cultivation	Plough	Plough	Plough	Plough	Plough
Cultivation depth	22 cm	22 cm	22 cm	22 cm	22 cm
Date sown	-	05/10/09	12/10/10	04/10/11	27/02/13
Soil pH	6.5	-	-	6.6	5.6
Extractable Ca mg/l	-	-	-	-	1451
Organic Matter %	-	-	-	2.6	-

Site 5: Cirencester, Gloucestershire

Soil series: Sherbourne   Soil texture: Silty clay loam over limestone

Table 5. Cropping, primary cultivation method and depth, sowing date, soil pH and % organic matter content for the Cirencester site (2008/09 = prior year, 2009/10 to 2012/13 = experiment years)

Crop year	2008/09	2009/10	2010/11	2011/12	2012/13
Cropping	Oilseed rape	Spring barley	Oilseed rape	First wheat	Spring barley
Primary cultivation	Non-inversion	Plough	Non-inversion	Non-inversion	Non-inversion
Cultivation depth	15 cm	15 cm	15 cm	15 cm	15 cm
Date sown	-	09/03/10	30/08/10	17/09/11	01/04/13
Soil pH	7.6	-	7.6	8.1	-
Extractable Ca mg/l	-	-	4810	-	-
Organic Matter %	-	-	-	5.3	-

Site 6: Cholsey, Oxfordshire

Soil series: Coombe 2 Soil texture: Silt loam over chalk

Table 6. Cropping, primary cultivation method and depth, sowing date, soil pH and % organic matter content for the Cholsey site (2008/09 = prior year, 2009/10 to 2012/13 = experiment years)

Crop year	2008/09	2009/10	2010/11	2011/12	2012/13
Cropping	First wheat	Second wheat	Third wheat	Oilseed rape	First wheat
Primary cultivation	Plough	Plough	Plough	Plough	Plough
Cultivation depth	20 cm	20 cm	20 cm	20 cm	20 cm
Date sown	-	16/10/09	14/10/10	30/08/11	14/10/12
Soil pH	7.6	-	7.8	7.8	-
Extractable Ca mg/l	-	-	4559	-	-
Organic Matter %	-	-	-	3.1	-

3.3. Plot size, experiment layout and design

The 18 large plots measured 18m wide x 10m long and were perpendicular to the normal direction of sowing and application of other fertilisers and agrochemicals, with 4m wide buffer areas between plots and 2m discard strips at the top and bottom of each plot (in which spray tramlines were located). The experiment area was then surrounded by a 24m wide guard area to protect the plots from P fertiliser applied to the rest of the field (Figure 2). Phosphate treatments were not replicated because the aim was to measure yield response to the 18 individual Olsen P values at each site.

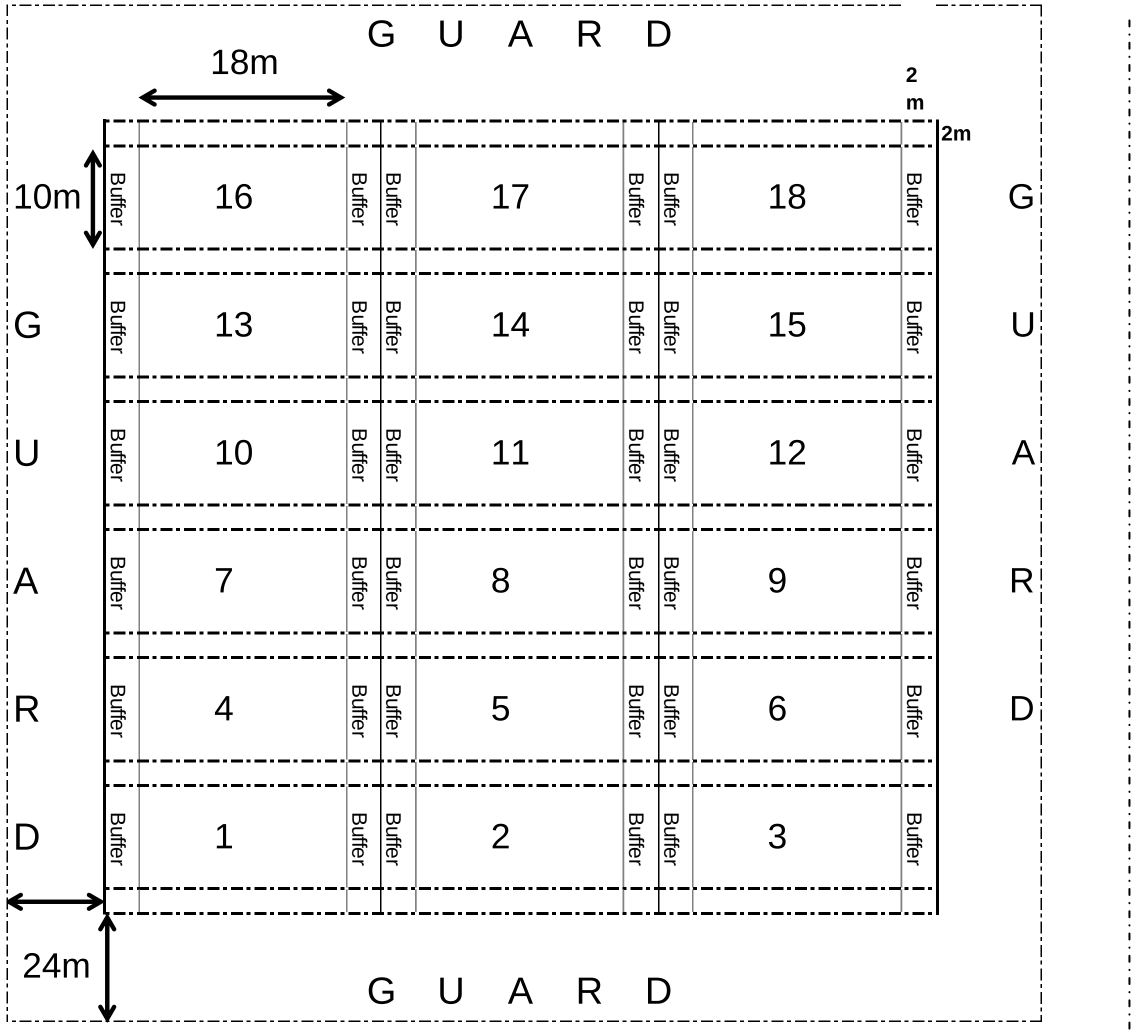

Figure 2. Plot size and experiment layout for the first (2009/10) and second (2010/11) years

For the third and fourth years, starting in autumn 2011, each of the eighteen large plots was split widthways into three 6m wide sub plots (Figure 3, ‘a’, ‘b’ and ‘c’), with fresh P fertiliser treatments applied cumulatively to one of the three sub plots (always ‘a’ or ‘c’ to enable application by machine without the need for excessive wheelings). Two sub plots in each large plot remained untreated with P fertiliser after autumn 2009.

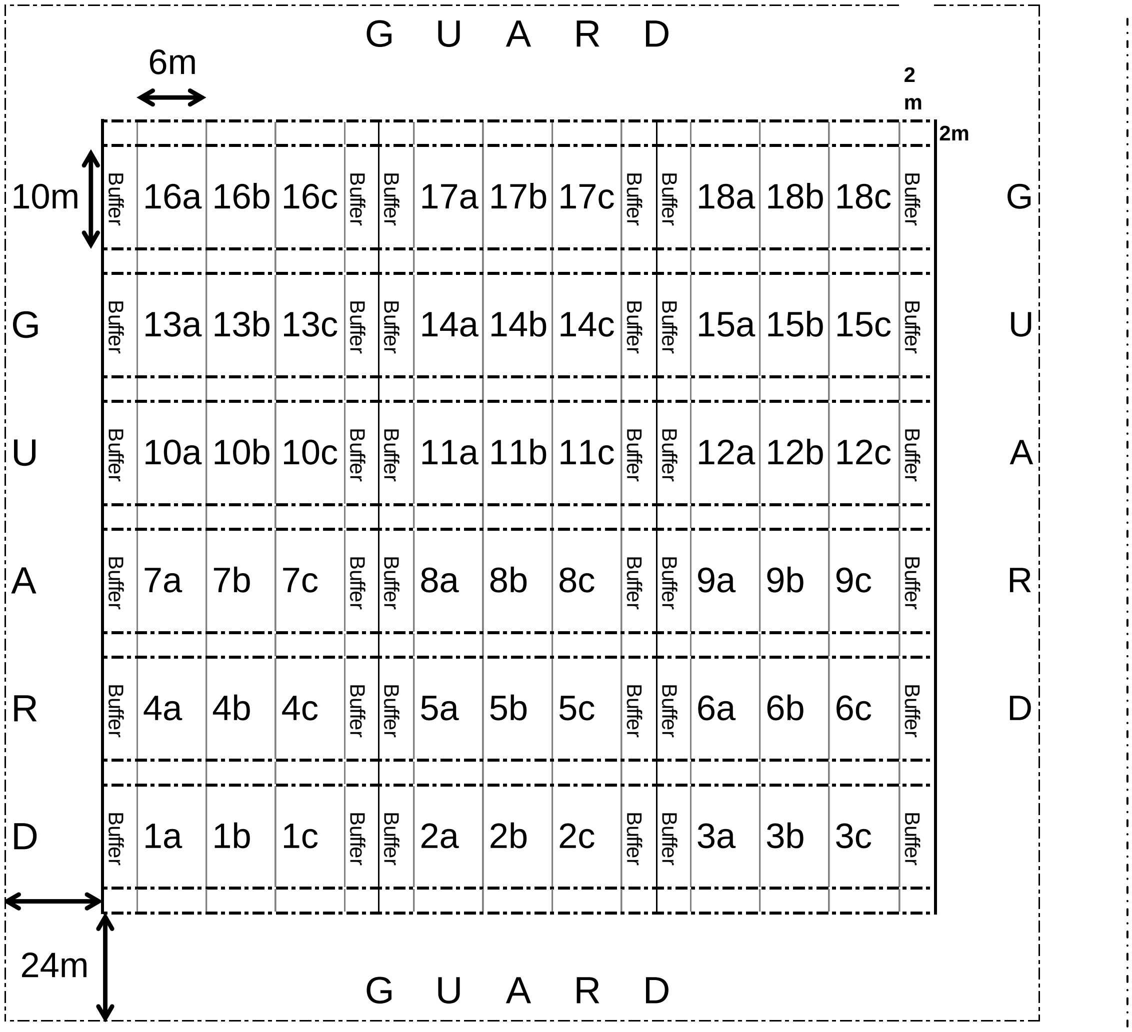

Figure 3. Plot size and experiment layout for the third (2011/12) and fourth (2012/13) years

3.4. P treatments

3.4.1. P treatment structure

The P treatments were not applied at random because, in each experiment, the aim was to increase the level of Olsen P on each individual plot to achieve a range of Olsen P levels from 10 mg/kg or less to 25 mg/kg or more to enable a yield/Olsen P response curve to be plotted. Consequently, in autumn 2009, each of the 18 large plots received one of nine P fertiliser treatments ranging from none (untreated) to an amount of phosphate intended to increase Olsen P by 24 mg/kg. The number of plots receiving each treatment (Table 7) varied at each site depending on the range of Olsen P levels that already existed (see section 4.2.1). No fresh P fertiliser treatments were applied in autumn 2010 to any plot at any site. In autumn 2011 and autumn 2012, a fresh P fertiliser treatment was applied to one of the 3 sub plots created within each large plot, but at a fixed rate across all sites.

Table 7. Number of plots at each site receiving each P fertiliser treatment in autumn 2009

Target increase in Olsen P (mg/kg)	0	1	2	3	6	9	13	18	24	Total Plots
	Number of plots receiving treatment to achieve above increase									
Peldon	8	2	0	1	2	1	3	1	0	18
Weston	4	0	0	4	2	2	2	2	2	18
Great Carlton	8	0	0	2	2	2	2	2	0	18
Caythorpe	8	3	0	0	2	2	2	1	0	18
Cirencester	8	1	0	3	0	2	1	2	1	18
Cholsey	6	0	2	2	1	1	2	2	2	18

3.4.2. P treatment application rates and method

Estimated amounts of TSP fertiliser required per plot in autumn 2009 were calculated for each site to achieve the target increases in Olsen P. The calculation took into account the weight of soil to be treated (based on cultivation depth and bulk density adjusted for stone content) and assumed that 15% of the P applied would remain plant–available as Olsen P after the added P had equilibrated with the existing soil P. This assumption was based on the findings from previous field experiments, as reported in HGCA Research Review 74 (Johnston and Poulton, 2011). The amount of TSP (containing 46% P_2O_5) required was calculated by multiplying the P required by 2.2915. The estimates of the amount of TSP needed to achieve a 1 mg/kg increase in Olsen P are shown in Table 8.

For the autumn 2011 and 2012 fresh P treatments, a fixed rate of 200 kg/ha P_2O_5 (435 kg/ha TSP) was applied at all sites. A high rate was used in order to test the assertion that no amount of fresh P fertiliser could give the same yield as that achievable by maintaining an Olsen P Index of 2.

Table 8. Estimated amounts of TSP needed to achieve each 1 mg/kg increase in Olsen P

	Cultivation depth (m)	Bulk density adjusted for stone content (g/cm^3)	Soil weight (Mkg/ha)	Increase in Olsen P (kg/ha)	Amount of P required (kg/ha)	Amount of P_2O_5 required (kg/ha)	Amount of TSP required (kg/ha)
Peldon	0.25	1.33	3.33	3.33	22.2	50.8	110.4
Weston	0.15	1.37	2.06	2.06	13.7	31.4	68.2
Great Carlton	0.22	1.37	3.01	3.01	20.1	46.0	100.1
Caythorpe	0.22	1.48	3.26	3.26	21.7	49.7	108.1
Cirencester	0.15	1.23	1.85	1.85	12.3	28.2	61.3
Cholsey	0.20	1.33	2.66	2.66	17.7	40.6	88.3

The treatments were applied using a 12m wide tractor-mounted pneumatic fertiliser spreader, accurately calibrated to deliver the required dose of TSP in one or more passes, or a self-propelled purpose-built plot fertiliser spreader delivering an exact quantity of TSP to each plot.

3.4.3. P treatment application timings

In autumn 2009, P fertiliser applications were split in half due to the large amounts to be applied to some plots. First splits were applied before primary cultivation and second splits before secondary cultivation or drilling (see Table 9 for application dates). As the first crop at the Cirencester site was spring barley, the second split was not applied until early spring. In autumn 2011 and autumn 2012, the fresh P top-up treatments were applied in one go prior to cultivation and drilling.

Table 9. P fertiliser application dates

Site	2009/10 First split	2009/10 Second split	2011/12 Single dose	2012/13 Single dose
Peldon	27/08/09	22/09/09	01/09/11	14/08/12
Weston	01/09/09	18/09/09	06/09/11	16/08/12
Great Carlton	25/08/09	02/09/09	30/08/11	18/09/12
Caythorpe	26/08/09	07/09/09	08/08/11	14/08/12
Cirencester	25/11/09	03/02/10	14/09/11	11/09/12
Cholsey	28/08/09	07/10/09	29/08/11	18/09/12

3.5. Olsen P analysis

3.5.1. Soil sampling procedure

In 2009, 2010 and 2011 the soil in each of the 18 large plots was sampled for Olsen P while in 2012 and 2013, the 54 sub plots were each sampled separately taking 16 individual soil cores randomly within each large or sub plot, using a gouge auger or similar. Soils were sampled to primary cultivation depth at that site (i.e. 15, 20, 22 or 25cm). The 16 soil cores were bulked together and mixed thoroughly, cutting any lumps into small pieces and removing vegetation and as many stones as possible. Two sub-samples of 1kg each were obtained for each large or sub plot, one for analysis and one to be retained as a back-up. Samples were partially air-dried prior to sending to the laboratory for preparation and analysis.

3.5.2. Timing of sampling for Olsen P

Initial sampling, to obtain baseline Olsen P data, on which to base the amount of P to be applied, took place between May and July 2009 as soon as sites had been confirmed and the plots marked out (Table 10). The target sampling time for subsequent years was March. In 2010, sampling at most sites was delayed slightly due to very cold and wet winter and spring conditions. In 2011, under exceptionally dry soil conditions, sampling at some sites had to be re-scheduled for May or immediately after harvest. After harvest in 2011 deeper soil samples (a 30cm layer below the normal sampling / cultivation depth for each site) were taken from selected plots at each site to determine Olsen P levels below cultivation depth. Based on the results of this exercise, in 2012 and 2013 the Cirencester site was sampled separately at 15–30cm depth in addition to the normal 0–15cm depth.

Table 10. Sampling dates for Olsen P analysis

Site	2009	2010	2011	2012	2013
Peldon	06/05/09	12/05/10	11/04/11	24/04/12	21/02/13
Weston	12/05/09	06/05/10	05/09/11	21/03/12	20/02/13
Great Carlton	13/05/09	23/03/10	01/03/11	19/03/12	14/03/13
Caythorpe	06/05/09	26/03/10	28/02/11	21/02/12	25/04/13
Cirencester	16/06/09	28/05/10	25/07/11	20/04/12	21/03/13
Cholsey	10/07/09	21/05/10	05/04/11	22/03/12	26/03/13

3.5.3. Analysis procedure for Olsen P

After air drying, soil samples were ground to pass through a 2mm screen and Olsen P (Olsen *et al*., 1954) determined at Rothamsted. Soils were analysed on a weight basis, rather than a volume basis (as is more typical for commercial laboratories), and therefore results are expressed as mg P/kg rather than mg P/l. However, for most mineral soils the results expressed either way are very similar.

3.6. Other soil and crop measurements and monitoring

A note of seedbed conditions after drilling was made at each site every year. A spade was used to examine soil structure within the cultivated layer. A more detailed assessment of seedbed quality was performed using the modified Peerlkamp procedure (Ball *et al*., 2007) once at each site in either 2011 or 2013. Where effects on crop growth, colour or health were evident that could be related to treatment or soil P status, a visual assessment was made of their incidence or severity in each plot, and photographs taken of affected and unaffected plots.

3.7. Harvesting and yield determination

Grain or seed yields were determined using a plot combine harvester. In 2010 and 2011 each large plot was divided into three and a full header width cut was harvested from the middle of each third, excluding buffer and discard areas, and an average of the three yields was recorded. In 2012 and 2013, a single full header width cut was harvested from the middle of each of the three sub plots within each large plot, excluding buffer and discard areas and border areas between sub plots and the yield of each sub plot was recorded separately. Each cut was about 10m long x 2m wide, but the exact length and width were used to calculate yield. Grain or seed moisture contents were determined and yields adjusted to 85% dry matter for cereals, 86% for pulses and 91% for oilseed rape. For cereals only, grain specific weight was measured on a sample of grain from each plot and adjusted to 85% dry matter as appropriate. A grain or seed sample of at least 1kg for cereals / pulses or 500g per plot for oilseeds, was also taken from each plot, dried to normal moisture content if harvested wet, and then stored until needed.

After taking the yield cuts, the remaining crop in each plot was harvested without weighing or sampling to clear the site, combining in such a way as to return the chopped straw as evenly as possible to the plot from which it came. The guard area surrounding the experiments was harvested by the host farmer by cutting around the outside of the trial.

3.8. Yield data analysis and curve plotting

For each site, mean grain or seed yields were calculated at each Olsen P level, using the values for each large plot in 2010 and 2011 or for each sub plot in 2012 and 2013. In plots that received large P fertiliser treatments in autumn 2009, Olsen P levels had not fully equilibrated when measured in spring 2010. In 2012 and 2013, yields were calculated separately for the sub plots that had received fresh P fertiliser, and were compared to the mean yield of the two sub plots in the same large plot that had not received fresh P fertiliser. The number of individual values comprising the mean yield at each P Index varied for each experiment. A standard deviation was calculated for yield means comprising two or more individual values.

Response curves were fitted to the yield and Olsen P data from 2011, 2012 and 2013. In 2012 and 2013, response curves were fitted for the 36 Olsen P sub plots and separately for the 18 fresh P sub plots. The form of the asymptotic curve fitted was:

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

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.

Three values were determined from each curve:

- The fitted asymptotic (maximum) grain yield and its standard error (s.e.).
- The percentage variance (variability) in yield accounted for by Olsen P. A percentage variance over 50% indicates that Olsen P was the single most important soil factor affecting yield.
- The concentration of Olsen P and its standard error (s.e.), at which 98% of the fitted maximum yield was reached. This ‘critical level’, at 98% of the fitted maximum yield, was calculated by solving the equation:

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

Standard errors for the fitted maximum yield and critical Olsen P level reflect how well the curve ‘fits’ the data. Where the standard errors of the yield or critical P level are unacceptably large (i.e.

the relationship between yield and Olsen P was very poor), the critical level has been discounted. Due to the shape of the response curve, the higher the percentage of maximum yield targeted, the larger the standard error on the critical P level. At 98% of maximum yield, the yield foregone for a 10 t/ha wheat crop is only 0.2 t/ha, worth £30/ha if wheat is valued at £150/t. Very few growers are likely to accept the increased cost of maintaining the soil at an even higher Olsen P level in order to reduce this even further. At 95% of maximum yield, the yield foregone for a 10 t/ha wheat crop is 0.5 t/ha, worth £75/ha if wheat is valued at £150/t. Very few growers are likely to accept lost output of more than this. For each curve, critical Olsen P levels have been determined for both 95% and 98% of maximum yield.

3.9. P offtake and balance

Average offtakes of P and P_2O_5 in harvested grain or seed, at each Olsen P Index, were calculated for each crop using actual yield data and standard values for grain or seed phosphate content published in the Fertiliser Manual 'RB209' (Defra, 2010), as follows:

Winter wheat and spring barley grain:	0.78% P_2O_5 = 0.34% P
Oilseed rape seed:	1.40% P_2O_5 = 0.61% P
Spring field bean seed:	1.10% P_2O_5 = 0.48% P

For large plots, and sub plots that continued to receive no fresh P that initially had at least 100 kg P/ha in autumn 2009, the overall P balance was calculated from the amount of P added less P offtake in grain or seed. Sub plots that received a fresh P treatment in autumn 2011 and 2012 were excluded. Harvest 2009 yields (prior to application of the 2009 P treatments) were not recorded and therefore 2009 offtake was ignored. The change in Olsen P from 2009 through to spring 2013 was converted from mg/kg to kg/ha based on the weight of soil per hectare (see section 3.4 Table 8), to enable the change in Olsen P to be calculated as a % of the P balance.

3.10. Economic analysis

The cost of raising the initial Olsen P level by one Index (Table 11) was calculated for each site, assuming P cost of £2 per kg (equivalent to a TSP fertiliser price of about £400 per tonne).
For each site the calculations were based on the weight of treated soil per hectare and the actual % of the P fertiliser remaining available (once equilibrated).

Table 11. Increase in Olsen P required to raise P Index by one level

Target change in P Index	Olsen P level (mg/kg)		
	Start (mid-point)	Finish (mid-point)	Increase
0 to 1	4.5	12.5	8.0
1 to 2	12.5	20.5	8.0
2 to 3	20.5	35.5	15.0

The yield increase or decrease obtained by raising the P Index from 0 to 1, 1 to 2 or 2 to 3 was converted to a financial value for each site each year based on the following average crop prices:

Wheat	£150 per tonne
Oilseed rape	£300 per tonne
Spring barley	£150 per tonne
Spring beans	£220 per tonne

At the end of each crop year, the cumulative net cost or benefit of having initially raised the soil from Index 0 to 1, 1 to 2 or 2 to 3, and then maintaining it at that level, was calculated as follows:

End of Year 1:

	Initial cost of P fertiliser to raise Index by one level, including cost of borrowing
LESS	Value of increase or decrease in crop yield
PLUS	Cost of replacing additional P offtake (due to higher yield) to maintain Index
EQUALS	Remaining cost of raising P Index at end of year 1

End of Year 2:

	Remaining cost of raising P Index by one level, including cost of borrowing
LESS	Value of increase or decrease in crop yield
PLUS	Cost of replacing additional P offtake (due to higher yield) to maintain Index
EQUALS	Remaining cost (or benefit) of raising P Index at end of year 2

Calculations for year 3 and beyond were as year 2. Cost of borrowing was calculated at 5% per annum. The number of cropping years required for the cumulative additional crop value to exceed the cost of achieving and maintaining an increase in P Index of one level was then calculated for each site. This was based on the average annual value of the additional yield less cost of replacing the additional offtake, obtained over the four experiment cropping years at that site.

4. Results

4.1. Seedbed conditions and quality

The general condition of the seedbed after drilling at each of the six sites for the seasons 2010 to 2013 are shown in Table 12.

Table 12. Seedbed conditions early after drilling

Site	2010	2011	2012	2013
Peldon	Dry and very cloddy	Fine, firm seedbed	Wet but fine seedbed	Poor, wet cloddy seedbed
Weston	Dry and cloddy	Very dry and hard	Coarse, firm seedbed	Firm seedbed
Great Carlton	Dry but fine seedbed	Fine, firm seedbed	Moist, firm seedbed	Wet, cloddy seedbed
Caythorpe	Dry but fine seedbed	Fine, firm seedbed	Fine, moist seedbed	Fine, friable seedbed
Cirencester	Dry, friable seedbed	Firm, level seedbed	Moist, coarse seedbed	Coarse, firm seedbed
Cholsey	Fine seedbed	Fine, firm seedbed	Fine, firm seedbed	Fine seedbed

A complete record of soil structure scores (using the modified Peerlkamp method) from each site in 2011 or 2013 is provided in Appendix 3, Table 4. The overall Seedbed quality (Sq) score is shown for each site in Table 13 along with a brief observation on soil and root structure. Values are calculated from scores relating to individual layers within the block (defined by changes in horizontal layers of differing structure).

Table 13. Seedbed quality (Sq)* assessment according to the Peerlkamp method

Site	Spring 2011	Spring 2013
Peldon	-	Sq 2.3 (Good rooting, no evidence of compacted layer)
Weston	-	Sq 4.6 (Poor rooting, saturated soil)
Great Carlton	Sq 3.7 (Relatively poor structure with roots restricted to pores or cracks between aggregates)	-
Caythorpe	Sq 1.5 (Good seedbed structure with roots throughout profile)	-
Cirencester	-	Sq 2.6 (Well structured shallow soil, stony below 15cm)
Cholsey	-	Sq 2.4 (Well structured soil, roots throughout soil)

*The Sq scale ranges from Sq1 (good structure) to Sq5 (poor structure)

4.2. Olsen P

4.2.1. Measured Olsen P levels from 2009 to 2013 (excluding fresh P plots)

A complete record of Olsen P levels within each large plot (2009, 2010 and 2011) or sub plot (2012 and 2013) at each site is in Appendix 4, Tables 5–11. The number of plots falling within each P Index at each site each year is shown in Appendix 4, Table 12.

Initial (2009) and final (2013) Olsen P levels in the normal cultivated layer are summarised in Table 14, excluding sub plots that received fresh P fertiliser in autumn 2011 and 2012. The experiment at Weston had to be repositioned slightly after the initial soil sampling and analysis had been completed. Therefore for 2009 an estimated initial Olsen P value of 4.6 mg/kg was assumed for each large plot, which was the average of the previously measured values (all within the range 3.4 –5.8 mg/kg). In 2009, all sites started with some plots at either P Index 0 or the lower end of P Index 1. At four sites there was substantial plot-to-plot variation in the initial Olsen P levels, with a small number of plots as high as Index 2. This existing variation was exploited to help create the wide range of Olsen P levels required within each experiment.

Changes in Olsen P by 2013 on plots that did not receive P in autumn 2009 varied between sites. At Peldon and Great Carlton, mean Olsen P levels had decreased and the range of values had narrowed (Table 14). At Caythorpe the mean Olsen P changed slightly, but the range had narrowed. At Weston, Cirencester and Cholsey, mean Olsen P had increased and the range of values had widened, we comment on this later. Mean Olsen P levels were higher in plots that received P fertiliser in 2009 than in those that did not. However, the differential varied considerably between sites, with only small differences in the mean for Weston and Cirencester.

Table 14. Summary of initial and final levels of Olsen P at each site

Site	Depth of cultivated layer (cm)	Olsen P (mg/kg)					
		Spring / Summer 2009 (All plots)		Spring 2013 (Plots not treated with P fertiliser in 2009)		Spring 2013 (Plots treated with P fertiliser in 2009)	
		Mean	Range	Mean	Range	Mean	Range
Peldon	0-25	11.4	7.0 - 18.2	8.8	6.6 - 12.0	27.2	9.2 - 68.2
Weston	0-15	(4.6)	(3.4 5.8)	17.1	9.7 - 24.6	21.4	9.3 - 54.9
Great Carlton	0-22	13.6	10.0 - 17.8	8.9	8.0 - 11.1	19.6	8.4 - 45.0
Caythorpe	0-22	10.4	6.0 - 25.4	10.8	8.4 - 14.8	21.6	10.1 - 33.0
Cirencester	0-15	10.2	6.6 - 17.0	17.6	13.1 - 24.4	20.6	6.3 - 36.4
Cholsey	0-20	6.6	4.6 - 8.0	12.1	8.7 - 20.3	17.6	8.5 - 37.2

Olsen P in the 30cm soil layer below the normal cultivated depth was measured in selected large plots at all sites in autumn 2011. At Peldon, levels were low (< 3 mg/kg) both in plots that did and did not receive P fertiliser in 2009. At Great Carlton, Olsen P levels were equally low in plots that had not received P fertiliser, but were higher (about 8 mg/kg) in plots that had received P. At Caythorpe Olsen P levels averaged 4 mg/kg in untreated plots and 6 mg/kg in P treated plots. Only P treated plots were tested at Cholsey, and Olsen P levels were 5 mg/kg or less in most cases but much higher in one plot that received a large dose of P fertiliser in 2009. At Weston Olsen P levels at 15–45cm depth were variable, ranging from 3–10 mg/kg but with no consistent difference between P treated and untreated plots. The site with the highest Olsen P levels below normal cultivated depth was Cirencester, ranging from 10–17 mg/kg in the 15–45cm soil layer, for P treated and untreated plots.

As a result of this assessment, Olsen P levels at 15–30cm depth were tested in all sub plots at Cirencester in spring 2012 and 2013. In plots that did not receive P fertiliser in autumn 2009, Olsen P levels averaged 7.4 mg/kg in 2012 and 7.3 mg/kg in 2013. For individual sub plots, there was a significant linear relationship (P <0.01) between the 2012 and 2013 15–30cm values, and between the 2013 0–15cm and 15–30cm values. However, there was no apparent relationship between the 2012 0–15cm and 15–30cm values. In plots that did receive P fertiliser in autumn 2009, Olsen P levels averaged 7.9 mg/kg in 2012 and 8.4 mg/kg in 2013.

Changes in Olsen P levels over time at two contrasting sites, Peldon and Cirencester, are shown in Figures 4 and 5, for plots receiving different amounts of P fertiliser in 2009. Measured values for 2009, 2010 and 2011 are for each large plot, whereas those for 2012 and 2013 are the mean of the two sub plots that did not receive fresh P fertiliser in autumn 2011 or 2012. Other sites are shown in Appendix Figures 1 to 4. At Peldon, there was little year to year change in Olsen P in plots that did not receive P fertiliser (Figure 4). Plots that received less than 100 kg P/ha fertiliser in autumn 2009 showed only small subsequent year to year changes in Olsen P. Plots that received more than 100 kg P/ha in 2009 showed a relatively large increase in Olsen P between 2009 and 2010, a partial decline between 2010 and 2011, and then a tendency to level out thereafter.

Great Carlton, Caythorpe and Cholsey (Appendix 4; Figures 2 to 4) showed similar patterns to Peldon; although there was a tendency for Olsen P levels to increase slightly in 2013, even in plots that had not received P fertiliser treatments in 2009. The reason for this is unclear but it was observed in other experiments with annual measurements of Olsen P and so may have been linked to seasonal factors. Summer and autumn 2012 were exceptionally wet, followed by an unusually cold spring leading to poor early crop growth, which could have affected P availability or uptake or both. At Weston, Olsen P levels increased in fertilised plots in 2010 and had partially declined by 2011 but thereafter they were highly variable with increases recorded even in unfertilised plots up to 2013. The cause of the variability is uncertain, although the increase reflects that seen elsewhere.

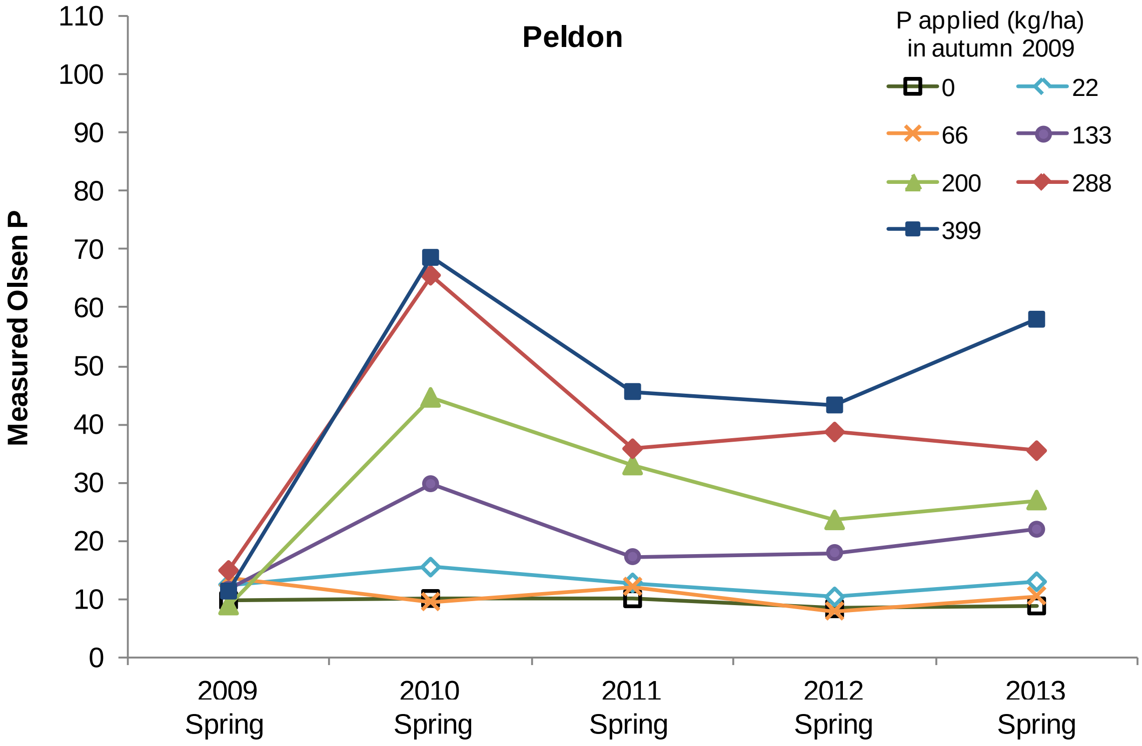

Figure 4. Average measured Olsen P, mg/kg, at the Peldon site from 2009 to 2013, for plots receiving different amounts of P fertiliser in autumn 2009

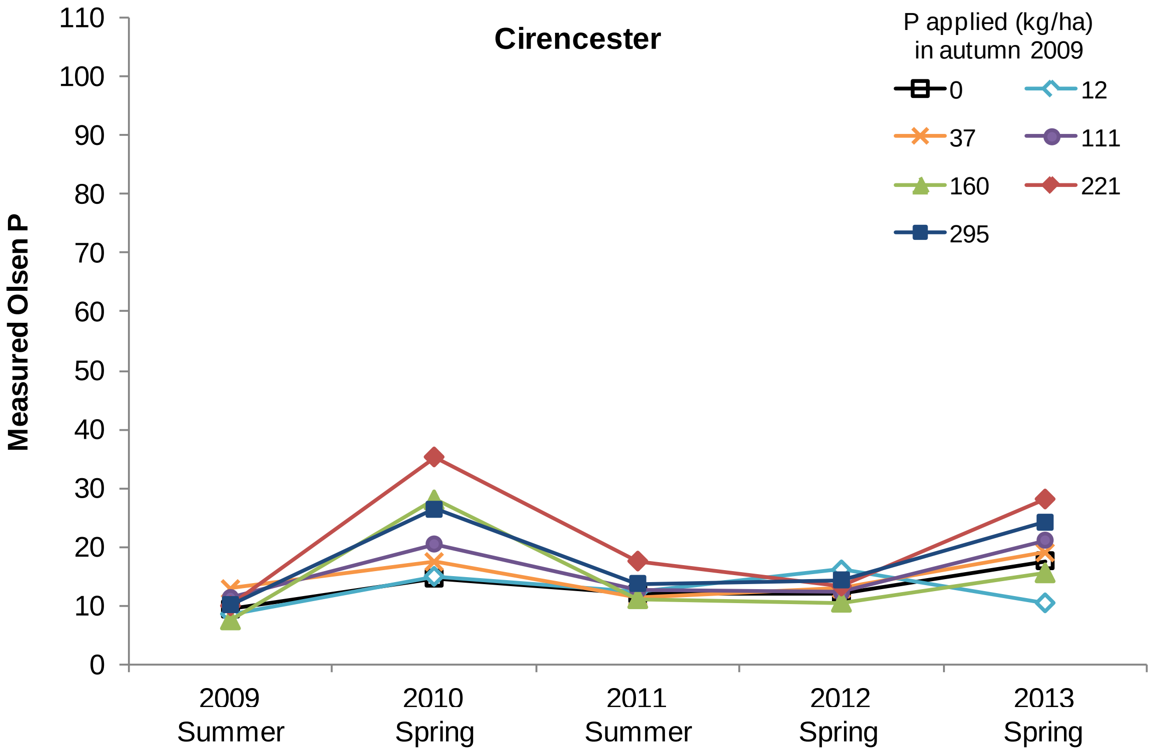

Figure 5. Average measured Olsen P, mg/kg, at the Cirencester site from 2009 to 2013, for plots receiving different amounts of P fertiliser in autumn 2009

At Cirencester (Figure 5), an increase in Olsen P was observed in all plots between 2009 and 2010, but this increase was fairly small even where large amounts of P had been applied in 2009. However, by 2011, Olsen P levels had dropped back even in plots that had received large amounts of P, and as a result there was only a narrow range of Olsen P values between treatments; the same was true in 2012. As at other sites, Olsen P levels showed an increase in 2013, but this tended to be greater in plots that had received the largest amounts of P fertiliser in 2009, such that the spread of Olsen P levels between treatments in 2013 was more similar to that seen in 2010.

4.2.2. Relationship between measured and expected Olsen P levels

The relationship between the measured (actual) Olsen P levels in 2010, 2011, 2012 and 2013 and the expected Olsen P are shown for each site in Figures 6 to 11. Measured values for 2010 and 2011 are for each large plot, whereas those for 2012 and 2013 are the mean of the two sub plots that did not receive fresh P fertiliser in autumn 2011 or 2012. The expected Olsen P for each plot is based on its initial Olsen P plus the expected increase resulting from any P fertiliser treatment added in autumn 2009, assuming 15% of the applied P would remain as measurable Olsen P once the added P had reacted with soil components and reached an equilibrium level. Further declines after the initial equilibration would be related to the amount of P removed in the harvested crops.

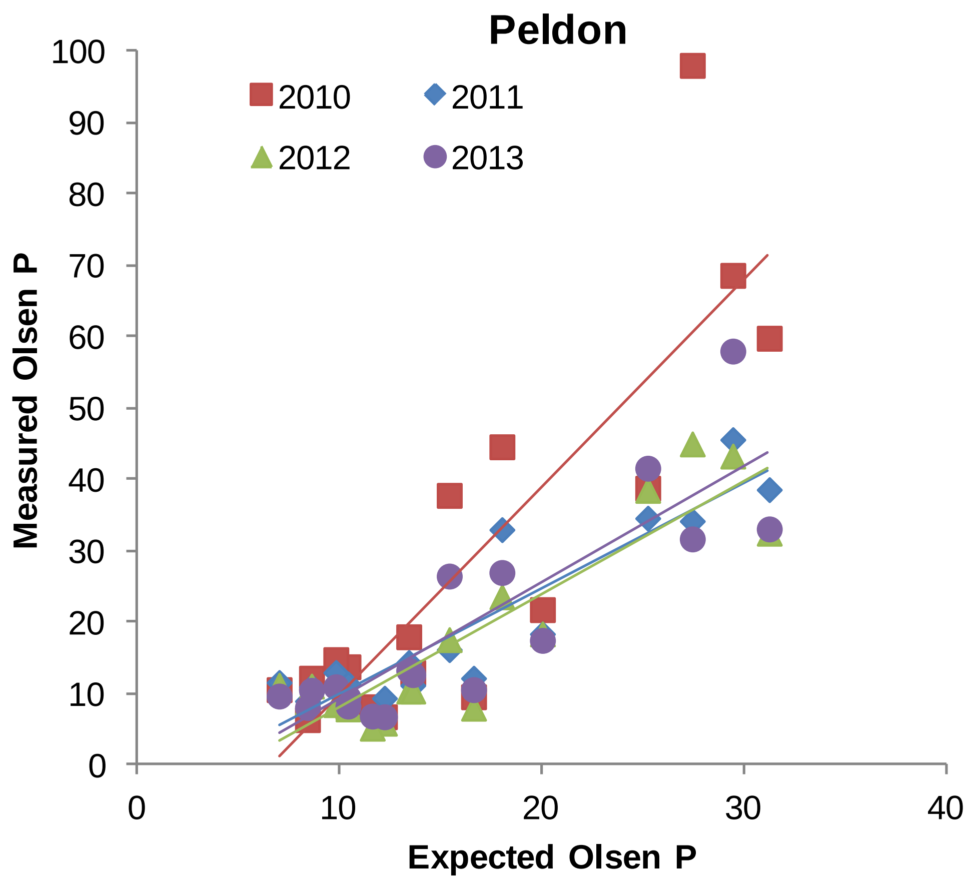

Figure 6. Measured compared to expected Olsen P, mg/kg, at the Peldon site

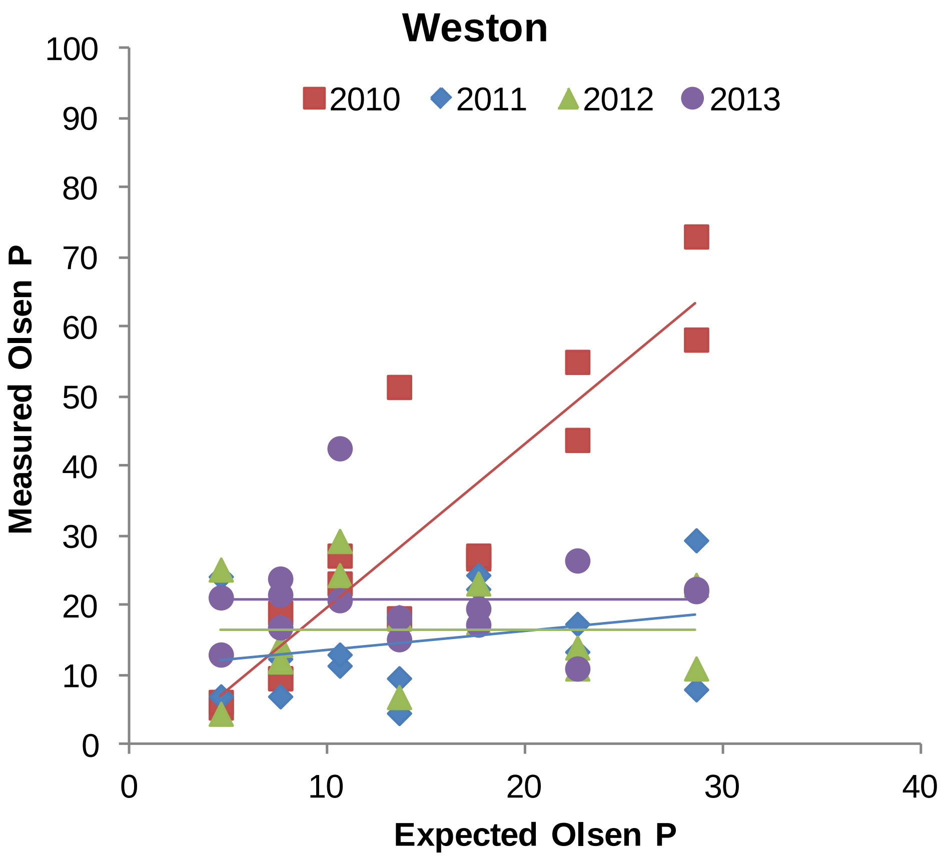

Figure 7. Measured compared to expected Olsen P, mg/kg, at the Weston site (excl. plots 16-18)

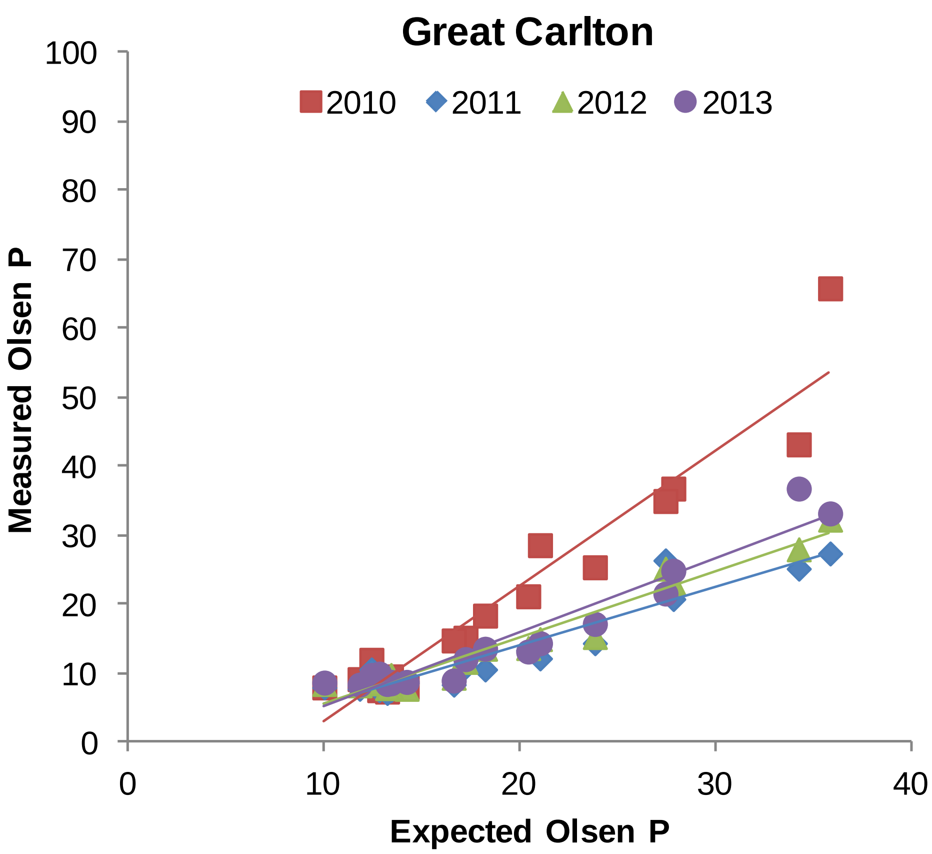

Figure 8. Measured compared to expected Olsen P, mg/kg, at the Great Carlton site

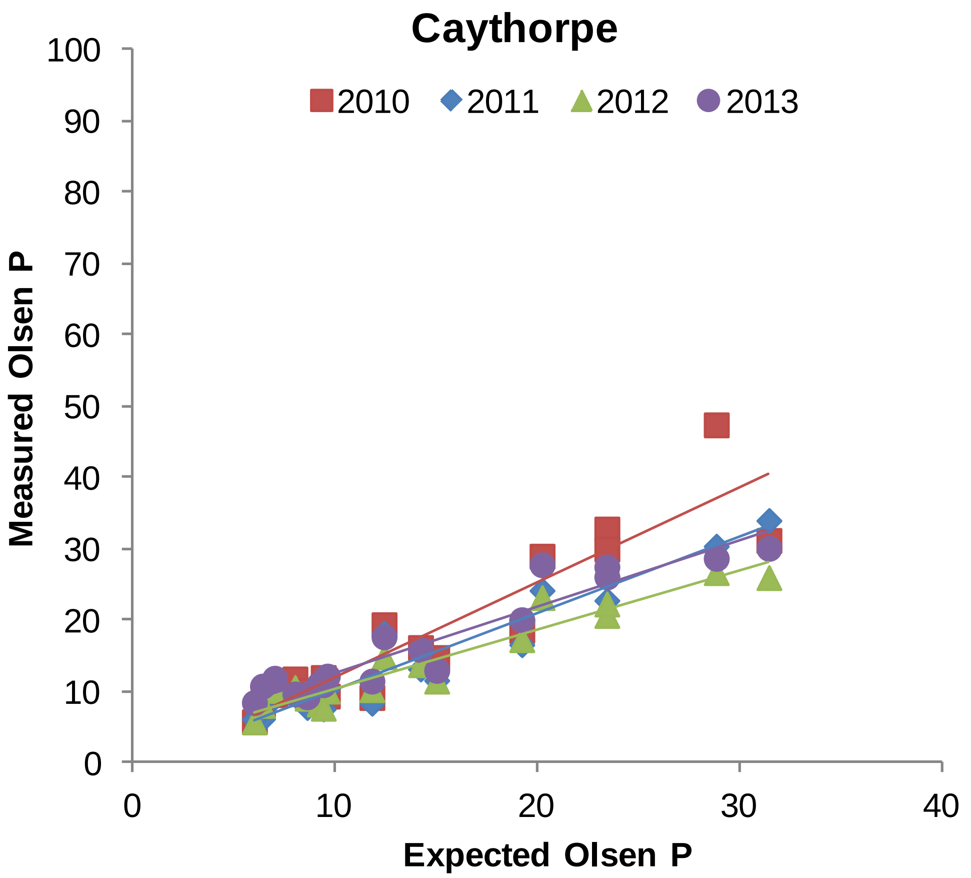

Figure 9. Measured compared to expected Olsen P, mg/kg, at the Caythorpe site

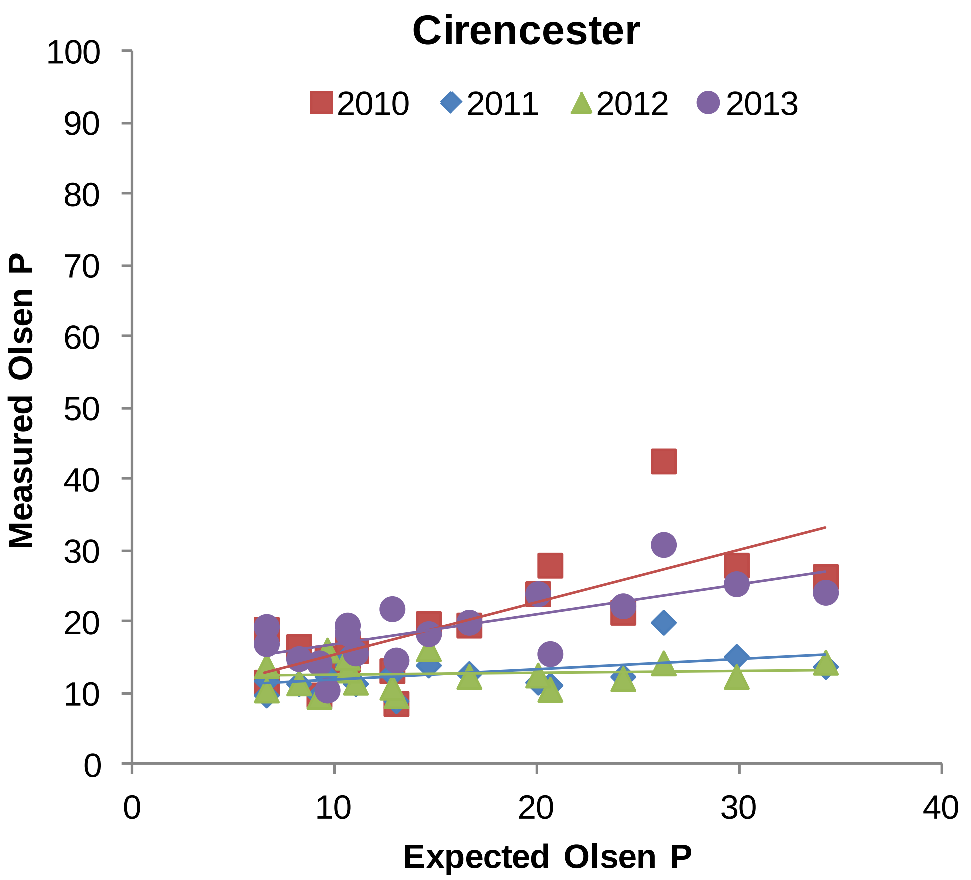

Figure 10. Measured compared to expected Olsen P, mg/kg, at the Cirencester site

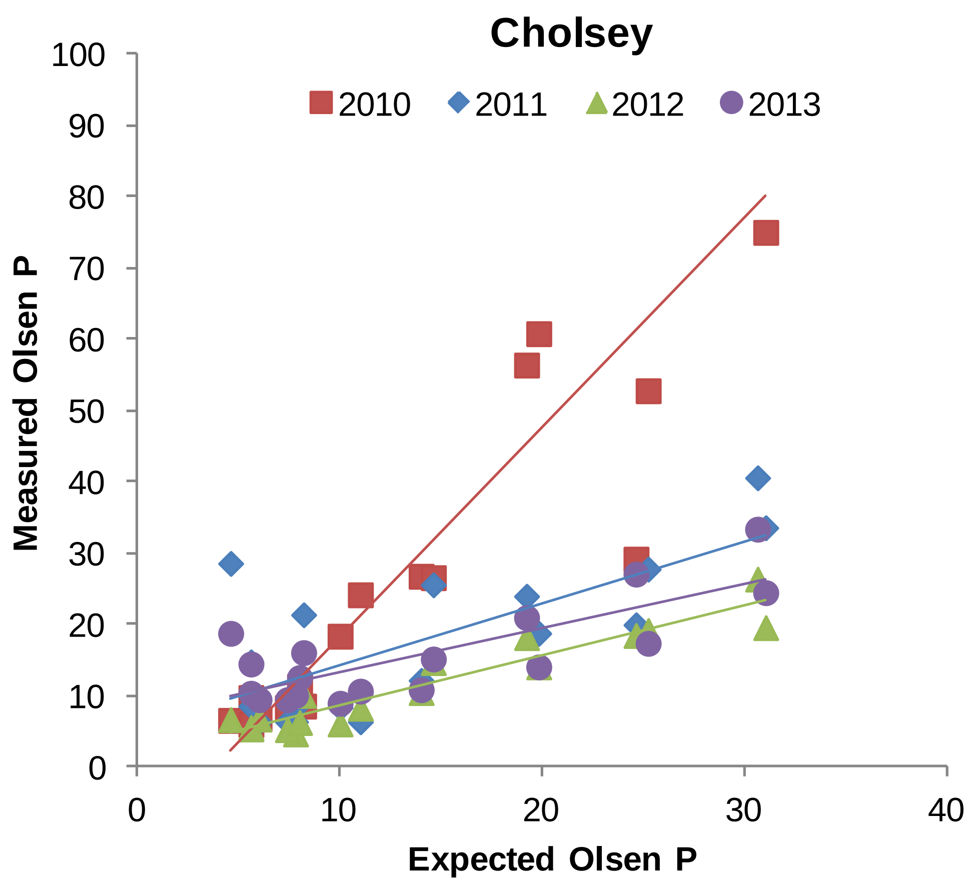

Figure 11. Measured compared to expected Olsen P, mg/kg, at the Cholsey site

At Peldon, measured Olsen P levels in spring 2010 in plots that had received P the previous autumn were typically about twice the expected levels, indicating that the added P had not yet equilibrated. By spring 2011, measured levels were much closer to those expected, although still slightly higher. After 2011, the relationship between measured and expected Olsen P showed little change, suggesting that the added P had fully equilibrated. At Great Carlton and Caythorpe, the pattern was similar, except measured levels were only slightly higher than expected in spring 2010, and equilibrated at or just below the expected levels from 2011. At Cholsey, measured Olsen P in spring 2010 were typically more than twice expected levels. By spring 2011, they were close to those expected, although there was a slight dip in values in 2012. At Weston, there was no apparent relationship between measured and expected Olsen P after 2010. Cirencester behaved differently, with measured levels already having reached those expected by spring 2010, but then falling further by 2011 when there was little relationship with expected levels. The levels were similar in 2012, but in 2013 there was some evidence of a relationship between measured and expected levels, which was closer to that seen in 2010.

4.2.3. Apparent availability of P fertiliser applied in autumn 2009

Table 15 shows the apparent availability of the P fertiliser applied in autumn 2009 (as an average for all plots that received an initial P application) in each of the four subsequent years, but excluding the fresh P sub plots in 2012 and 2013. Availability was calculated as the measured difference in the amount of Olsen P compared to spring 2009, as a percentage of the amount of P applied in autumn 2009. This calculation was done after adjustment for the underlying change in Olsen P (based on plots that did not receive P fertiliser in 2009) and after taking account of the additional P offtake (through higher yield) in plots that did receive P fertiliser compared to those that did not.

Table 15. Apparent availability in each subsequent year of P fertiliser applied in autumn 2009

	Apparent % availability of P applied in autumn 2009				
Site	2010	2011	2012	2013	2011-13 Mean
Peldon	50	25	26	28	26
Weston	38	8	14	19	13
Great Carlton	29	10	13	13	12
Caythorpe	31	31	18	22	24
Cirencester	12	6	17	7	10
Cholsey	42	21	12	10	14
Average	**34**	**17**	**17**	**17**	**17**

In spring 2010, (six months after the P fertiliser was applied) initial P availability, as assessed by the change in Olsen P ranged from 12 to 50%, and the change was not obviously related to time of application of the P fertiliser in autumn 2009 or time of soil sampling for Olsen P in spring 2010. Subsequently, P availability decreased between 2010 and 2011 at all sites but Caythorpe, where P availability averaged 24% between 2011 and 2013. Similarly at Peldon, availability decreased from about 50% in 2010 to 25% in 2011 but then remained about the same percentage in 2012 and 2013. This was higher than the 15% assumed when initial P treatment application rates were calculated. At Great Carlton, availability had decreased to around 10% by 2011, but did not decrease further in 2012 or 2013. At Cholsey, availability was still over 20% in 2011, but had fallen to less than 15% by 2012. At the other sites, the calculated availability varied from season to season, between 6 and 31%. Although across all sites, average P availability was 17% in 2011, 2012 and 2013 (very close to the 15% that had been assumed when determining the initial P fertiliser treatment rates). The higher percentage P availability at Caythorpe and Peldon is interesting and suggests that there is an inherent soil factor affecting the retention of added P extractable by the Olsen reagent which may vary between groups of soils and would be worth investigating to provide more accurate information on how much P to add to increase Olsen P by a required amount.

4.2.4. Measured Olsen P levels in fresh P sub plots

Mean Olsen P levels in the normal cultivated soil layer for the fresh P sub plots in 2012 and 2013 are in Table 16 for each site. The average change in Olsen P from 2011 to 2012 or from 2011 to 2013 is also shown for each site, along with the calculated % availability of the fresh P fertiliser applied in autumn 2011 or autumn 2011 plus 2012. The apparent availability in 2012 of the fresh P fertiliser applied in autumn 2011 varied considerably between sites, from nil to over 30%. The changes in average Olsen P levels were measured 6 months after P fertiliser was applied and this may not have allowed the fresh P to become equilibrated within the soil. The range of availabilities in 2013 for the total fresh P fertiliser applied in autumn 2011 plus 2012 was slightly narrower, with all but one site between 15 and 28%. Across all sites, availability averaged 13% in 2012 and 17% in 2013, again very close to the 15% that had been assumed.

Table 16. Change in average Olsen P levels for the fresh P sub plots

	Olsen P (mg/kg)			Apparent	Olsen P (mg/kg)		Apparent
Site	2011 average	2012 average	Change 2012-2011	% available	2013 average	Change 2013-2011	% available
Peldon	18.8	24.4	5.6	+21	26.5	7.7	+15
Weston	14.7	14.2	-0.6	-1	19.4	4.6	+6
Great Carlton	13.1	16.9	3.8	+13	29.1	16.0	+28
Caythorpe	15.1	23.7	8.7	+32	27.7	12.7	+24
Cirencester	12.7	21.0	8.3	+18	27.6	14.9	+16
Cholsey	17.7	16.7	-1.0	-3	29.0	11.3	+17
Mean				**+13**			**+17**

4.3. Yield response to Olsen P

4.3.1. Winter wheat

Fifteen wheat crops were grown in total over the six sites and four years. At Cirencester in 2012 the full range of Olsen P Indices was not represented so this crop has been excluded from Tables 17 and 18. Largest grain yields were obtained in 2010 and 2012 at Peldon, but in 2011 and 2013 at Cholsey. At Caythorpe yields were low in 2010 and 2011 due to a combination of drought conditions and take-all, and very low in 2012 due to waterlogging caused by high rainfall and poor drainage. Mean yields at each P Index, and the standard deviation for each mean, are shown in Table 17.

Table 17. Effect of P Index on mean wheat grain yield

Site	Year	Mean yield (t/ha)				Standard deviation on mean			
		Index 0	Index 1	Index 2	Index 3+	Index 0	Index 1	Index 2	Index 3+
Peldon	2010	9.76	10.24	10.76	11.26	0.427	0.265	0.733	0.428
	2011	6.96	7.85	8.43	8.82	0.642	0.226	0.278	0.481
	2012	10.73	11.29	11.78	12.11	0.879	0.193	0.091	0.473
	2013	6.48	7.91	7.94	9.02	1.145	1.061	1.361	0.788
	Mean	8.48	9.32	9.73	10.30				
Weston	2010	7.19	8.78	9.12	9.21	0.593	0.682	0.229	0.586
	2012	7.47	10.65	10.28	10.10	1.729	1.163	1.102	0.821
	Mean	7.33	9.72	9.70	9.65				
Great Carlton	2011	7.17	7.98	8.79	8.48	0.461	0.900	0.264	0.547
	2012	6.40	7.63	8.21	8.17	1.184	0.752	0.565	0.759
	Mean	6.78	7.80	8.50	8.33				
Caythorpe	2010	5.11	6.33	7.75	7.16	1.129	1.097	0.634	0.657
	2011	4.43	5.36	5.64	6.94	1.110	0.727	1.793	0.692
	2012	1.56	2.99	4.21	3.82	1.010	0.905	1.511	0.156
	Mean	3.70	4.89	5.87	5.97				
Cholsey	2010	7.49	7.83	8.40	8.91	0.746	0.212	0.280	0.819
	2011	8.38	8.58	10.26	10.22	0.864	1.034	1.151	0.883
	2013	9.19	9.73	10.51	10.91	0.637	0.803	0.664	0.676
	Mean	8.36	8.72	9.72	10.02				
Mean 14 site years		**7.02**	**8.08**	**8.72**	**8.94**				

Mean yields at each P Index, and the standard deviation for each mean, are shown in Table 18 for winter wheat, together with the decrease or increase in yield relative to that at P Index 2 for all sites (except Cirencester). All soils at Index 0 gave smaller yields than at Index 2, with the penalty ranging from about 0.9 t/ha to 2.8 t/ha. Thirteen crops gave a lower mean yield at Index 1 than at Index 2, with the penalty ranging from about 0.3 t/ha to 1.7 t/ha. Seven crops gave a larger mean yield at Index 3 than at Index 2, with the advantage ranging from about 0.3 t/ha to more than 1.0

t/ha. Over five sites and fourteen crops, when compared to an Olsen P Index of 2, the mean yield penalty was 1.7 t/ha at Index 0 and 0.6 t/ha at Index 1. The mean yield advantage at Index 3 was 0.2 t/ha.

Table 18. Increase or decrease in wheat grain yield compared to a P Index of 2

Site	Year	Yield increase (+) or decrease (-) vs Index 2 (t/ha)		
		Index 0	Index 1	Index 3+
Peldon	2010	-1.00	-0.52	+0.50
	2011	-1.47	-0.58	+0.39
	2012	-1.05	-0.49	+0.33
	2013	-1.46	-0.03	+1.08
	Mean	-1.25	-0.41	+0.57
Weston	2010	-1.93	-0.34	+0.09
	2012	-2.81	+0.37	-0.18
	Mean	-2.37	+0.02	-0.05
Great Carlton	2011	-1.62	-0.81	-0.31
	2012	-1.81	-0.58	-0.04
	Mean	-1.72	-0.70	-0.17
Caythorpe	2010	-2.64	-1.42	-0.59
	2011	-1.21	-0.28	+1.30
	2012	-2.65	-1.22	-0.39
	Mean	-2.17	-0.98	+0.10
Cholsey	2010	-0.91	-0.57	+0.51
	2011	-1.88	-1.68	-0.04
	2013	-1.32	-0.78	+0.40
	Mean	-1.36	-1.00	+0.30
Mean 14 site years		**-1.70**	**-0.64**	**+0.22**

4.3.2. Winter oilseed rape

Four of the five oilseed rape crops grown were harvested, one in each year at four of the sites. Mean yields at each P Index, and the standard deviation for each mean, are shown in Table 19. Seed yields were moderate at Cholsey in 2012, but relatively high in other cases.

Table 19. Effect of P Index on mean winter oilseed rape yield

Site	Year	Mean yield (t/ha)				Standard deviation on mean			
		Index 0	Index 1	Index 2	Index 3+	Index 0	Index 1	Index 2	Index 3+
Great Carlton	2010	3.87	3.92	4.08	4.24	0.185	0.206	0.127	0.110
Cholsey	2012	2.92	3.20	3.51	(3.53)	0.163	0.265	0.114	-
Mean 2 site years		**3.40**	**3.56**	**3.79**	**3.89**				
Cirencester	2011	(4.00)	4.15	(4.39)	-	-	0.404	-	-
Weston	2013	(4.41)	4.40	4.28	4.38	-	0.364	0.313	0.186

( ) Value based on only 1 plot

At Great Carlton and Cholsey, yields were lower at P Indices of 0 or 1 than at Indices of 2 or 3, with yield penalties ranging from about 0.2 t/ha to 0.6 t/ha (Table 20). At Cirencester the full range of P Indices was not represented but similar yield penalties were indicated at Indices of 0 or 1. At Weston there was no relationship between P Index and seed yield.

Table 20. Increase or decrease in oilseed rape yield compared to a P Index of 2

Site	Year	Yield increase (+) or decrease (-) vs Index 2 (t/ha)		
		Index 0	Index 1	Index 3+
Great Carlton	2010	-0.21	-0.16	+0.16
Cholsey	2012	-0.59	-0.31	+0.02
Mean 2 site years		**-0.39**	**-0.23**	**+0.10**
Cirencester	2011	-0.39	-0.24	-
Weston	2013	+0.13	+0.12	+0.10

4.3.3. Spring barley

There were three spring barley crops, two at Cirencester (2010 and 2013) and one at Caythorpe (2013). Mean yields at each P Index, and the standard deviation for each mean, are shown in Table 21. Two of the crops were relatively high yielding, notably at Caythorpe where the crop was higher yielding than any of the wheat crops grown in the previous three years. However, yields were moderate and variable at Cirencester in 2013. Mean grain yields showed no clear relationship with P Index, with better than expected yields at P Index 0 (Table 22).

Table 21. Effect of P Index on mean spring barley grain yield

Site	Year	Mean yield (t/ha)				Standard deviation on mean			
		Index 0	Index 1	Index 2	Index 3+	Index 0	Index 1	Index 2	Index 3+
Caythorpe	2013	8.12	8.00	8.47	8.36	0.278	0.584	0.400	0.923
Cirencester	2010	(7.38)	7.15	7.29	7.52	-	0.536	0.773	0.514
	2013	(5.81)	6.11	5.49	5.58	-	0.891	0.723	0.344
Mean 3 site years		**7.10**	**7.09**	**7.08**	**7.15**				

( ) Value based on only 1 plot

Table 22. Increase or decrease in spring barley yield compared to a P Index of 2

Site	Year	Yield increase (+) or decrease (-) vs Index 2 (t/ha)		
		Index 0	Index 1	Index 3+
Caythorpe	2013	-0.35	-0.47	-0.11
Cirencester	2010	+0.09	-0.14	+0.23
	2013	+0.32	+0.62	+0.09
Mean 3 site years		**+0.02**	**+0.01**	**+0.07**

4.3.4. Spring beans

The only spring bean crop was at Weston. Seed yields were very low due to severe spring drought. Yields averaged 1.35 t/ha at P Index 0 or 1, and 1.80 t/ha at P Index of 2 or 3, a benefit of about 0.45 t/ha.

4.4. Yield response to fresh P

4.4.1. Winter wheat

Data on wheat yield response to fresh P fertiliser were obtained for seven crops, one at each site in 2012 or 2013, and in both years at Peldon (Table 23). For each site yields with fresh P are shown at each P Index, based on the average Olsen P of the two sub plots in each large plot that did not receive fresh P to make clear any benefit of fresh P. The yield increase or decrease with fresh P was then calculated relative to the yield without fresh P for each P Index (Table 24). Yield responses to fresh P at Caythorpe in 2012 were abnormally large, even for plots at Index 3. This was due to the very low yields achieved under waterlogged conditions in plots that did not receive fresh P. Data from Cirencester in 2012 were limited by the narrow range of soil P Indices represented.

Excluding Caythorpe and Cirencester, yield increases with fresh P ranged from 0.5 to 1.75 t/ha at Index 0. Four crops showed an increase of more than 0.5 t/ha at Index 1, and three an increase of more than 0.3 t/ha at Index 2. At Index 3+, apart from one crop, there was little benefit from fresh P. The mean yield increase with fresh P of about 1.0 t/ha at Index 0 was not sufficient to raise yields to the level achieved with soils maintained at Index 2. The mean increase with fresh P of about 0.6 t/ha at Index 1 was sufficient to raise yields to the level achieved with soils maintained at Index 2.

Table 23. Wheat grain yield with fresh P fertiliser at each P Index

Site	Year	Mean yield (t/ha) with fresh P				Standard deviation on mean			
		Index 0	Index 1	Index 2	Index 3+	Index 0	Index 1	Index 2	Index 3+
Peldon	2012	11.73	11.86	11.84	12.20	0.599	0.102	0.205	0.385
	2013	7.29	8.81	(7.70)	9.38	0.820	0.974	-	0.876
Weston	2012	7.18	10.71	9.90	(11.66)	0.099	1.504	0.628	-
Great Carlton	2012	8.27	8.61	8.45	8.22	0.517	0.567	0.460	0.453
Cholsey	2013	(10.69)	10.41	11.07	10.76	-	0.728	0.502	0.375
Mean 5 site years		**9.03**	**10.08**	**9.79**	**10.44**				
Caythorpe	2012	4.31	5.33	4.80	6.27	0.753	0.502	0.919	1.032
Cirencester	2012	-	7.39	7.72	-	-	0.305	0.290	-

( ) Value based on only 1 plot

Table 24. Wheat grain yield response to fresh P fertiliser at each P Index

Site	Year	Increase (+) or decrease (-) in yield at each P Index			
		Index 0	Index 1	Index 2	Index 3+
Peldon	2012	+1.09	+0.60	+0.06	+0.09
	2013	+1.14	+1.02	+0.89	+0.36
Weston	2012	+0.48	+0.01	-0.06	+0.18
Great Carlton	2012	+1.74	+0.88	+0.31	-0.08
Cholsey	2013	+0.86	+0.64	+0.59	-0.29
Mean 5 site years		**+1.06**	**+0.63**	**+0.36**	**+0.05**
Caythorpe	2012	+2.99	+2.27	+0.62	+2.34
Cirencester	2012	-	+0.01	+0.35	-

4.4.2. Winter oilseed rape

Data on oilseed rape yield response to fresh P fertiliser were obtained for two crops (Table 25). However, only at Cholsey was there a yield response to soil P level. Here there was a yield benefit compared to plots without fresh P, at P Indices of 0 and 1 (Table 26). The increases were sufficient to raise yields to the level achieved at the next P Index above (1 and 2, respectively).

Table 25. Oilseed rape yield with fresh P fertiliser at each P Index

Site	Year	Mean yield (t/ha) with fresh P				Standard deviation on mean			
		Index 0	Index 1	Index 2	Index 3+	Index 0	Index 1	Index 2	Index 3+
Weston	2013	-	4.50	4.43	4.48	-	0.283	0.384	0.127
Cholsey	2012	3.36	3.45	3.51	(3.30)	0.128	0.091	0.250	-

( ) Value based only on 1 plot

Table 26. Oilseed rape yield response to fresh P fertiliser at each P Index

Site	Year	Increase (+) or decrease (-) in yield at each P Index			
		Index 0	Index 1	Index 2	Index 3+
Weston	2013	-	-0.06	+0.15	+0.24
Cholsey	2012	+0.43	+0.23	-0.01	-0.21

4.4.3. Spring barley

Data on spring barley yield response to fresh P fertiliser were also obtained for two crops (Table 27). Although neither of these had shown a consistent yield response to Olsen P, both tended to show a benefit to fresh P, of between 0.5 and 1.0 t/ha (Table 28). At Caythorpe this was sufficient to raise the overall mean yield from 8.2 t/ha without fresh P to 8.8 t/ha with fresh P, although there was no response at P Index 3 and above.

Table 27. Spring barley yield with fresh P fertiliser at each P Index

Site	Year	Mean yield (t/ha) with fresh P				Standard deviation on mean			
		Index 0	Index 1	Index 2	Index 3+	Index 0	Index 1	Index 2	Index 3+
Caythorpe	2013	9.31	9.01	8.99	8.28	0.099	0.680	0.821	0.659
Cirencester	2013	-	6.80	6.00	(5.90)	-	0.500	0.910	-

( ) Value based only on 1 plot

Table 28. Spring barley yield response to fresh P fertiliser at each P Index

Site	Year	Increase (+) or decrease (-) in yield at each P Index			
		Index 0	Index 1	Index 2	Index 3+
Caythorpe	2013	0.91	1.11	0.53	-0.13
Cirencester	2013	-	0.70	0.47	0.63

4.5. Critical P levels

For each site response curves were fitted to the yield/Olsen P data in 2011, 2012 and 2013, as described in section 3.8. In 2011 the relationship was based on yield and Olsen P data from the 18 large plots. In 2012 and 2013 separate response curves were fitted for those sub plots that received no fresh P in 2012 and 2013, and those that did receive fresh P in these two years using the appropriate Olsen P values for the sub plots with and without fresh P.

4.5.1. Winter wheat

Response curves for wheat crops at Peldon over three successive years are shown in Figures 12 (2011), 13 (2012) and 14 (2013). The yield response plateaued at a lower level of Olsen P in 2012 and 2013 than in 2011. Response curves for wheat crops at two other sites in 2012 are shown for comparison in Figures 15 (Great Carlton) and 16 (Caythorpe). Great Carlton showed a similar response to Peldon. At Caythorpe the yield response was much steeper and plateaued at a higher level of Olsen P, partly due to the very low yields obtained at low P levels at this waterlogged site. Response curves for wheat crops at two sites in 2012 that had received fresh P fertiliser in autumn 2011 are shown in Figures 17 (Peldon) and 18 (Great Carlton). At Peldon and Great Carlton yield responses to Olsen P were flatter where fresh P fertiliser had been applied, but this was not the case at other sites.

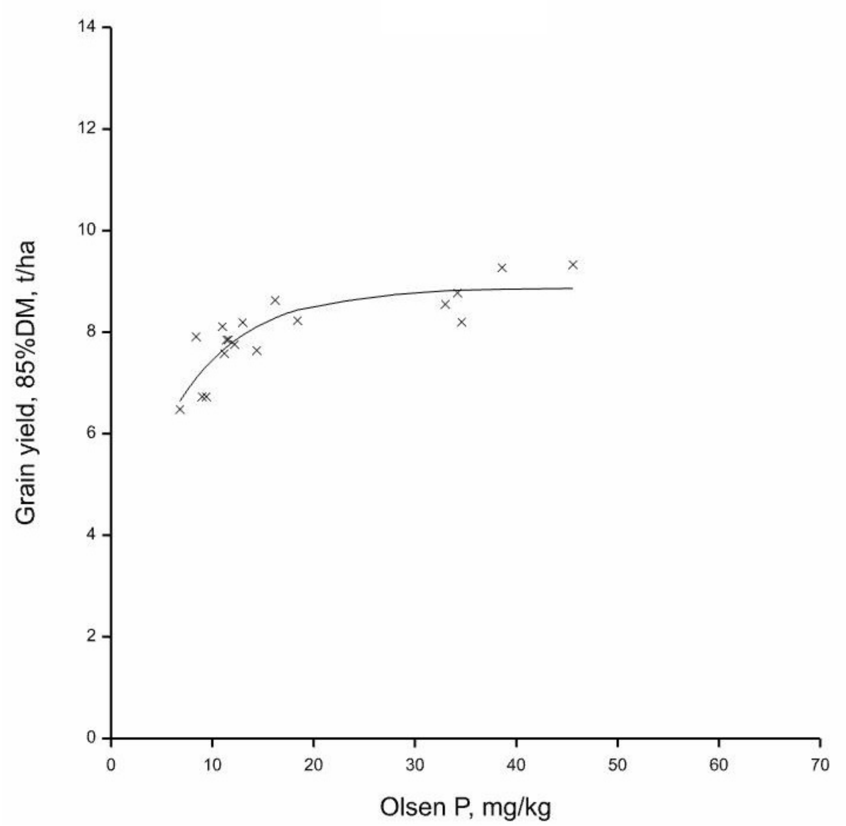

Figure 12. Fitted yield response curve for the 2011 wheat crop at the Peldon site

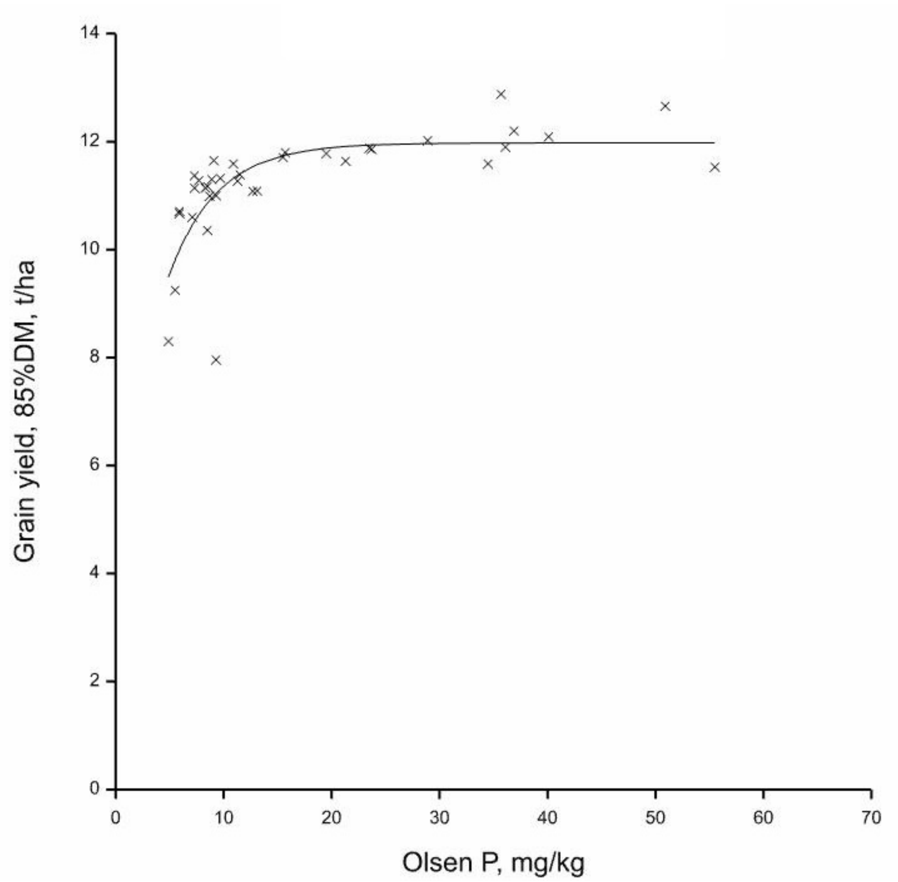

Figure 13. Fitted response curve for the 2012 wheat crop at the Peldon site (no fresh P)

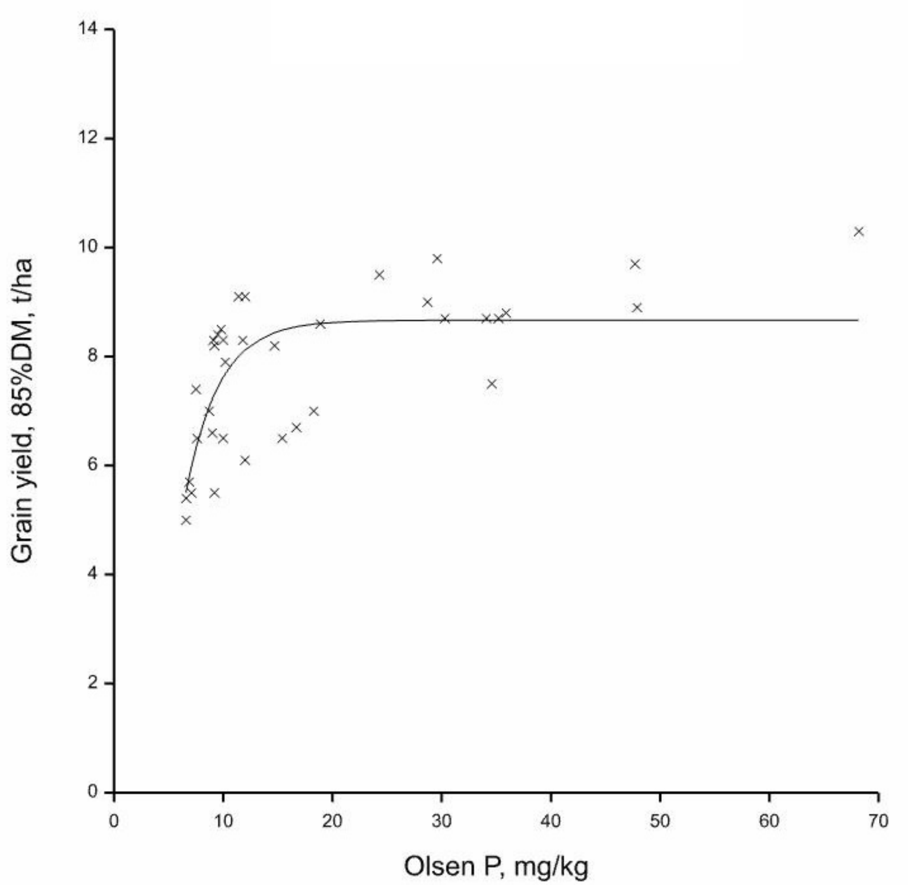

Figure 14. Fitted response curve for the 2013 wheat crop at the Peldon site (no fresh P)

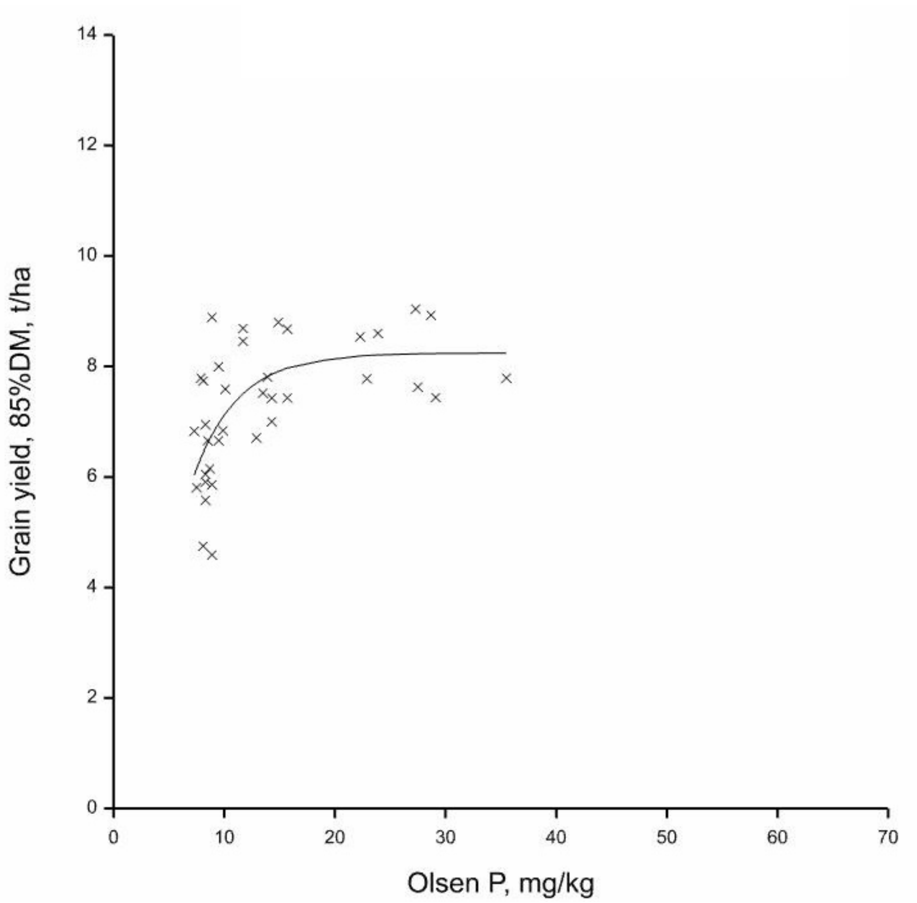

Figure 15. Fitted response curve for the 2012 wheat crop at the Great Carlton site (no fresh P)

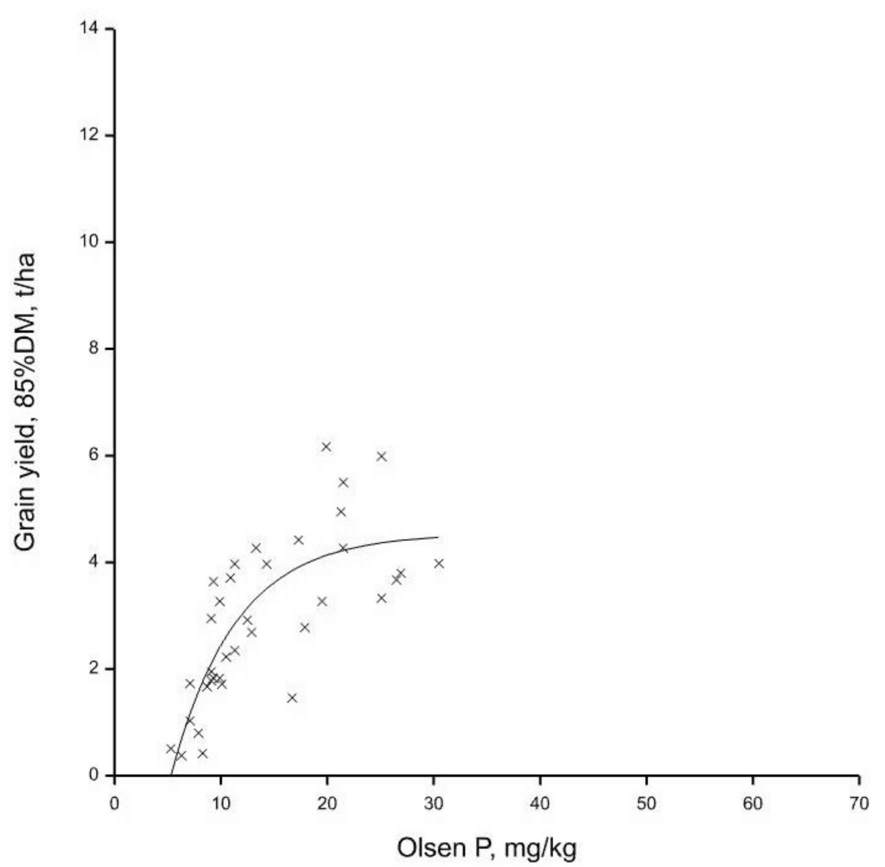

Figure 16. Fitted response curve for the 2012 wheat crop at the Caythorpe site (no fresh P)

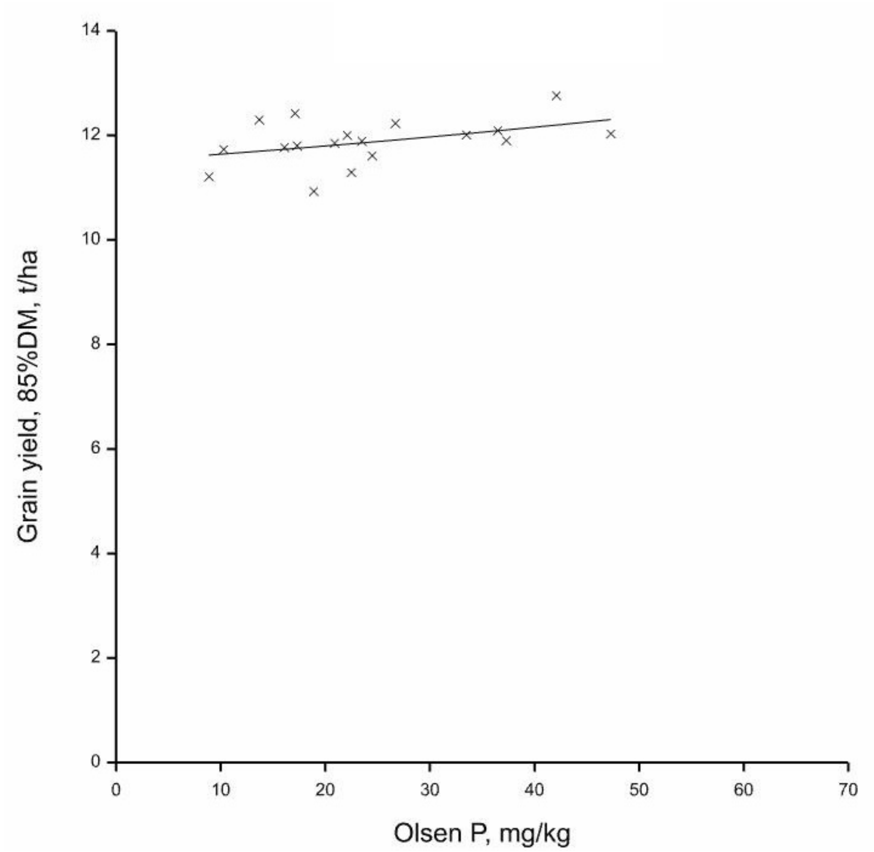

Figure 17. Fitted response curve for the 2012 wheat crop at the Peldon site with fresh P

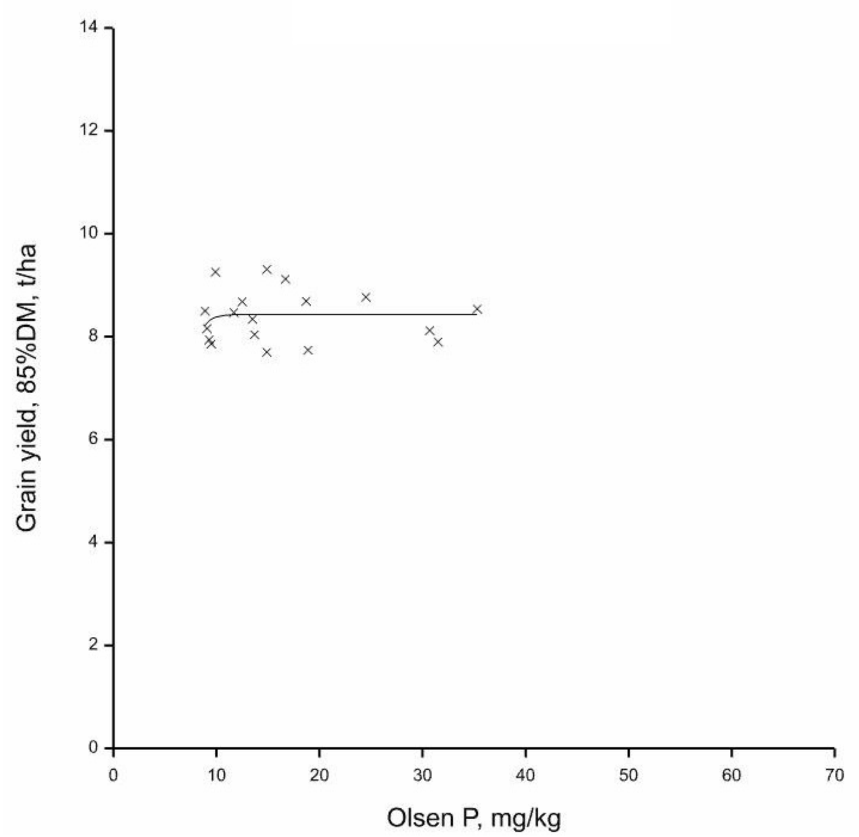

Figure 18. Fitted response curve for the 2012 wheat crop at the Great Carlton site with fresh P

Meaningful estimates of the fitted maximum (plateau) yield and critical Olsen P levels associated with 95% or 98% of maximum yield were obtained for eight of the ten wheat crops from 2011, 2012 or 2013 that had an adequate range of Olsen P (Table 29). The critical P values for Cholsey in 2013 had large standard errors and should be treated with caution. Levels of Olsen P associated with 95% of maximum yield ranged from 9.2 mg/kg (Index 0) to 23.5 mg/kg (Index 2), and for 98% of maximum yield the range was 11.4 mg/kg (Index 1) to 32.0 mg/kg (Index 3). Over all eight wheat crops, average critical P levels were around 16 mg/kg for 95% of maximum yield and 20 mg/kg for 98% of maximum yield, which are within the lower half of P Index 2.

Table 29. Fitted maximum wheat yield and Olsen P to achieve 95% and 98% of maximum yield

Site	Year	Plot values on which analysis is based	Fitted maximum yield		Olsen P for 95% max yield		Olsen P for 98% max yield		variance accounted for (%)
			t/ha	s.e.	mg/kg	s.e.	mg/kg	s.e.	
Peldon	2011	Large plots (18)	8.87	0.23	18.2	3.90	24.7	6.23	70
	2012	Sub plots (36)	11.98	0.22	11.3	2.06	15.4	3.50	48
	2013	Sub plots (36)	8.67	0.28	12.7	2.08	15.5	3.10	48
Weston	2012	Sub plots (36)	10.40	0.29	9.2	2.49	11.4	3.62	42
Great Carlton	2011	Large plots (18)	8.64	0.35	13.3	4.03	17.2	6.53	50
	2012	Sub plots (36)	8.24	0.36	14.0	3.98	17.7	6.22	36
Caythorpe	2012	Sub plots (36)	4.54	0.47	23.5	5.88	29.1	7.86	59
Cholsey	2013	Sub plots (36)	11.33	0.76	22.3	13.3	32.0	21.1	38

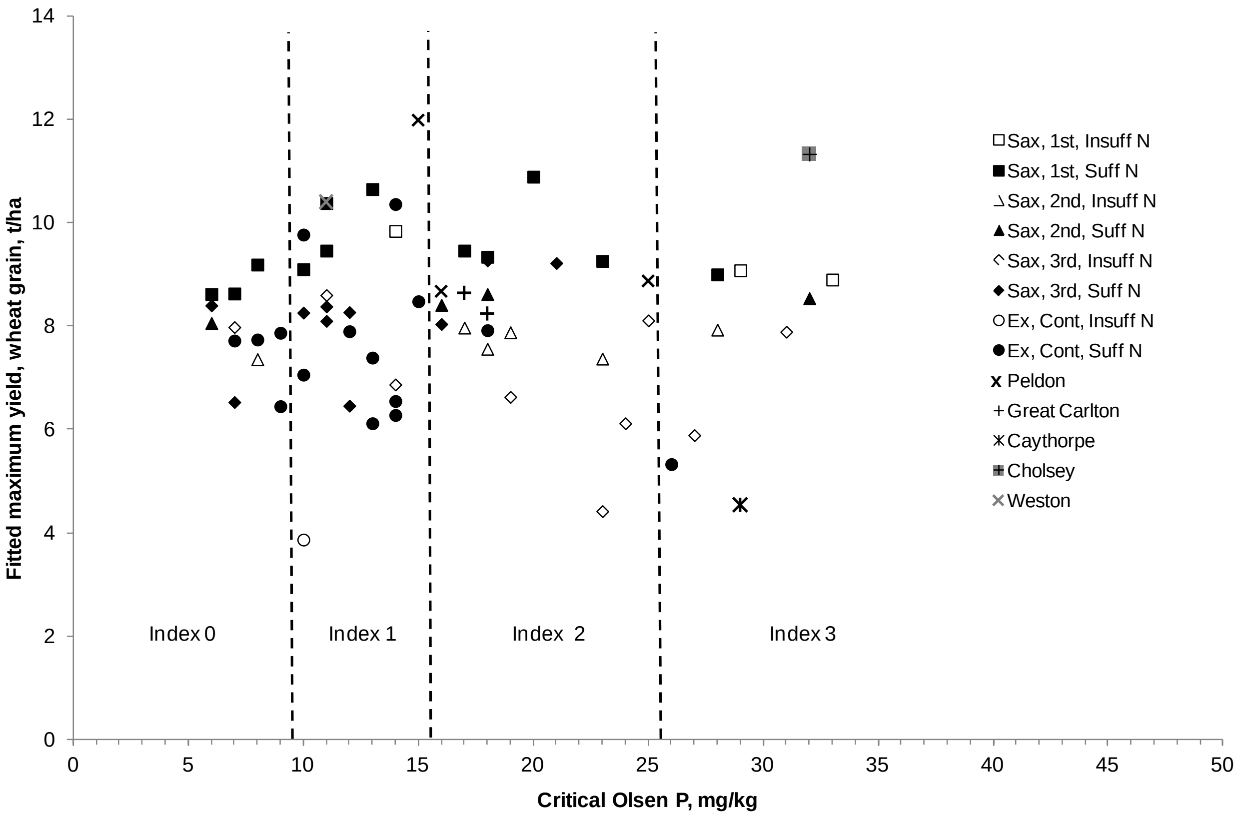

Figure 19. Fitted maximum wheat yields and critical Olsen P compared to previous experiments

Fitted maximum wheat yields and the critical Olsen P levels associated with 98% of maximum yield for the eight wheat crops grown in these experiments have been included in the Figure that was presented in HGCA Research Review 74 (Johnston and Poulton, 2011), and the combined data are shown in Figure 19. The previous wheat data includes first, second and third wheat crops at Saxmundham, grown with sufficient or insufficient N fertiliser, and continuous wheats on the Exhaustion Land at Rothamsted, with sufficient or insufficient N fertiliser. All the data points for the crops grown in these experiments fall within the range of critical P values obtained previously, but two (Cholsey 2013 and Caythorpe 2012) were at the upper extreme for crops receiving adequate N fertiliser.

4.5.2. Winter oilseed rape

Response curves for the oilseed rape crops at Cirencester in 2011 and Cholsey in 2012 are shown in Figures 20 and 21, respectively. Seed yield was more responsive to Olsen P and appeared to plateau at a higher Olsen P level at Cholsey than at Cirencester. However, where fresh P was applied in autumn 2011, the 2012 yield response at Cholsey was equally flat (Figure 22). Good estimates of the fitted maximum yields were obtained for both of the above crops and similarly at Weston in 2013. However, even though Olsen P explained 68% of the variance in seed yield at Cholsey, it was not possible to obtain meaningful estimates of the critical P level associated with 95% or 98% of maximum yield for any of the oilseed rape crops.

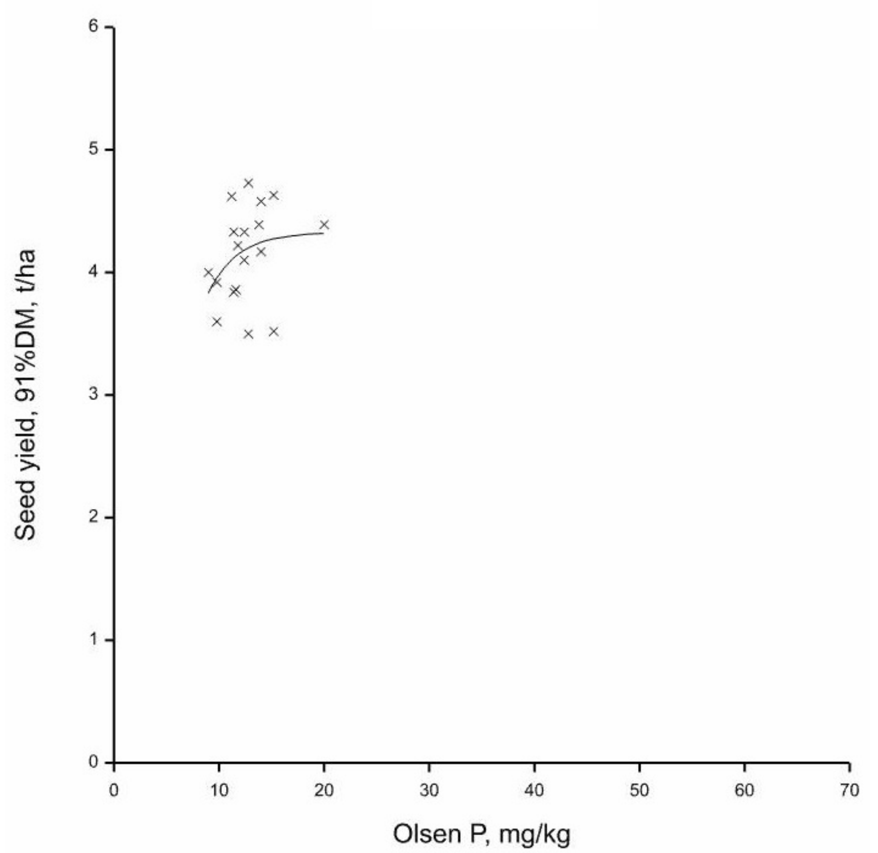

Figure 20. Fitted response curve for the 2011 oilseed rape crop at the Cirencester site

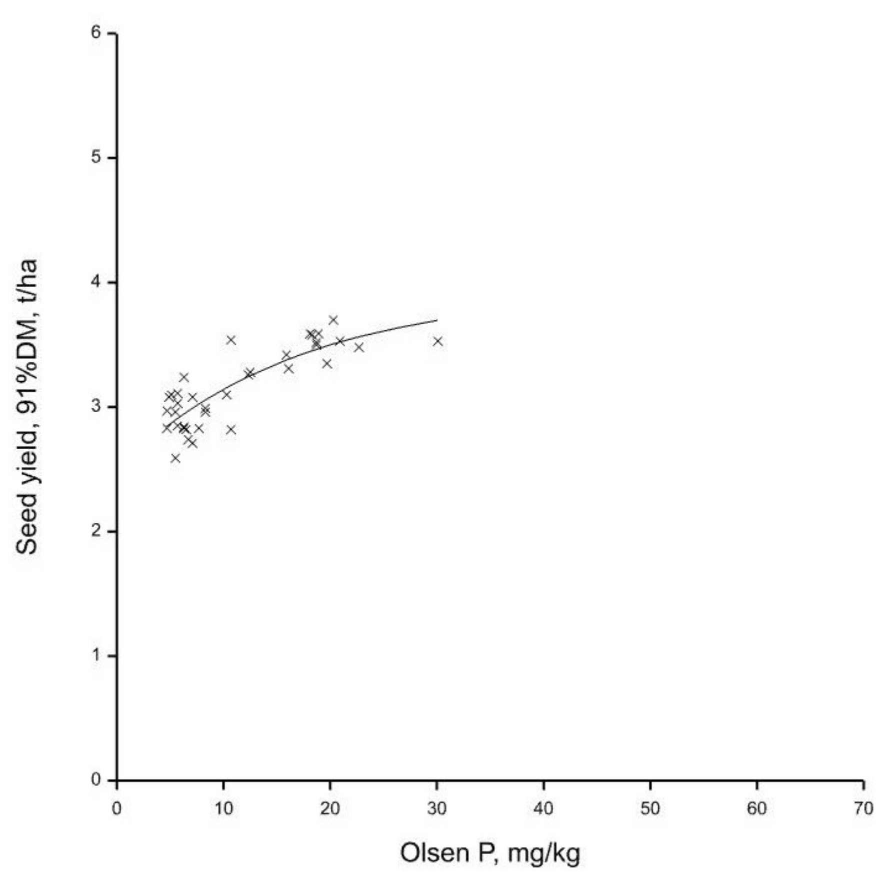

Figure 21. Fitted response curve for the 2012 oilseed rape crop at the Cholsey site (no fresh P)

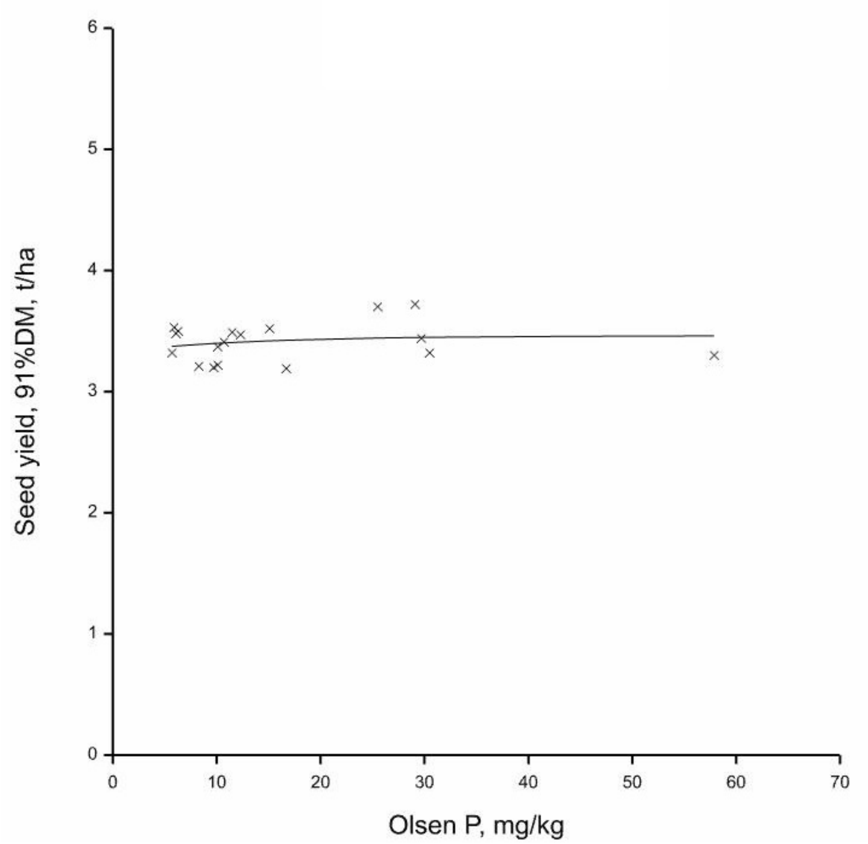

Figure 22. Fitted response curve for the 2012 oilseed rape crop at the Cholsey site with fresh P

4.5.3. Spring barley

The response curve for spring barley at Caythorpe in 2013 is shown in Figure 23. There was a small grain yield response to Olsen P, but no clear plateau. It was not possible to obtain meaningful estimates of the critical P levels associated with 95% or 98% of the maximum yield for either of the two spring barley crops in 2013.

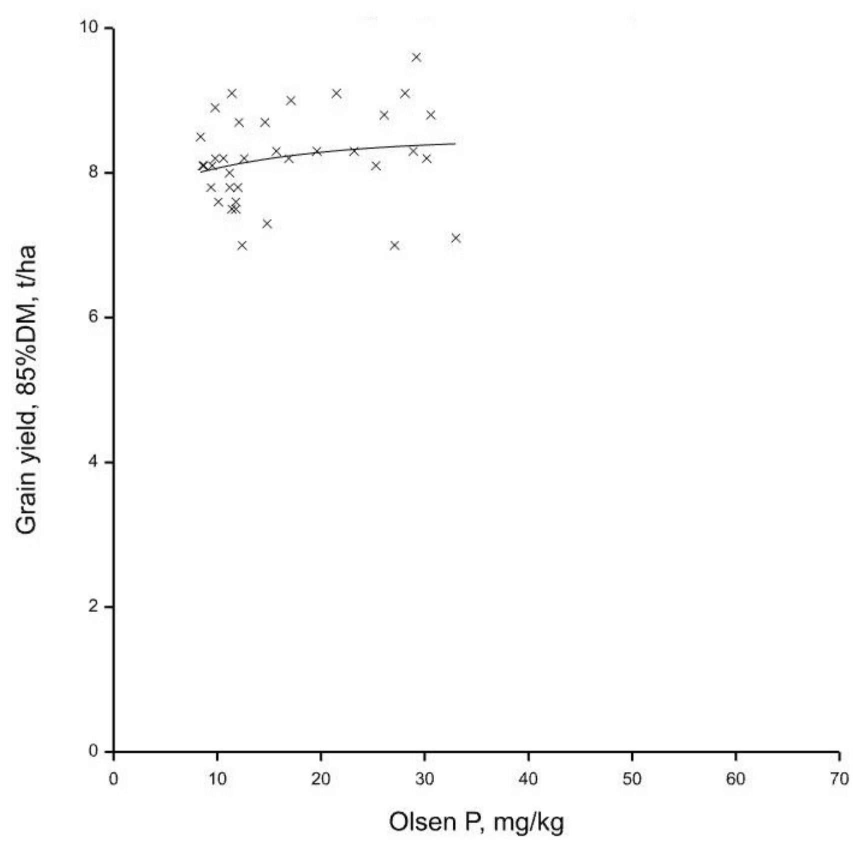

Figure 23. Fitted response curve for the 2013 spring barley crop at the Caythorpe site (no fresh P)

4.6. P offtake and balance

Calculated annual offtakes of P (and as P_2O_5) in grain or seed are shown in Appendix 5 Tables 14 (wheat), 15 (oilseed rape) and 16 (spring barley). Table 30 shows the overall P balance (based on P added in 2009 minus total P removed in three crops harvested in 2010–12) and increase in Olsen P (mg/kg and kg/ha) from 2009 through to spring 2013 for plots that received a treatment of at least 100 kg/ha P fertiliser in autumn 2009. Sub plots that received fresh P treatment in autumn 2011 and 2012 have been excluded. The change in Olsen P is also shown as a % of the P balance.

Table 30. P balance and Olsen P increase for plots receiving >100 kg/ha P fertiliser in autumn 2009

Site	P added	P offtake	P balance	Olsen P mg/kg		Increase in Olsen P		
	kg/ha	kg/ha	kg/ha	2009	2013	mg/kg	kg/ha	% of P balance
Peldon	133	106	27	11.7	22.0	10.3	34	126
	200	108	92	9.0	27.0	18.0	60	66
	288	109	179	14.9	35.5	20.6	68	38
	399	113	286	11.4	58.0	46.6	155	54
Mean	**247**	**109**	**138**	**12.7**	**33.6**	**20.9**	**70**	**69**
Weston	123	66	57	4.6	16.8	12.2	25	45
	178	75	103	4.6	18.5	13.9	29	28
	247	70	177	4.6	18.8	14.2	29	16
	329	74	255	4.6	22.3	17.7	36	14

Mean	**219**	**71**	**148**	**4.6**	**19.1**	**14.5**	**30**	**26**
Great Carlton	121	75	46	13.3	13.4	0.1	0.3	1
	181	83	98	13.4	15.8	2.4	7	7
	261	83	178	14.6	23.3	8.7	26	15
	362	84	278	17.0	35.0	18.0	54	20
Mean	**231**	**81**	**150**	**14.6**	**21.9**	**7.3**	**22**	**11**
Caythorpe	130	59	71	16.8	23.0	6.2	20	29
	195	54	141	10.7	24.0	13.3	43	31
	282	65	217	10.4	26.8	16.4	54	25
	391	67	324	10.8	28.7	17.9	58	18
Mean	**229**	**60**	**169**	**12.4**	**25.2**	**12.8**	**42**	**27**
Cirencester	111	76	35	11.4	21.2	9.8	18	54
	160	80	80	7.6	15.6	8.0	15	19
	221	76	145	10.0	28.2	18.2	34	23
	295	80	215	10.2	24.2	14.0	26	12
Mean	**187**	**78**	**109**	**10.1**	**23.1**	**13.0**	**24**	**31**
Cholsey	106	71	35	8.0	10.9	2.9	8	22
	160	92	68	5.6	15.2	9.6	26	37
	230	89	141	6.5	17.6	11.1	29	21
	319	82	237	6.9	22.3	15.4	41	17
	426	90	336	6.8	29.0	22.2	59	18
Mean	**277**	**85**	**192**	**6.8**	**20.5**	**13.7**	**36**	**21**

The increase in Olsen P as a percentage of the P balance varied considerably between sites and the amounts of P fertiliser applied. Highest values were at Peldon, with an average of 69% for all plots receiving at least 100 kg/ha P fertiliser, while the lowest values were at Great Carlton with an average of 11%. The averages for the other four sites were all within the range 21–31%. At three sites, values were lower for plots that had received the highest amounts of P fertiliser, at the other three sites there was no consistent trend but a tendency for the values to decline as the P balance increased.

Figures 24 to 28 show, for each site (except Weston), the increase in Olsen P between 2009 and spring 2013 against the P Balance (input in autumn 2009 minus offtake in 2010-12). For all P treatments a straight line relationship was fitted to the change in Olsen P / P balance data. This was not constrained to go through the origin as the increase or decrease in Olsen P for a P balance of zero was substantial at some sites. The P balance over three seasons required to give an increase in Olsen P of 1 mg/kg was then calculated for each site (Table 31), based on the soil weights given in Table 8, which also gives the initial estimates for the amount of P required to increase Olsen P by 1 mg/kg. Given that the data in Table 31 are net of crop offtake the amounts of P required to raise Olsen P by 1 mg/kg are similar to the estimates given in Table 8 for Great Carlton, Caythorpe and Cholsey, while at Peldon the amount required was over-estimated. There was an anomaly at Cirencester, where, although the initial increase in Olsen P was as expected,

Figure 10 shows that the initial increase was not maintained when no further P was applied, it would be worth seeking an explanation for this observation. To raise the soil P by 1 Index (8 mg/kg) from mid Index 0 to 1 or 1 to 2 required as little as 67 kg P/ha (154 kg P_2O_5/ha) at Peldon but as much as 204 kg P/ha (470 kg P_2O_5/ha) at Cirencester.

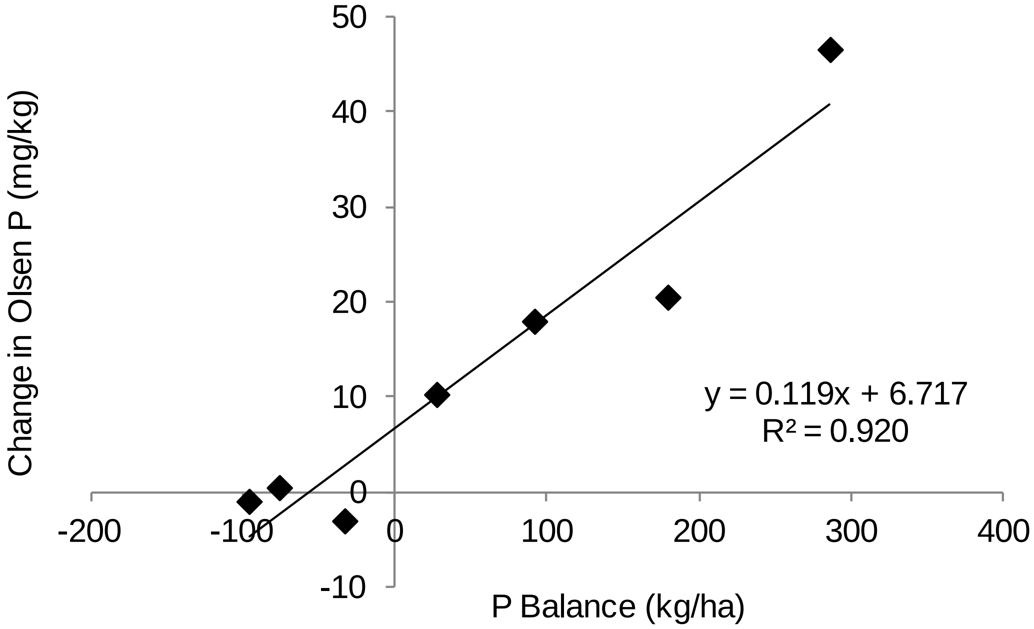

Figure 24. Change in Olsen P (mg/kg) in relation to P balance (kg/ha) at Peldon

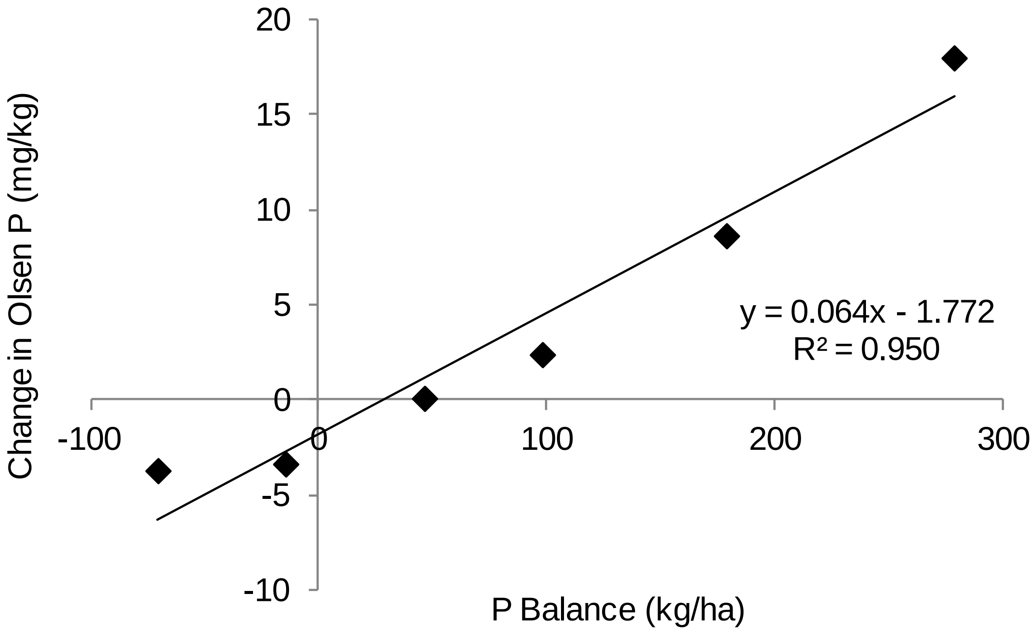

Figure 25. Change in Olsen P (mg/kg) in relation to P balance (kg/ha) at Great Carlton

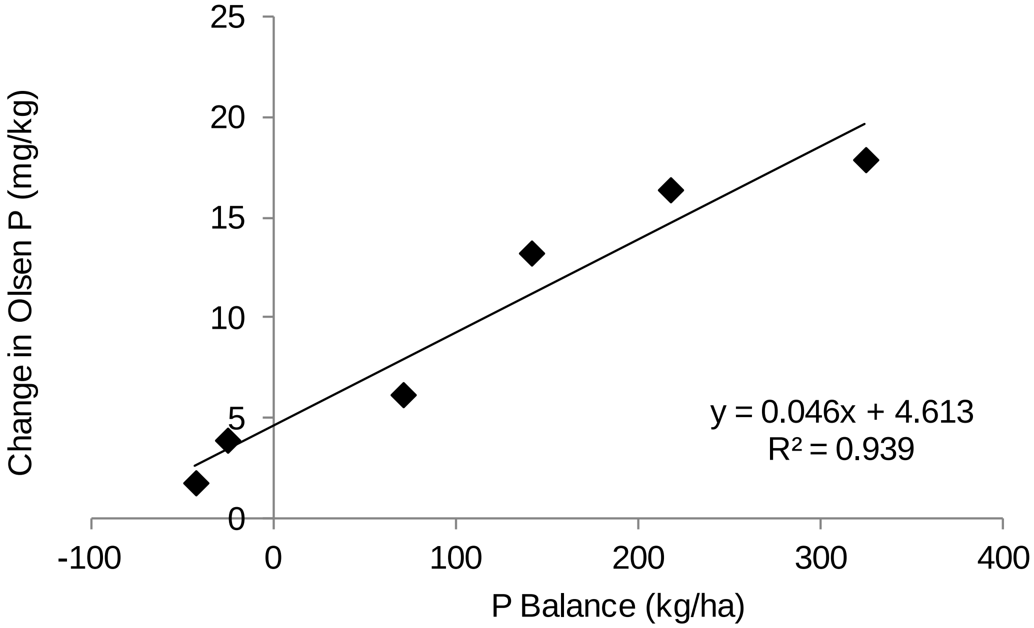

Figure 26. Change in Olsen P (mg/kg) in relation to P balance (kg/ha) at Caythorpe

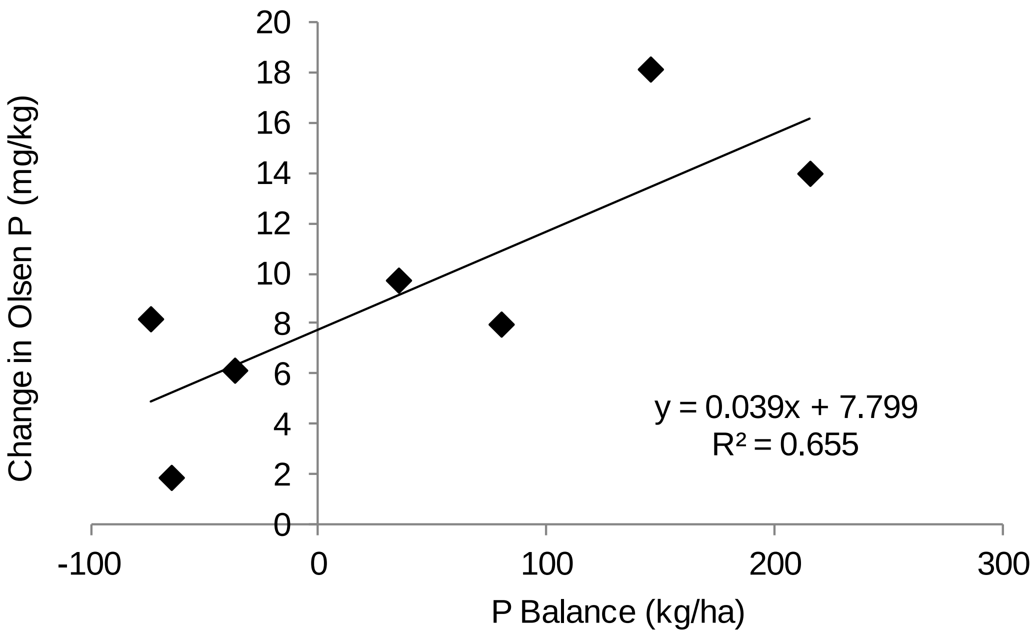

Figure 27. Change in Olsen P (mg/kg) in relation to P balance (kg/ha) at Cirencester

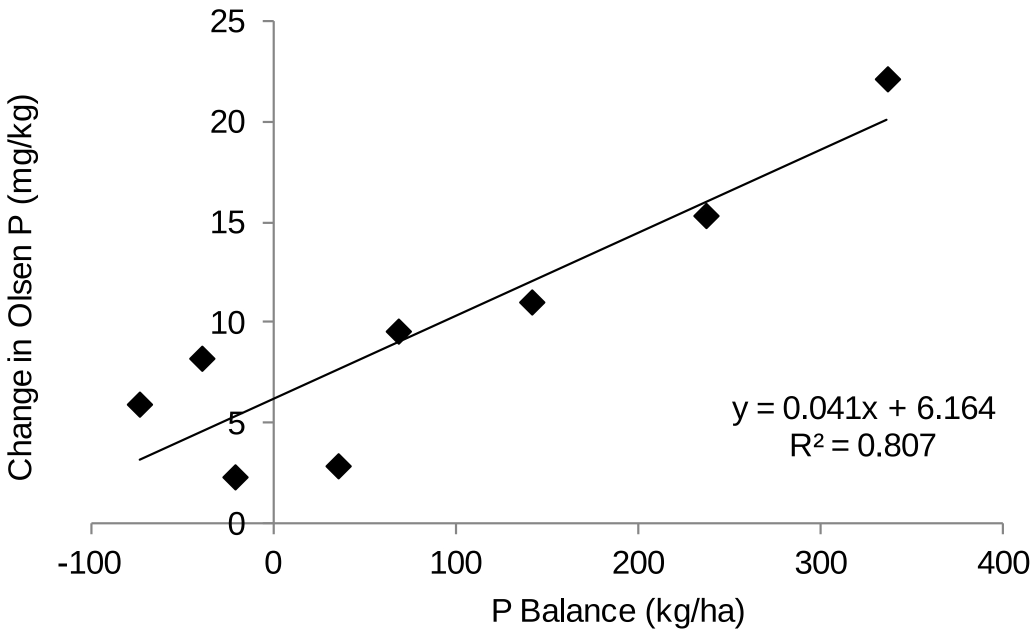

Figure 28. Change in Olsen P (mg/kg) in relation to P balance (kg/ha) at Cholsey

Table 31. Amount of P or P_2O_5 required (net of offtake) to raise Olsen P by 1 mg/kg or 1 Index

	To raise Olsen P by 1 mg/kg		To raise Olsen P from mid Index 0 to 1 or 1 to 2		To raise Olsen P from mid Index 2 to 3	
Site	kg P/ha	kg P_2O_5/ha	kg P/ha	kg P_2O_5/ha	kg P/ha	kg P_2O_5/ha
Peldon	8.4	19.2	67	154	126	288
Great Carlton	15.6	35.7	125	286	234	536
Caythorpe	21.7	49.7	174	398	326	746
Cirencester	25.6	58.7	205	470	384	881
Cholsey	24.4	55.9	195	447	366	839

4.7. Economic analysis

For each site and experiment year, the value of the extra yield obtained less the cost of replacing the amount of P removed (required to maintain the Olsen P level) was calculated, for an increase in P Index from 0 to 1, 1 to 2 or 2 to 3. The net cost or benefit at the end of each experiment year was then determined as described in section 3.10. Results are shown in full in Appendix 8.6, Table 17. With a limited range of Olsen P levels, there were no economic benefits from raising the P Index at Cirencester. At the other sites, over four years (three for Great Carlton), the average value of the extra yield less the cost of replacing the P offtake ranged from £59–165/ha for an increase in P Index from 0 to 1, and from £16–131/ha for an increase in P Index from 1 to 2. Only Peldon gave a consistent economic benefit from raising the P Index from 2 to 3.

Using the average annual value of the extra yield less the cost of replacing the P offtake, the number of cropping years required at each site for the cumulative additional crop value to exceed the cost of first achieving and then maintaining an increase in P Index from 0 to 1, 1 to 2 or 2 to 3 was calculated. In Table 32 the number of years required was calculated using the percentage of the added P that remained as Olsen P that was specific to each site (see Table 4.4, 2011–13 means). In Table 33 the calculation was done using the average for all sites of the percentage (17%) of the added P that remained as Olsen P.

Table 32. Number of cropping years required for the cumulative additional crop value to exceed the cost of achieving and maintaining an increase in P Index (based on P availability at each site)

	Time required for benefit to exceed cost when raising P level		
Site	from Index 0 to 1	from Index 1 to 2	from Index 2 to 3
Peldon	2 years	5 years	6 years
Weston	2 years	>20 years	-
Great Carlton	5 years	6 years	-
Caythorpe	2 years	2 years	-
Cholsey	6 years	3 years	>20 years

Excluding Cirencester, the number of years required for the benefit of raising the P Index from 0 to 1 to exceed the cost ranged from 2 to 6 cropping years. At four of the five sites a similar number of years was required when raising the P Index from 1 to 2. However, more than 20 years would have been required at Weston. Peldon was the only site at which benefit exceeded cost within 6 years for an increase in P Index from 2 to 3. At other sites this could not be determined or would have taken more than 20 years.

Table 33. Number of cropping years required for the cumulative additional crop value to exceed the cost of achieving and maintaining an increase in P Index (based on average P availability)

	Time required for benefit to exceed cost when raising P level		
Site	from Index 0 to 1	from Index 1 to 2	from Index 2 to 3
Peldon	3 years	6 years	7 years
Weston	2 years	>20 years	-
Great Carlton	3 years	4 years	-
Caythorpe	3 years	3 years	-
Cholsey	5 years	3 years	>20 years

Using average rather than site specific P availability, the time required for the benefit of raising the P Index from 0 to 1 to exceed the cost ranged from 2 to 5 cropping years. At four of the five sites the range in cropping years required was 3–6 years when raising the P Index from 1 to 2. More than 20 years would again have been required at Weston. At Peldon, benefit exceeded cost within 7 years for an increase in P Index from 2 to 3. At other sites this could not be determined or again would have taken more than 20 years.

5. Discussion and conclusions

5.1. Discussion

The field experiments reported here have generated a significant amount of new data, but it is important that the limitations of this dataset are recognised. Current advice is based on the findings of extensive research conducted over decades. The duration of this project was limited to four cropping years, although three sites are now continuing within a new HGCA project. The experiments required a range of Olsen P levels to be established in large plots on the same site, on soils for which this did not already exist. It was necessary to achieve this by building-up sites that started with low Olsen P levels, rather than running down sites with high levels, which would not have been possible within the duration of the project.

It was accepted that some time would be required for the increase in Olsen P to stabilise following the application of some very large amounts of TSP required to give the desired range in Olsen P levels at each site. Overall the results support this, although there was some year to year variation at most sites. The large increase in Olsen P measured in spring 2010 following P application in autumn 2009 was not maintained, and Olsen P had declined by spring 2011, the second cropping year. When calculating how much TSP to apply to each plot to create the desired range of Olsen P levels, an assumption had to be made as to what proportion of the P applied would remain as Olsen P after equilibration. Based on previous results from long-term Rothamsted phosphate experiments on three soil types, a value of 15% was assumed, and this proved to be remarkably close to the average value of 17% that was found for the experiments reported here. However, as well as year to year variation, there were differences between sites, with Peldon closer to 25% whereas P availability at Cirencester averaged 10%.

The results highlight both the extent of the spatial variation in Olsen P that can occur in similarly treated soils within one experiment, and the shifts that can occur from year to year in either direction, even where there has been no recent application of P fertiliser. This underlines that Olsen P should be considered as an indication of the amount of plant-available P, not an exact measurement, and that monitoring over a period of years and relating changes to the P balance for each field gives a better indication of plant-available soil P status than a single result in any one year. At all sites, all levels of Olsen P increased between 2012 and 2013 and while this is intriguing the cause is uncertain but may relate to P release through wetting and drying. Further investigation is justified as there could be implications for testing on farm.

At Cirencester it is evident that applying and incorporating a large dose of TSP fertiliser was ineffective at achieving a sustained increase in Olsen P above Index 1. Interestingly, this site was chosen partly because growers reported difficulty in achieving and maintaining a P Index of 2 on similar soils. As shallow soils over limestone and chalk respectively, Cirencester and Cholsey had extractable calcium levels above 4500 mg/l and average pH values above 7.5. This may have contributed to reduced P availability. Research in areas with calcareous soils has shown that the availability of P to plants for uptake is impaired due to the formation of poorly soluble calcium phosphate minerals. In these situations the effect of reduced P availability in alkaline soil is driven by the reaction of P with calcium forming a strong calcium phosphate bond (Hopkins and Ellsworth, 2005). Research in the United States and Southern Australia has shown that fertiliser P management strategies including higher P fertiliser rates, concentrated P fertiliser bands and foliar application using liquid P can be used as alternative strategies on calcareous soils (Hopkins and Ellsworth, 2005 and GRDC, 2012). However, these methods would need further testing under UK production systems to determine their overall effectiveness. Peldon had the next highest level of extractable calcium at about 3000 mg/l, with an average pH of 7.3, but in contrast to Cirencester, the largest proportion of the added P remained as Olsen P at this site.

Cirencester had the highest Olsen P levels in the 30 cm layer below cultivated depth, which suggests that there could have been some leaching of P or physical movement of P or P-enriched mineral soil particles down the profile. As the soil is very shallow and has a high limestone brash content, vertical soil displacement is conceivable and may have contributed to the apparent low availability of the applied P fertiliser. However, despite the large increase in Olsen P in the cultivated layer between 2012 and 2013, there was little change in the 30 cm layer below, suggesting that this was due to an increase in P availability in the cultivated layer rather than P being moved back to the soil surface by cultivation.

Combinable crop yields are greatly influenced by weather. Of the four cropping years included within this project, 2010 was not unusual but the following three years were characterised by extremes. Spring 2011 was exceptionally dry, especially in the East, and this adversely affected wheat yields at Caythorpe and Peldon, and severely limited spring bean yields at Weston. In contrast, 2012 was very wet in all areas from April onwards; with cereal yields affected by waterlogging and a lack of sunshine during grain fill. Essex escaped the worst extremes in the weather and for once was not short of water, leading to very high yields at Peldon. However, at Caythorpe drainage was inadequate and yields were substantially reduced by waterlogging. As a result the field had to be drained after harvest 2012 to enable a crop to be sown in spring 2013. Wet and damaged soils meant difficult establishment conditions at all sites in autumn 2012. This was followed by one of the coldest springs on record. Growth of all crops was affected in early 2013, but most notably, winter oilseed rape, with widespread crop failures including Great Carlton. In many cases wheat yields were better than expected, but poor seedbeds led to greater variability than in previous seasons, including at Peldon. Conversely, spring barley yields at Caythorpe were higher than the wheat yields obtained in any of the previous three seasons.

As Olsen P levels had not yet equilibrated, the yield data from 2010 were excluded from the estimation of critical P levels. However, yields from all years were analysed and means calculated at each P Index. Although the comparisons are based on an unequal number of values such that differences should be treated with caution, there were consistent and often large penalties in the mean yield of wheat grown on soils at P Index 0 or 1 compared to Index 2. Even though Olsen P levels had yet to equilibrate, the penalties seen in 2010 were comparable with those in subsequent years and are considered to be representative. Mean yield penalties were 1.7 t/ha at Index 0 and 0.6 t/ha at Index 1. Even with a large dose of fresh P fertiliser, there was a mean yield penalty of about 0.6 t/ha at Index 0.

According to the Professional Agricultural Analysis Group soil analysis data (PAAG, 2012), 5% of UK arable soil samples tested in 2011/12 were at P Index 0 and 18% were at P Index 1. Assuming that only 40% of these received fresh P fertiliser, based on British Survey of Fertiliser Practice data (Defra, 2013), over the UK wheat area of about 1.9M hectares, this could equate to a loss of as much as 100,000 tonnes of wheat grain each year in fields maintained at Index 0, and 200,000 tonnes on fields maintained at Index 1, worth up to £45M in total. Even if all wheat fields at Index 0 or 1 received fresh P fertiliser, this would still equate to a loss of 60,000 tonnes of wheat worth up to £9M.

Economic analysis shows that the payback from raising the P Index from 0 to 1 can be very rapid (6 years or less), even when a large dose of P fertiliser is used to achieve this in one go. This result compares with current advice in RB209 which is to raise soil P levels by applying higher than maintenance applications of P fertiliser over several years. This latter approach may be important if there is a risk of loss of P on eroded soil to the aquatic environment.

At Peldon, critical Olsen P levels to achieve 98% of maximum yield were very similar in 2012 and 2013, at around 15 mg/kg. This was despite a 40% higher yield in 2012 due to more favourable weather. However, seedbed conditions were poorer for the 2013 crop. In contrast, the critical Olsen P level was much higher in 2011 at about 25 mg/kg, despite a similar yield to 2013. The reason for this is unclear. Great Carlton gave similar critical P levels, at around 17 mg/kg, and maximum yields in 2011 and 2012 under very different weather conditions, although seedbed conditions were good in both years. The two wheat crops with the highest critical P levels, at around 30 mg/kg, were Caythorpe in 2012 and Cholsey in 2013. Caythorpe was very low yielding due to poor soil conditions and waterlogging, which are also likely to have affected rooting and nutrient uptake, but Cholsey had a high maximum yield under better soil conditions. Caythorpe is notable for having fairly large wheat yield penalties at P Indices below 2 in the first three cropping years. However, after the field had been drained in autumn 2012, not only was the spring barley much higher yielding but the yield penalties at P Indices of 0 or 1 were quite small.

Current advice in the Fertiliser Manual RB209 (Defra, 2010) states that "…where crops are grown on soils below the target Index applying large amounts of phosphate (and potash) rarely produces yields equal to those where the crop is grown on soil at the target Index. This is particularly likely where soil P or K Index is 0...” The responses to fresh P fertiliser in this project confirm that even a large amount of P applied to crops at Index 0 will not usually be sufficient to raise wheat yields to the levels achieved at P Index 1, let alone P Index 2. However, a large amount of fresh P fertiliser (larger than that recommended in RB209) applied to crops at Index 1 was, in general, effective at raising yields to the levels achieved at P Index 2. Fresh P was also effective at raising yields for the one oilseed rape crop on which this was tested. This suggests that there is the possibility to maintain soils at P Index 1 rather than 2, provided fresh P is applied annually to each crop although the amount needed is likely to be much larger than the normal maintenance application, and the method of application could be important also. A large application to a soil at P Index 1 could slowly increase the P Index from 1 to 2. More importantly, it would still be necessary to replace the amount of P removed in the harvested crop irrespective of whether soils was being maintained at P Index 1 or 2. It may also be possible to maintain soils at P Index 1 if the application of fresh P and maximum root growth were restricted to the same volume of soil. The economics of such an approach would need to be carefully monitored.

HGCA Research Review 74 reported that Olsen P increased by 18–20% of the P balance on the silty clay loam on the Exhaustion land from 1986–1991, and by 6–25% on the sandy clay loam at Saxmundham from 1965–1967 (Johnston and Poulton, 2011). The mean Olsen P increases of 11 to 31% of P balance observed at five of the six new sites are therefore comparable with the previous findings, but at the Peldon site the mean increase was much higher at 69%. P balances required to raise Olsen P by 8 mg/kg from Index 1 to 2 were 143 kg P/ha for the Exhaustion land and 133 kg P/ha at Saxmundham. These values are in the middle of the range recorded here. The difference between Peldon and Cirencester in the amount of P required reflects the apparent availability at each site of the P fertiliser applied in autumn 2009. Clearly there is still much to be researched about the link between soil type and P equilibria.

5.2. Conclusions

Results over four cropping years from six new sites on contrasting soils generally support current advice, which is to maintain soil at P Index 2 for combinable crops. As in most experiments, there were a few cases where the critical Olsen P to achieve 98% of maximum yield exceed 25 mg/kg (i.e.at P Index 3) but in these few cases it could not be justified economically to increase the Olsen P to these higher values, and to be able to make an economic case for raising soils above Index 2 on some soils would require consistent results over many years. There were differences between sites and crops or years in the responsiveness of yield to Olsen P. These were not obviously related to soil conditions or other crop or site factors. However, the extremes of weather experienced during the project mean that further cropping years are required to enable any appreciable change in current recommendations. At Index 0 even a large dose of fresh P fertiliser did not raise wheat yields to the level achieved at Index 1, but in some cases yields at Index 1 were raised to those at Index 2 when a large amount of fresh P was added. This offers the possibility to manage soils for optimum yield at P Index 1, but this would be very dependent on soil type and the frequency, amount and method of application of fresh P fertiliser.

There were differences between sites in the apparent availability of the applied P fertiliser once the increases in Olsen had equilibrated, although the average of 17% in these experiments was very similar to the 13-15% reported in other experiments. Availability was highest and lowest on the two soils with pH above 7.5; it was highest on the heavy clay soil at Peldon and lowest on the shallow limestone soil at Cirencester. When cropping continued without further P addition, the initial increase in Olsen P at Peldon declined slightly but at Cirencester it was not maintained in subsequent years. This difference between the two soils with similar pH is a matter of considerable interest and warrants further investigation to explain the difference in view of the large area of calcareous soils growing combinable crops in the UK, and to seek alternative sources of P that could be added to such soils to increase and maintain Olsen P levels.

6. Acknowledgements

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8. Appendices

Appendix 1 P analysis

Classification of P analysis into indices

In the UK plant-available phosphorus in soil is typically determined by one of two methods. The most widely used by commercial soil analysis laboratories in England, Wales and Northern Ireland, and the method used for analyses reported in this project, is 'Olsen's Method' (Olsen *et al.*, 1954). This involves extracting a representative soil sample with a dilute solution of sodium bicarbonate (0.5 M $NaHCO_3$) at pH 8.5, with the P extracted referred to as Olsen P. The second method used to determine plant-available P is Resin P, developed by Levington Agriculture (Hislop and Cooke, 1968). This involves equilibration with an anionic resin in a soil suspension. The 8^{th} edition of the Fertiliser Manual (RB209) (Defra, 2010) assigns soil to a P Index according to the values obtained with either method. Most agricultural soils are within the range P Index 0 to 5. The corresponding Olsen P and resin P values are shown in Appendix Table 1.

Appendix Table 1. Olsen P and resin P values for each P Index

P Index	Olsen P (mg/litre)	Resin P (mg/litre)
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
6	101-140	
7	141-200	
8	201-280	
9	>280	

Conventions used for expressing P content

Results for crop and soil analyses are usually reported in terms of phosphorus (P) content. Most commercial laboratories, following the procedure described in MAFF booklet RB427, The Analysis of Agricultural Materials, use a volume of soil and known volume of extractant, with Olsen P results reported in mg P/litre. For this project, as with most research laboratories, Rothamsted used a known mass of soil and volume of extractant, so Olsen P results are reported in mg P/kg.

Phosphorus concentration in a fertiliser is given in terms of phosphate (P_2O_5), as required by The Fertilisers Regulations (1991). In the Fertiliser Manual (RB209) (Defra, 2010), recommendations for phosphate applications are also given as P_2O_5 to facilitate calculation of the amount of fertiliser needed. Also in RB209 typical removals of phosphorus by crops are also expressed in terms of P_2O_5 so that the amount of P removed by a crop can be easily related to the amount of fertiliser need to replace the amount of P removed.

Appendix 2 additional site details

Appendix Table 2. Previous cropping and manure history for each site

	Cropping History					Manure use				
Site	04/05	05/06	06/07	07/08	08/09	04/05	05/06	06/07	07/08	08/09
Peldon	wheat	wheat	wheat	wheat	wheat	-	-	-	-	-
Weston	barley	w beans	wheat	barley	s beans	-	-	-	-	yes
Great Carlton	barley	osr	wheat	barley	wheat	-	-	-	-	-
Caythorpe	grass	grass	grass	grass	wheat	-	-	-	-	-
Cirencester	barley	osr	wheat	barley	osr	-	-	-	-	-
Cholsey	-	wheat	wheat	osr	wheat	-	-	-	-	-

Appendix Table 3. Soil K and Mg levels for each site in spring 2009 and 2012

		Spring 2009		Spring 2012	
Site	Field Name	Soil K (mg/l)	Soil Mg (mg/l)	Soil K (mg/l)	Soil Mg (mg/l)
Peldon	Tanners	137	186	184	167
Weston	Hungry Hill	158	77	169	97
Great Carlton	-	95*	94	96	123
Caythorpe	New Field	152*	110	170	107
Cirencester	Paddimore	209	70	289	99
Cholsey	8D	264	66	171	43

*These sites received 115 kg/ha K_2O as 60% muriate of potash on 18/03/2010

Appendix 3 Full soil structure quality assessment results

Appendix Table 4. Seedbed quality scores assessed early after drilling.

Site	Date	Area	Overall block	First (top) layer		Second layer		Third (bottom) layer		Overall block
			Depth (cm)	Depth of (cm)	Sq score	Depth (cm)	Sq score	Depth (cm)	Sq score	Sq score*
Great Carlton	10/05/11	1	20	10	3.5	5	2.0	5	2.0	2.8
		2	10	10	4.0	-	-	-	-	4.0
		3	15	15	4.5	-	-	-	-	4.5
		4	15	15	3.5	-	-	-	-	3.5
Caythorpe	10/05/11	1	20	14	1.0	6	1.5	-	-	1.2
		2	20	20	1.5	-	-	-	-	1.5
		3	20	10	1.0	10	2.0	-	-	1.5
		4	20	15	1.5	5	2.0	-	-	1.6
Weston	20/02/13	1	20	20	4.0	-	-	-	-	4.0
		2	20	20	5.0	-	-	-	-	5.0
		3	20	20	5.0	-	-	-	-	5.0
		4	20	20	5.0	-	-	-	-	5.0
Peldon	21/02/13	1	20	4	1.0	10	2.5	4	3.5	2.2
		2	20	4	1.5	10	2.5	4	3.0	2.2
		3	20	6	1.0	9	2.0	5	2.5	1.8
		4	20	8	2.0	12	3.5	-	-	2.9
Cholsey	13/03/13	1	20	5	1.0	15	2.5	-	-	2.1
		2	20	5	2.0	15	2.5	-	-	2.4
		3	20	8	1.5	12	2.5	-	-	2.1
		4	20	5	2.0	15	3.0	-	-	2.8
Cirencester	13/03/13	1	20	5	2.5	15	3.0	-	-	2.9
		2	15	4	2.5	11	2.5	-	-	2.5
		3	20	4	2.0	16	2.5	-	-	2.4

*Overall block score = ((thickness of first layer) x (score of first layer)/overall block depth)

+ ((thickness of second layer) x (score of second layer)/overall block depth)

+ ((thickness of third layer) x (score of third layer)/overall block depth)

e.g. (7 x 1)/25 + (5 x 3)/25 + (13 x 3.5)/25 = 0.28 + 0.6 + 1.82 = Sq 2.7

Appendix 4 Full Olsen P data, mg/kg

Appendix Table 5. Peldon, Olsen P in 0–25cm depth of soil

Large plot	2009	2010	2010	2011	2012 Actual		2013 Actual	
(and sub plot)	Initial	Expected	Actual	Actual	No fresh P	Fresh P	No fresh P	Fresh P
1 a					35.7		47.7	
b	11.4	29.4	68.6	45.6	50.9		68.2	
c						42.1		40.1
2 a						17.1		17.4
b	10.4	10.4	13.8	11.4	9.1		9.8	
c					7.3		9.1	
3 a					8.3		10.0	
b	9.8	9.8	14.8	13.0	8.7		12.0	
c						26.7		17.0
4 a					15.7		18.9	
b	9.4	15.4	37.8	16.2	19.5		34.1	
c						23.5		21.8
5 a						33.5		35.2
b	9.0	18.0	44.6	33.0	23.5		24.3	
c					23.7		29.6	
6 a					10.9		9.5	
b	8.6	8.6	12.2	11.0	11.3		11.4	
c						16.1		17.1
7 a					36.9		35.2	
b	12.2	25.2	38.8	34.6	40.1		47.9	
c						36.5		48.8
8 a						12.9		24.1
b	7.0	7.0	10.6	11.6	12.7		10.2	
c					9.7		9.2	
9 a					7.7		11.8	
b	12.4	13.4	18.0	14.4	13.1		14.7	
c						22.1		24.7
10 a					28.9		35.9	
b	18.2	31.2	59.8	38.6	36.1		30.3	
c						37.3		41.6
11 a						10.3		29.4
b	10.4	10.4	8.2	8.4	7.3		7.6	
c					8.5		9.0	
12 a					34.5		28.7	
b	14.4	27.4	98.0	34.2	55.5		34.6	
c						47.3		38.1
13 a					11.5		10.0	
b	12.6	13.6	13.0	11.2	9.3		15.4	
c						17.3		14.6
14 a						24.5		23.7
b	14.0	20.0	21.8	18.4	21.3		16.7	
c					15.5		18.3	
15 a					8.5		8.7	
b	8.4	8.4	6.4	9.0	9.3		7.5	
c						18.9		19.3
16 a					5.9		6.6	
b	12.2	12.2	6.8	9.4	5.9		6.9	
c						8.9		16.1
17 a						13.7		25.4
b	13.6	16.6	9.6	12.2	8.9		12.0	
c					7.1		9.2	
18 a					5.5		7.1	
b	11.6	11.6	8.2	6.8	4.9		6.6	
c						22.5		22.7

Appendix Table 6. Weston, Olsen P, mg/kg, in 0–15cm depth of soil

Large plot (and sub plot)	2009 Initial*	2010 Expected	2010 Actual	2011 Actual	2012 Actual No fresh P	2012 Actual Fresh P	2013 Actual No fresh P	2013 Actual Fresh P
1 a						12.0		12.8
b	4.6	22.6	55.0	13.4	16.0		40.0	
c					12.0		13.0	
2 a						8.2		10.1
b	4.6	13.6	51.4	4.6	8.4		17.5	
c					5.4		12.8	
3 a					4.8		16.2	
b	4.6	4.6	5.4	7.0	4.2		9.7	
c						3.4		14.8
4 a						15.0		13.3
b	4.6	7.6	19.0	17.0	17.8		16.9	
c					11.0		26.2	
5 a						12.4		34.9
b	4.6	7.6	9.6	7.0	10.0		16.4	
c					14.0		17.3	
6 a					14.6		19.5	
b	4.6	28.6	58.2	8.0	7.4		25.2	
c						13.6		10.8
7 a						12.4		8.5
b	4.6	10.6	23.2	11.4	30.2		23.9	
c					18.6		17.7	
8 a						19.4		19.0
b	4.6	17.6	26.8	24.4	14.0		26.1	
c					21.2		13.0	
9 a					28.4		17.7	
b	4.6	4.6	6.2	24.2	22.0		24.6	
c						14.8		50.0
10 a						9.6		16.0
b	4.6	7.6	9.6	12.4	12.2		24.5	
c					12.2		23.2	
11 a						20.8		24.2
b	4.6	10.6	27.2	13.0	23.0		54.9	
c					35.6		30.2	
12 a					12.0		12.6	
b	4.6	22.6	43.8	17.4	10.0		9.3	
c						6.6		10.6
13 a						10.6		16.8
b	4.6	13.6	18.2	9.6	22.0		16.9	
c					14.8		19.6	
14 a						25.4		18.4
b	4.6	28.6	73.0	29.4	23.4		18.0	
c					22.6		26.2	
15 a					25.8		17.8	
b	4.6	17.6	27.2	22.4	20.6		16.7	
c						28.4		30.7
16 a						19.8		46.2
b	4.6	4.6	5.8	21.2	22.4		15.1	
c					10.2		14.6	
17 a						18.6		29.9
b	4.6	7.6	13.0	25.8	38.4		22.1	
c					32.0		26.7	
18 a					22.8		15.4	
b	4.6	4.6	6.0	30.8	27.8		21.0	
c						17.4		27.2

*Experiment had to be repositioned slightly after sampling so 2009 is an average of the measured values (range 3.4-5.8).

Appendix Table 7. Great Carlton, Olsen P, mg/kg, in 0–22cm depth of soil

Large plot (and sub plot)	2009 Initial	2010 Expected	2010 Actual	2011 Actual	2012 Actual		2013 Actual	
					No fresh P	Fresh P	No fresh P	Fresh P
1 a					8.9		9.5	
b	12.4	12.4	12.0	10.6	9.5		10.0	
c						12.5		20.4
2 a						16.7		27.1
b	14.8	23.8	25.4	14.4	14.9		16.2	
c					15.7		18.2	
3 a						14.9		25.4
b	14.2	17.2	15.2	11.0	11.7		11.8	
c					11.7		12.3	
4 a					23.9		25.1	
b	14.8	27.8	36.8	20.8	22.3		24.7	
c						24.5		47.1
5 a						8.9		23.8
b	14.2	14.2	8.0	8.6	7.3		8.7	
c					8.3		8.9	
6 a						9.9		31.0
b	13.4	13.4	8.0	7.6	7.9		9.4	
c					8.1		8.2	
7 a					27.3		45.0	
b	16.2	34.2	43.2	25.2	28.7		28.5	
c						35.3		25.3
8 a						11.7		19.4
b	13.4	13.4	9.6	8.6	9.5		8.5	
c					10.1		8.7	
9 a						18.7		25.9
b	14.4	20.4	21.2	13.4	13.9		12.5	
c					13.5		13.8	
10 a					8.5		8.8	
b	12.8	12.8	7.6	7.6	8.7		11.1	
c						9.3		20.0
11 a						9.5		25.2
b	11.8	11.8	9.2	7.8	8.3		8.6	
c					8.3		8.2	
12 a						9.1		26.6
b	13.2	13.2	7.4	7.2	8.3		8.0	
c					7.5		9.0	
13 a					22.9		20.2	
b	14.4	27.4	35.0	26.4	27.5		23.0	
c						30.7		43.0
14 a						14.9		26.6
b	10.0	10.0	8.0	8.0	8.9		9.2	
c					8.1		8.1	
15 a						13.5		27.6
b	12.2	18.2	18.4	10.6	14.3		13.2	
c					12.9		13.9	
16 a					35.5		40.0	
b	17.8	35.8	65.8	27.4	29.1		26.4	
c						31.5		49.0
17 a						13.7		33.6
b	13.6	16.6	14.8	8.4	9.9		9.6	
c					8.9		8.4	
18 a						18.9		26.6
b	12.0	21.0	28.6	12.2	15.7		14.6	
c					14.3		14.2	

Appendix Table 8. Caythorpe, Olsen P, mg/kg, in 0–22cm depth of soil

Large plot	2009	2010	2010	2011	2012 Actual		2013 Actual	
(and sub plot)	Initial	Expected	Actual	Actual	No fresh P	Fresh P	No fresh P	Fresh P
1 a						54.1		63.0
b	25.4	31.4	31.2	34.0	30.5		33.0	
c					21.5		27.1	
2 a					25.1		30.2	
b	11.2	20.2	29.0	24.2	21.3		25.3	
c						30.7		33.4
3 a					9.9		12.4	
b	7.0	7.0	9.6	9.2	10.5		11.4	
c						15.3		16.5
4 a						28.3		28.7
b	11.4	12.4	19.4	18.2	17.3		19.6	
c					12.5		15.7	
5 a					19.9		26.1	
b	10.4	23.4	32.8	22.8	21.5		28.9	
c						30.1		26.1
6 a					10.9		11.8	
b	9.6	9.6	9.4	10.4	9.3		12.6	
c						13.1		23.9
7 a						24.5		40.6
b	15.0	15.0	14.8	11.6	12.9		14.8	
c					10.1		11.2	
8 a					11.3		9.5	
b	8.0	8.0	11.8	9.8	9.9		9.8	
c						17.7		22.2
9 a					9.1		9.8	
b	8.6	8.6	10.2	7.8	9.1		8.7	
c						14.9		16.7
10 a						44.9		52.2
b	10.8	28.8	47.4	30.4	26.9		29.2	
c					26.5		28.1	
11 a					11.3		11.8	
b	11.8	11.8	9.2	8.4	9.3		11.2	
c						16.5		18.2
12 a					14.3		17.1	
b	8.2	14.2	16.2	13.2	13.3		14.6	
c						17.1		20.8
13 a						29.3		38.5
b	10.2	19.2	18.6	16.6	16.7		16.9	
c					17.9		23.2	
14 a					9.1		12.1	
b	6.4	6.4	8.0	6.2	7.1		9.4	
c						12.1		21.6
15 a					6.3		8.4	
b	6.0	6.0	5.8	6.2	5.3		8.6	
c						12.3		15.8
16 a						30.5		38.2
b	10.4	23.4	30.0	26.2	19.5		21.5	
c					25.1		30.6	
17 a					8.7		12.0	
b	8.2	9.2	9.8	8.4	7.9		10.1	
c						16.5		13.4
18 a					8.3		11.4	
b	8.4	9.4	12.0	7.6	7.1		10.6	
c						19.5		9.1

Appendix Table 9. Cirencester, Olsen P, mg/kg, in 0–15cm depth of soil

Large plot (and sub plot)	2009 Initial	2010 Expected	2010 Actual	2011 Actual	2012 Actual		2013 Actual	
					No fresh P	Fresh P	No fresh P	Fresh P
1 a						24.1		29.9
b	7.6	16.6	19.6	12.8	14.1		21.1	
c					10.7		18.9	
2 a						18.7		21.3
b	7.6	20.6	28.0	11.2	9.7		14.0	
c					11.5		17.2	
3 a						19.3		20.3
b	9.2	9.2	9.8	9.8	10.7		15.4	
c					8.5		13.1	
4 a						10.9		31.0
b	10.2	34.2	26.4	13.8	14.7		23.4	
c					14.1		24.9	
5 a						23.7		29.1
b	8.6	9.6	15.0	12.4	16.5		6.3	
c					15.7		14.7	
6 a						18.1		21.0
b	6.6	6.6	11.6	9.8	10.3		21.0	
c					10.7		17.7	
7 a						12.7		17.0
b	10.0	13.0	8.6	9.0	10.1		17.8	
c					9.3		11.6	
8 a						44.1		25.0
b	8.2	26.2	42.6	20.0	14.1		36.4	
c					14.5		25.4	
9 a						25.9		20.9
b	6.6	6.6	19.0	11.8	12.7		20.5	
c					15.1		13.5	
10 a						16.9		33.0
b	11.0	11.0	16.0	11,4	11.5		15.6	
c					11.7		15.7	
11 a						15.9		29.9
b	17.0	20.0	24.0	11.6	14.7		26.0	
c					10.5		22.0	
12 a						18.1		37.0
b	15.2	24.2	21.4	12.4	11.5		23.2	
c					12.7		21.3	
13 a						18.7		34.8
b	10.6	10.6	14.8	15.2	13.7		17.5	
c					12.9		21.6	
14 a						25.5		34.0
b	12.8	12,8	13.2	12.8	11.5		24.4	
c					10.3		19.3	
15 a						24.7		33.7
b	11.8	29.8	28.0	15.2	13.5		27.0	
c					11.3		23.7	
16 a						19.3		27.1
b	10.6	10.6	16.6	14.0	15.5		18.1	
c					14.7		18.8	
17 a						21.1		33.9
b	11.6	14.6	19.8	14.0	16.5		17.2	
c					16.1		19.5	
18 a						20.7		18.5
b	8.2	8.2	16.6	11.4	12.3		14.5	
c					10.7		15.3	

Appendix Table 10. Cirencester, Olsen P, mg/kg, in 15–30cm depth of soil

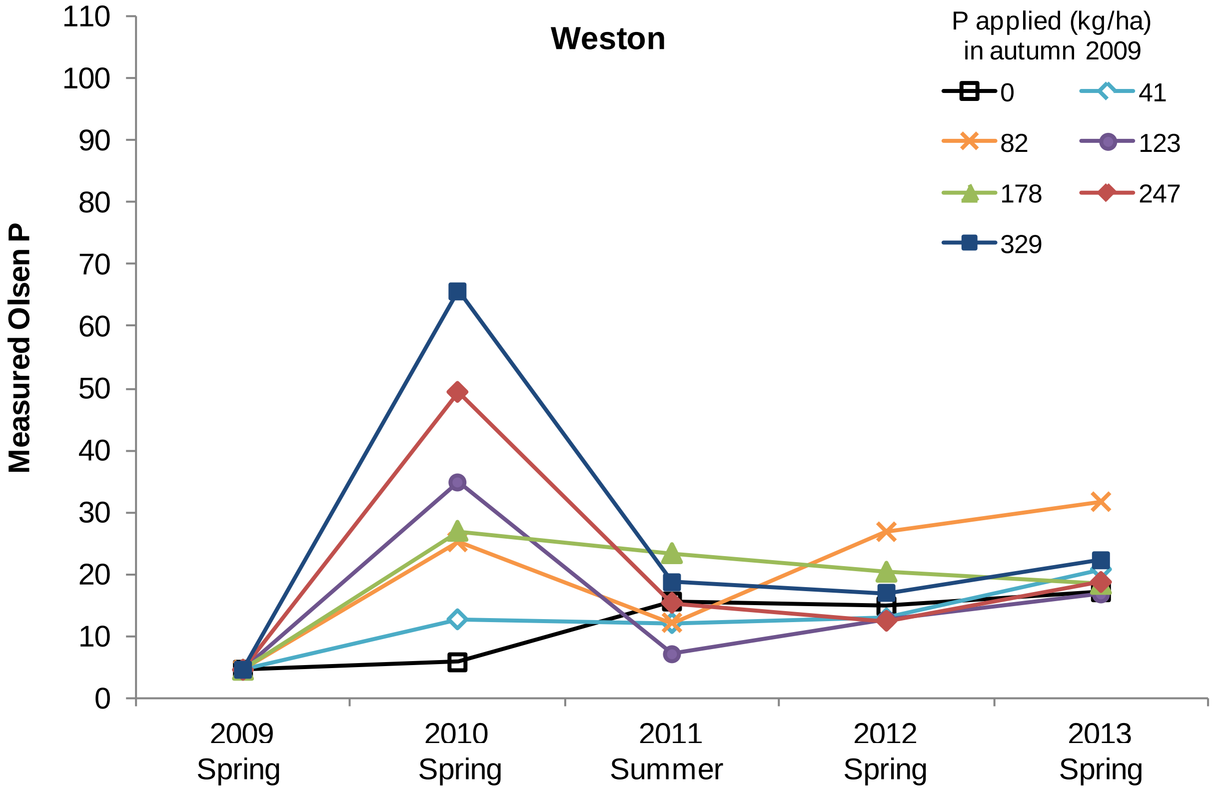
Large plot	2012 Actual		2013 Actual	
(and sub plot)	No fresh P	Fresh P	No fresh P	Fresh P
1 a		11.6		13.6
b	6.8		12.2	
c	10.4		6.7	
2 a		8.4		8.5
b	6.0		5.2	
c	5.8		6.4	
3 a		5.6		5.8
b	5.6		4.7	
c	5.0		3.1	
4 a		8.2		11.2
b	8.4		8.0	
c	8.2		8.0	
5 a		9.4		5.8
b	9.0		6.0	
c	7.0		7.5	
6 a		8.0		10.0
b	6.8		7.8	
c	5.6		7.5	
7 a		7.4		6.7
b	6.8		5.2	
c	6.6		4.0	
8 a		12.8		7.6
b	7.6		7.7	
c	8.4		8.3	
9 a		8.8		7.1
b	10.8		7.0	
c	6.4		7.4	
10 a		8.2		7.5
b	7.2		8.4	
c	7.6		9.5	
11 a		9.6		9.3
b	8.8		10.9	
c	7.8		7.4	
12 a		8.2		10.6
b	11.4		12.8	
c	9.4		9.8	
13 a		10.8		11.2
b	10.4		8.9	
c	8.6		8.6	
14 a		9.4		10.4
b	7.6		8.9	
c	7.6		8.3	
15 a		11.4		14.4
b	9.2		15.5	
c	7.6		12.4	
16 a		8.2		7.0
b	7.6		7.5	
c	8.2		7.1	
17 a		7.6		10.5
b	6.6		6.0	
c	6.4		7.3	
18 a		6.2		9.9
b	7.6		4.7	
c	5.6		6.9	

Appendix Table 11. Cholsey, Olsen P, mg/kg, in 0–20cm depth of soil

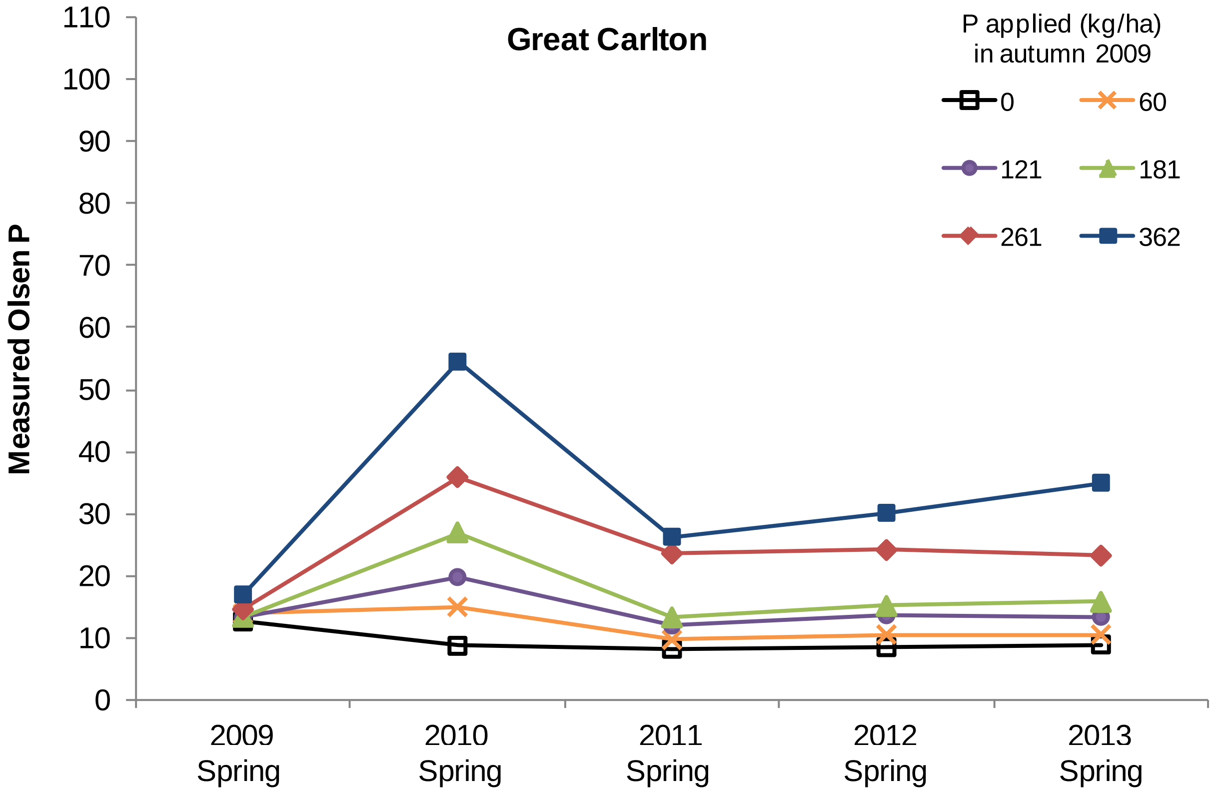
Large plot (and sub plot)	2009 Initial	2010 Expected	2010 Actual	2011 Actual	2012 Actual		2013 Actual	
					No fresh P	Fresh P	No fresh P	Fresh P
1 a						12.3		23.4
b	8.0	14.0	26.8	12.2	10.3		10.7	
c					10.7		11.0	
2 a						10.1		19.8
b	6.0	6.0	6.8	6.4	7.1		10.2	
c					6.5		8.8	
3 a						9.7		24.1
b	8.0	11.0	24.2	6.4	8.3		11.2	
c					8.3		10.1	
4 a						29.7		27.9
b	7.2	25.2	52.8	27.8	19.7		17.9	
c					18.7		16.8	
5 a						10.1		26.7
b	7.8	7.8	9.4	6.4	4.7		10.9	
c					4.7		9.3	
6 a						6.1		29.5
b	7.4	7.4	8.4	6.4	5.7		9.5	
c					4.9		9.5	
7 a						25.5		40.6
b	7.0	31.0	75.0	33.6	20.3		25.7	
c					18.9		23.2	
8 a						5.9		27.5
b	5.6	5.6	9.8	14.8	5.1		10.0	
c					5.7		10.8	
9 a						29.1		36.2
b	6.2	19.2	56.4	24.0	18.3		23.5	
c					18.1		18.4	
10 a						16.7		36.9
b	6.6	24.6	29.2	20.0	16.1		28.7	
c					20.9		25.5	
11 a						57.9		39.4
b	6.6	30.6	105.0	40.6	22.7		37.2	
c					30.1		29.6	
12 a						10.7		21.9
b	4.6	4.6	6.6	28.6	7.1		17.3	
c					6.3		20.3	
13 a						5.7		30.5
b	5.6	5.6	6.0	8.6	5.5		15.9	
c					5.7		13.0	
14 a						30.5		29.2
b	5.6	14.6	26.6	25.6	10.7		16.4	
c					18.7		13.9	
15 a						6.3		28.5
b	6.2	8.2	8.6	21.4	12.5		16.4	
c					7.7		15.7	
16 a						11.5		30.0
b	7.0	10.0	18.4	8.4	6.7		9.5	
c					5.5		8.5	
17 a						8.3		19.8
b	6.0	8.0	11.4	9.0	6.3		14.5	
c					6.3		10.7	
18 a						15.1		30.8
b	6.8	19.8	60.8	18.8	12.3		12.4	
c					15.9		15.7	

Appendix Table 12. Number of plots in each P Index in 2010, 2011, 2012 and 2013

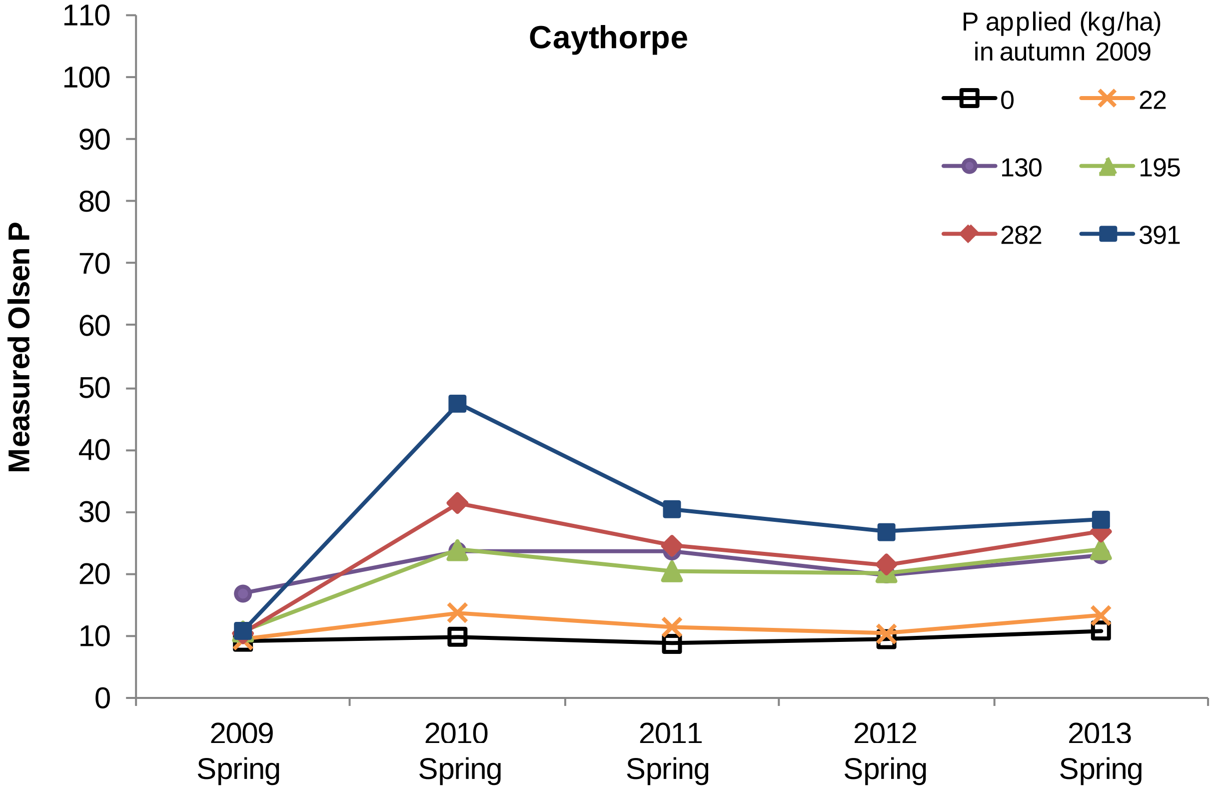
Site	P Index	Olsen P mg/kg	2009 Large	2010 Large	2011 Large	2012 No fresh P		2013 No fresh P	
						Individ.	Mean	Individ.	Mean
Peldon	0	0-9	5	4	4	16	7	11	4
	1	10-15	12	6	7	6	4	11	7
	2	16-25	1	2	2	6	3	4	1
	3	26-45	0	3	4	6	4	7	5
	4+	46+	0	3	1	2	0	3	1
Weston (plots 16-18 excluded after 2010)	0	0-9	18	4	4	5	2	1	0
	1	10-15	0	3	5	11	6	5	3
	2	16-25	0	3	5	10	6	18	10
	3	26-45	0	4	1	4	1	5	2
	4+	46+	0	4	0	0	0	1	0
Great Carlton	0	0-9	0	6	8	14	8	14	7
	1	10-15	16	4	6	12	6	12	6
	2	16-25	2	3	2	5	2	6	3
	3	26-45	0	4	2	5	2	4	2
	4+	46+	0	1	0	0	0	0	0
Caythorpe	0	0-9	8	4	7	12	5	4	2
	1	10-15	9	6	4	11	7	17	8
	2	16-25	1	3	4	10	4	7	3
	3	26-45	0	4	3	3	2	8	5
	4+	46+	0	1	0	0	0	0	0
Cirencester	0	0-9	8	1	1	2	0	1	0
	1	10-15	9	5	16	29	16	8	4
	2	16-25	1	8	1	5	2	24	13
	3	26-45	0	4	0	0	0	3	1
	4+	46+	0	0	0	0	0	0	0
Cholsey	0	0-9	18	6	7	19	9	3	1
	1	10-15	0	2	2	5	4	16	10
	2	16-25	0	2	4	11	4	12	5
	3	26-45	0	3	5	1	1	5	2
	4+	46+	0	5	0	0	0	0	0



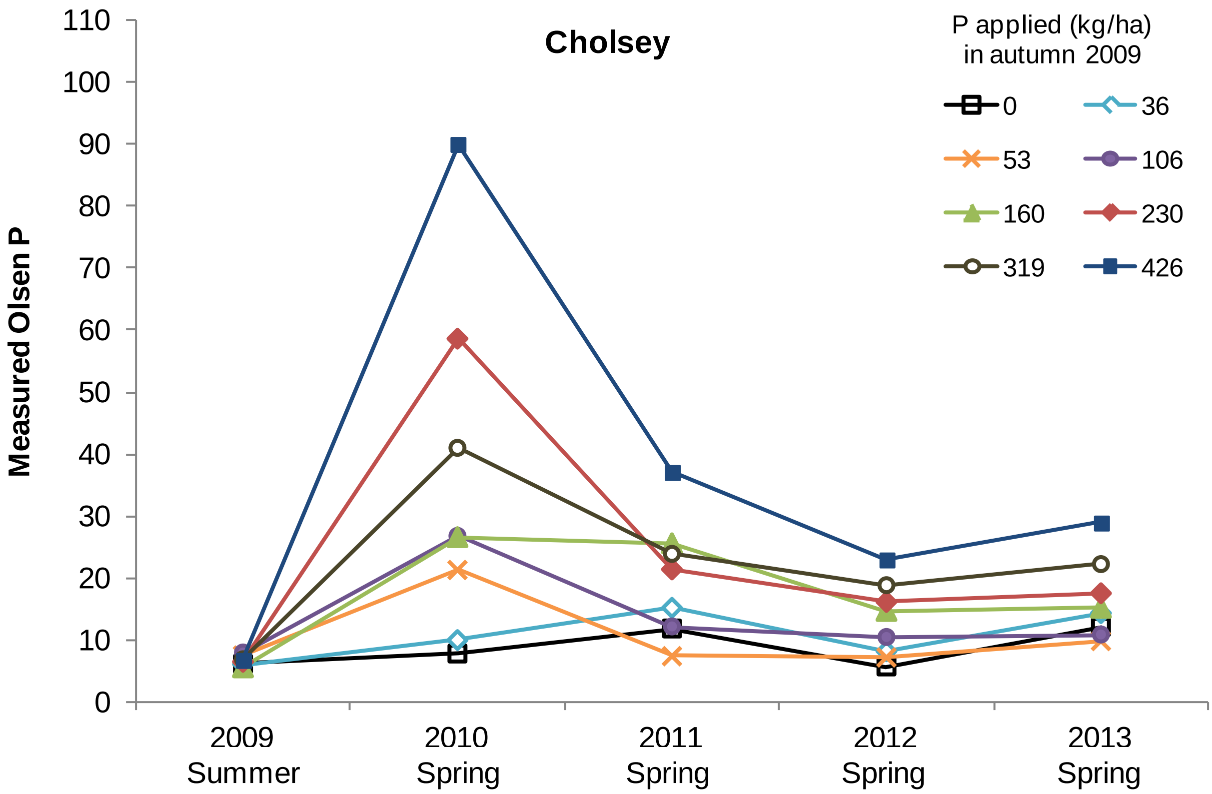
Appendix Figure 1. Average measured Olsen P, mg/kg, at the Weston site from 2009 to 2013, for plots receiving different amounts of P fertiliser in autumn 2009



Appendix Figure 2. Average measured Olsen P, mg/kg, at the Great Carlton site from 2009 to 2013, for plots receiving different amounts of P fertiliser in autumn 2009



Appendix Figure 3. Average measured Olsen P, mg/kg, at the Caythorpe site from 2009 to 2013, for plots receiving different amounts of P fertiliser in autumn 2009



Appendix Figure 4. Average measured Olsen P, mg/kg, at the Cholsey site from 2009 to 2013, for plots receiving different amounts of P fertiliser in autumn 2009

Appendix Table 13. Change in average Olsen P levels for the fresh P sub plots, grouped by their initial P Index in 2011

		Olsen P (mg/kg)			Apparent	Olsen P (mg/kg)		Apparent
Site	2011 P Index	2011 average	2012 average	Change 2012-11	% available	2013 average	Change 2013-11	% available
Peldon	0	8.4	15.2	6.8	25.8	21.9	13.5	25.7
	1	12.1	19.1	7.0	26.8	20.0	7.9	15.1
	2	17.3	24.0	6.7	25.6	22.8	5.5	10.4
	3+	37.2	39.3	2.1	8.2	40.8	3.6	6.8
Weston	0	6.7	9.4	2.8	6.5	17.7	11.0	13.0
	1	12.0	13.1	1.1	2.6	15.7	3.7	4.4
	2	21.1	16.8	-4.2	-10.0	24.7	3.6	4.3
	3+	29.4	25.4	-4.0	-9.4	18.4	-11.0	-13.0
Great Carlton	0	8.0	10.9	2.9	10.0	25.8	17.8	30.7
	1	12.0	15.9	3.8	13.2	25.5	13.5	23.2
	2	23.0	29.9	6.9	23.8	36.2	13.2	22.8
	3+	26.9	31.1	4.2	14.5	46.0	19.1	32.9
Caythorpe	0	7.7	15.3	7.6	28.4	15.9	8.2	15.3
	1	11.3	18.1	6.9	25.6	26.9	15.6	29.2
	2	20.5	29.6	9.2	34.2	31.7	11.2	21.0
	3+	30.2	43.2	13.0	48.4	51.1	20.9	39.1
Cirencester	0	(9.0)	12.7	3.7	7.8	17.0	8.0	8.5
	1	12.5	20.1	7.6	16.2	28.5	16.0	16.9
	2	(20.0)	44.1	24.1	51.1	25.0	5.0	5.3
	3+	-	-	-	-	-	-	-
Cholsey	0	7.4	8.8	1.4	4.3	25.8	18.4	28.0
	1	13.5	9.1	-4.4	-13.4	25.5	12.0	18.2
	2	21.1	16.8	-4.3	-13.0	33.1	12.1	18.4
	3+	31.2	30.9	-0.4	-1.2	31.8	0.6	0.9

Appendix 5 Offtake of P and P_2O_5 by crop

Appendix Table 14. Average offtake of P and P_2O_5 in wheat grain at each P Index

Site		Offtake of P (kg/ha)					Offtake of P_2O_5 (kg/ha)				
	Index	2010	2011	2012	2013	Mean	2010	2011	2012	2013	Mean
Peldon	0	33	24	36	21	29	76	54	83	48	65
	1	35	27	38	26	32	80	61	88	61	72
	2	37	29	40	23	32	84	66	92	53	74
	3+	38	30	41	31	35	88	69	94	70	80
	Mean	36	27	38	26	32	82	62	88	61	73
Weston	0	24		23		24	56		52		54
	1	30		36		33	68		83		76
	2	3		34		32	71		78		74
	3+	31		39		35	72		89		81
	Mean	29		34		32	68		77		72
Great Carlton	0		24	22		23		56	51		53
	1		27	26		27		62	60		61
	2		30	28		29		69	63		66
	3+		29	28		29		66	65		65
	Mean		26	25		26		61	57		59
Caythorpe	0	17	15	4		12	40	35	10		28
	1	22	18	10		17	49	42	24		38
	2	26	19	14		20	60	44	33		46
	3+	24	24	13		20	56	54	31		47
	Mean	22	18	10		17	51	42	23		38
Cholsey	0	25	29		33	29	58	65		77	67
	1	27	29		33	30	61	67		76	68
	2	29	35		36	33	65	80		82	76
	3+	30	35		38	34	69	80		86	78
	Mean	28	32		34	31	64	73		79	72

Appendix Table 15. Average offtake of P and P_2O_5 in oilseed rape at each P Index

Site		Offtake of P (kg/ha)					Offtake of P_2O_5 (kg/ha)				
	Year	0	1	2	3+	Mean	0	1	2	3+	Mean
Weston	2013	-	28	26	26	26	-	64	59	59	60
Great Carlton	2010	24	25	25	26	25	54	55	57	59	56
Cirencester	2011	24	25	27	-	25	56	56	61	-	58
Cholsey	2012	18	20	21	21	19	41	45	49	49	44

Appendix Table 16. Average offtake of P and P_2O_5 in spring barley at each P Index

Site		Offtake of P (kg/ha)					Offtake of P_2O_5 (kg/ha)				
	Year	0	1	2	3+	Mean	0	1	2	3+	Mean
Caythorpe	2013	29	27	29	29	28	65	62	66	66	64
Cirencester	2010	25	24	25	26	25	58	56	57	59	57
	2013	-	21	19	18	19	-	48	43	41	44

Appendix 6 Cost Or Benefit from Raising P Index

Appendix Table 17. Cumulative net cost or benefit from raising P level by one Index

Site	Year	Value of extra yield less cost of replacing higher P offtake (£/ha)			Cumulative net cost (-) or benefit (+) (£/ha)		
		Index 0 to 1	Index 1 to 2	Index 2 to 3	Index 0 to 1	Index 1 to 2	Index 2 to 3
Peldon	2010	69	64	72	-146	-150	-331
	2011	127	83	56	-26	-74	-291
	2012	80	70	47	53	-8	-259
	2013	205	4	155	261	-4	-117
	Mean	120	56	82			
Weston	2010	228	49	13	-19	-198	-449
	2011	-19	103	13	-39	-104	-459
	2012	455	-53	-26	415	-163	-508
	2013	-3	-35	29	433	-205	-504
	Mean	165	16	7			
Great Carlton	2010	14	46	46	-406	-374	-742
	2011	116	116	-44	-310	-277	-823
	2012	176	83	-6	-149	-207	-870
	Mean	102	82	-1			
Caythorpe	2010	175	203	-85	-53	-24	-511
	2011	133	40	186	78	15	-350
	2012	205	175	-56	287	190	-424
	2013	-17	67	-17	284	267	-462
	Mean	124	121	7			
Cholsey	2010	49	82	73	-269	-237	-524
	2011	29	241	-6	-254	-8	-555
	2012	81	89	6	-186	81	-577
	2013	77	112	57	-118	197	-549
	Mean	59	131	33			