December 2017

Project Report No. 570

Cost-effective phosphorus management on UK arable farms

Report on Work Package 2: Critical levels of soil P

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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). This is considered to be 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 are used effectively. 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. 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 without risk of yield loss. The work reported here updates the findings from a previously reported project (Knight *et al*., 2014) and adds a further three years of new data obtained for three of the six original field experiments. Outputs from the project have contributed to the revision of phosphate management advice for cereals and oilseed rape within the AHDB Nutrient Management Guide 'RB209'.

At the start of the original project in 2009, six sites with low Olsen P levels (15 mg/l or less, Index 0 or 1) were identified, representing soil types (clay soils, loams and shallow soils over limestone or chalk) on which cereals and oilseed rape are widely grown but for which critical Olsen P levels had not been determined specifically. Field experiments were established on each site in autumn 2009 and were continued on the same plots for four successive cropping years (2009/10 to 2012/13). From autumn 2013 through to harvest 2016, the experiments were continued for a further three years at three of the sites, for the follow-on project.

In autumn 2009 varying amounts of triple superphosphate (TSP) fertiliser were applied to eighteen large plots (with some unfertilised) to create a range of Olsen P levels, and grain or seed yields were then related to Olsen P measured in that year. A range of combinable crops (mainly winter wheat, oilseed rape and barley) were grown following the farmer's normal rotation. For the third and subsequent 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, 2012, 2014 and 2015 to assess the crop response to freshly applied P, and maintain a range of Olsen P levels.

Results over 32 site years, from up to six sites on contrasting soils suggest that current advice, which is to maintain soils at P Index 2 for combinable crops will ensure that yields are not significantly limited by availability of P under a wide range of conditions. Across 10 site years, the 'Critical P' level for wheat (to achieve 98% of maximum yield) ranged from 8.5 to 21.9 mg/kg, but with the critical P level falling within Index 1 for the majority of sites. There were differences between sites and crops or years in the responsiveness of yield to Olsen P, which may have been related to soil conditions or other crop or site factors. Maintaining all fields for combinable cropping at below soil P Index 2 has

been shown here to risk significant yield loss but, in the right circumstances (in particular where soil structure and crop rooting are good) maintaining fields at Index 1 would be sufficient, and the risk of yield loss could be further reduced by ensuring an annual application of fresh P fertiliser. This would have potential economic and environmental benefits. On calcareous soils where establishing or maintaining a soil P Index of 2 has proven difficult, such a strategy may be preferable.

There were differences between sites in the apparent availability of the applied P fertiliser once the increases in Olsen had equilibrated and accounting for offtake. Over five sites the proportion of P remaining available 2-4 years after its application ranged from 1-20%, with availability highest on a heavy clay soil and lowest on a shallow limestone soil. There were differences between the two soils in measured pH (although less so at the time that the P fertiliser was applied), and in the amount of extractable calcium present. When calculated over a longer time period (up to 7 years after P fertiliser application), apparent P availability on the clay soil had decreased further, suggesting that differences in the rate at which P availability decreases may be important, but P availability was still higher for the clay soil than a shallow soil over chalk.

In most cases, P balances for the period 2009-13 or 2009-16 (P added in autumn 2009 minus P removed in subsequent harvests) indicated small increases in soil Olsen P where P balance was zero. Measured P contents (%) in cereal grain were less than those quoted in the Nutrient Management Guide RB209, and they declined with decreasing soil Olsen P level. Therefore, actual P_2O_5 offtakes per tonne of fresh grain yield (around 4.5-6.0 kg/t for wheat) would have been less, than that indicated in RB209 (7.8 kg/t). On farms, where maintenance dressings are being applied, lower than expected P offtake could partly explain observed increases in soil Olsen P and it would be of considerable interest to investigate further, to help understand the dynamics between P offtake, P fertiliser additions and soil Olsen P. It important to emphasise again that the potential for systematic differences with a test such as Olsen P underlines the advantage of, where possible, sticking to the same laboratory when monitoring changes in soil Olsen P over years.

2. Introduction

2.1. Background

In the period from 2011 to 2015 the average application of phosphate fertiliser (P) to winter wheat, spring barley and oilseed rape was 62, 50 and 60 kg/ha, respectively *where phosphate was applied.* This compares favourably with the average amounts, 55, 42 and 61 kg P_2O_5/ha, applied to these three crops, respectively, in 1983 -1987. However, in 2011-2015 only about 40% of these crops received any P fertiliser and the average application to the total area growing winter wheat, spring barley and oilseed rape was only 27, 33 and 27 kg P_2O_5/ha, respectively (Anon, 2015). This raises the question whether farmers are adjusting P application to these crops based on soil analysis and whether current recommendations for P applications based on soil analysis are correct. Recent surveys (PAAG, 2010 to 2014) of soil samples tested indicate that some soils are well supplied with P, whereas others have too little, with only 30% of ‘arable’ soils tested between 2009/10 and 2013/14 reported to be at the recommended Olsen P Index of 2 for arable cropping, although some of these soils may also be growing field vegetables where an Olsen P Index of 3 is recommended.

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 (Fig. 2.1). The level of readily plant-available P required to achieve near (*e.g.* 98% of) 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 soil 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).

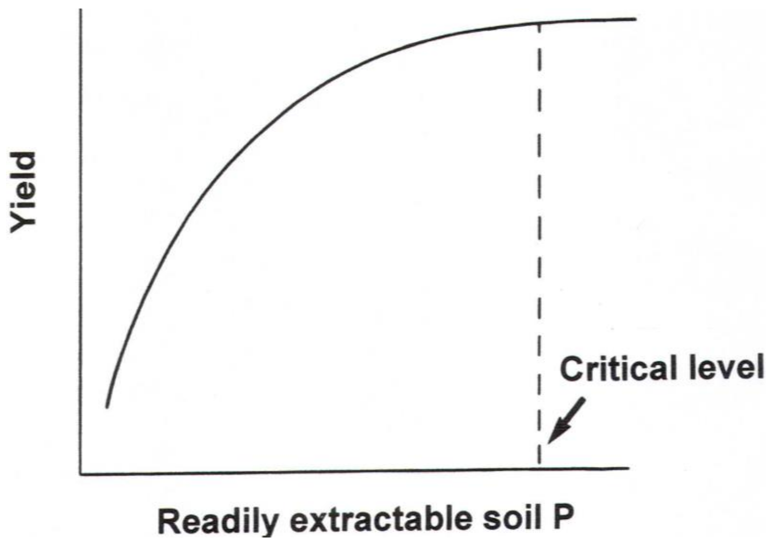


Fig. 2.1. Relationship between readily extractable (plant-available) soil P and crop yield, showing the ‘critical level’ at which 98% of the maximum yield is achieved

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 into 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 that 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.

Current advice for arable and forage crop rotations in the Nutrient Management Guide ‘RB209’ (AHDB, 2017) 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).

However, many of the field experiments on which the phosphate recommendations were based were on a limited range of soil types, mostly silty clay loam and sandy clay loam soils, whereas cereals and oilseeds are grown on a wider range of soil textures and variable soil depth explored by roots. 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. Previously there have not been sufficient data available to warrant changing the recommendations in RB209. However, there has been increasing debate as to whether or not it is necessary to maintain arable soils at a P Index of 2, given the cost of P fertilisers, concerns about future supply and the environmental impacts of P loss to water.

Findings from existing knowledge on the response of cereal crops to soil and fertiliser P were reported in AHDB Cereals & Oilseeds Research Review 74 (Johnston and Poulton, 2011). There was insufficient information available to include oilseed rape. The Olsen P levels recorded were those determined in the Rothamsted laboratory, and the critical P levels reported were those associated with achieving 98% of maximum yield. Data were reviewed on the yield response of winter wheat and spring barley to Olsen P for 102 crops from 1969 to 2008 grown on three contrasting soils, each with a wide range of Olsen P levels. 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 poorly structured sandy clay loam at Saxmundham (Suffolk), 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, larger concentrations of Olsen P were needed where SOM was low and soil structure was poor.

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. However, taking the average Olsen P level at which maximum yield was achieved, this supported 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.

The work reported here updates the findings from a previously reported project (Knight *et al*., 2014) and adds a further three years of new data obtained for three of the six original field experiments. Outputs from the project have contributed to the revision of phosphate management advice for cereals and oilseed rape within the Nutrient Management Guide ‘RB209’ (AHDB, 2017).

2.2. Aim and Objectives

For work package 2 these were as follows:

Aim

Provide robust evidence on critical levels of soil P for modern combinable crops.

Specific Objective

To provide confidence in specifying critical P levels for modern combinable crop rotations on different soil types.

3. Materials and methods

3.1. Overview

At the start of the original project in 2009, 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 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). From autumn 2013 through to harvest 2016, the field experiments were continued for a further three years at three of the sites, for the follow-on project.

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 subsequent 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, 2012, 2014 and 2015 to assess the crop response to freshly applied P, and maintain a range of Olsen P levels.

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 3.1 to 3.6. Soil pH, % organic matter and extractable calcium (Ca) content were measured by potentiometric titration, loss on ignition and atomic absorption spectrophotometry respectively, at a commercial laboratory.

Previous cropping and manure history are recorded in Appendix 2, Table 2. Available soil potassium (K) and magnesium (Mg) levels are recorded in Appendix 2, Table 3. Each experimental site was 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 3.1. 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 2015/16 = 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	-
Crop year	2013/14	2014/15	2015/16		
Cropping	Cont. wheat	Cont. wheat	Cont. wheat		
Primary cultivation	Plough	Plough	Plough		
Cultivation depth	25 cm	25 cm	25 cm		
Date sown	29/09/13	03/10/2014	13/10/15		
Soil pH	-	-	6.6		
Extractable Ca mg/l	-	-	-		
Organic Matter %	-	-	4.3		

Site 2: Weston, Suffolk

Soil series: Ragdale Soil texture: Chalky clay loam

Table 3.2. 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 3.3. 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 2015/16 = 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	-
Crop year	2013/14	2014/15	2015/16		
Cropping	First wheat	Second wheat	Winter barley		
Primary cultivation	Plough	Plough	Plough		
Cultivation depth	22 cm	22 cm	22 cm		
Date sown	29/09/13	18/10/14	13/10/15		
Soil pH	-	-	6.2		
Extractable Ca mg/l	-	-	-		
Organic Matter %	-	-	3.7		

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

Site 4: Caythorpe, Lincolnshire

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

Table 3.4. 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: Sherborne

Soil texture: Silty clay loam over limestone

Table 3.5. 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 3.6. 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 2015/16 = 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	-
Crop year	2013/14	2014/15	2015/16		
Cropping	Second wheat	Winter oats	First wheat		
Primary cultivation	Plough	Plough	Plough		
Cultivation depth	20 cm	20 cm	20 cm		
Date sown	11/10/13	20/10/14	13/10/15		
Soil pH	-	-	8.0		
Extractable Ca mg/l	-	-	-		
Organic Matter %	-	-	4.2		

3.3. Plot Size, Experiment Layout and Design

The 18 large plots each 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 (Fig. 3.1). Phosphate treatments were not fully replicated because the aim was create a wide range of individual soil Olsen P values in order to be able to determine the yield response.

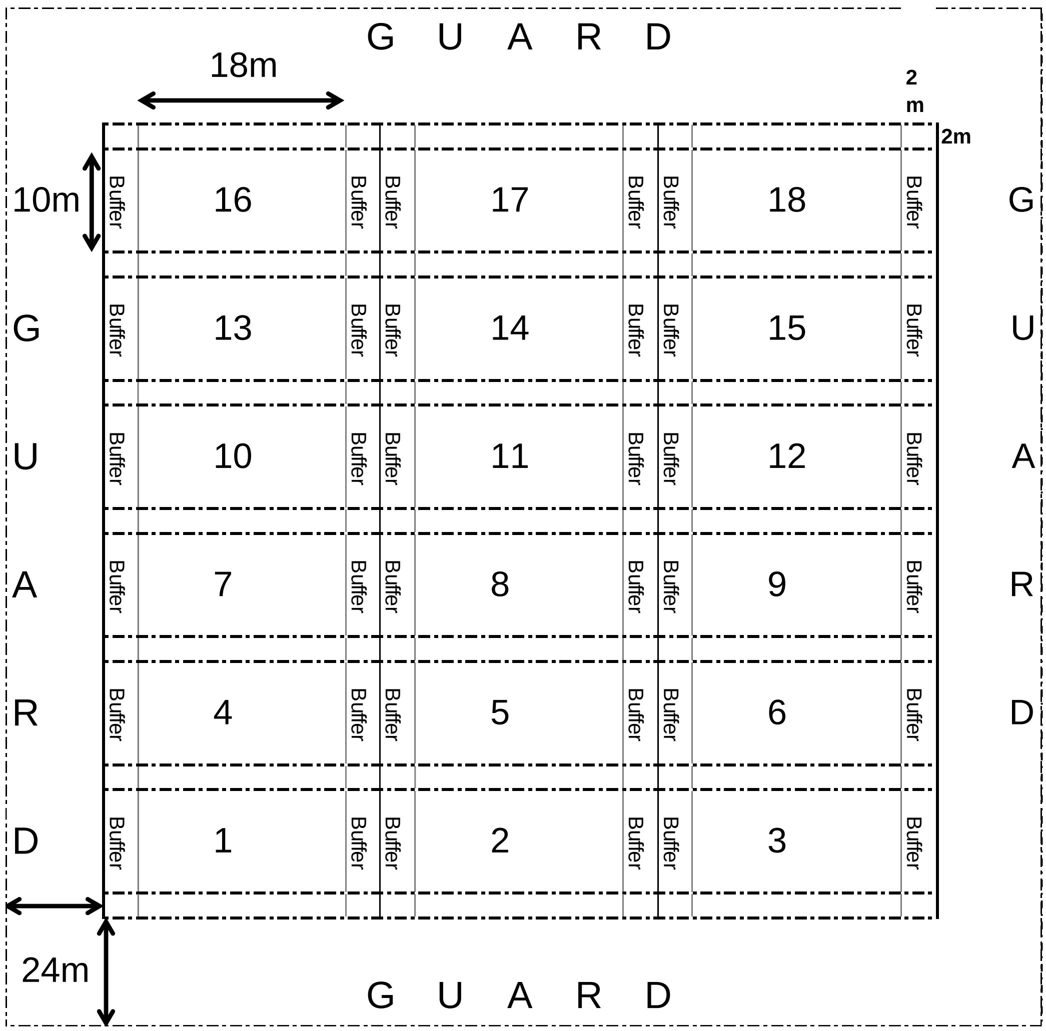


Fig. 3.1. Plot size and experiment layout for the first (2009/10) and second (2010/11) years

For the third and subsequent years, starting in autumn 2011, each of the eighteen large plots was split widthways into three 6m wide sub plots (Fig. 3.2, ‘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.

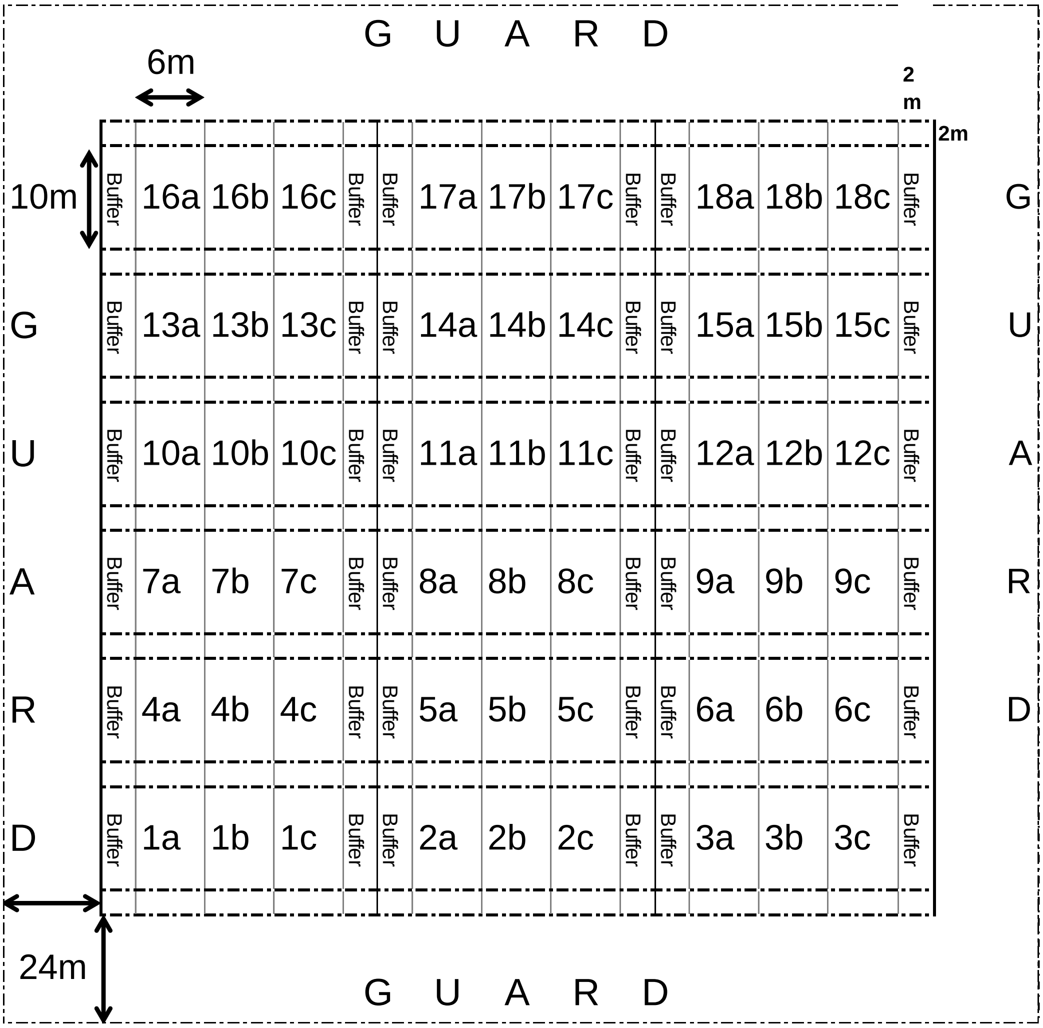


Fig. 3.2. Plot size and experiment layout for the third (2011/12) to seventh (2015/16) years

3.4. P Treatments

P Treatment Structure

The P treatments were not applied fully 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 up 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 about 24 mg/kg. The number of plots receiving each treatment (Table 3.7) 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 the autumns of 2011 and 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. For the three experiments that continued after harvest 2013 (Peldon, Great Carlton and Cholsey) fixed rate fresh P fertiliser treatments were again applied to the same sub-plots in the autumns of 2014 and 2015, but not in autumn 2013.

Table 3.7. 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

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 AHDB Cereals & Oilseeds Research Review 74 (Johnston and Poulton, 2011). To calculate the amount of TSP (containing 46% P_2O_5) required, the amount of P needed was multiplied by 2.2915 to convert P to P_2O_5. The estimates of the amount of TSP needed to achieve each 1 mg/kg increase in Olsen P are shown in Table 3.8.

For the fresh P treatments in the autumns of 2011, 2012, 2014 and 2015, a fixed rate of 200 kg/ha P_2O_5 (435 kg/ha TSP) was applied at all six (or from 2014 three) 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 3.8. 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.

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 3.9 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, 2012, 2014 and 2015 the fresh P top-up treatments were applied in one split prior to cultivation and drilling.

Table 3.9. P fertiliser application dates

Site	2009/10 First split	2009/10 Second split	2011/12 Single dose	2012/13 Single Dose	2013/14 Single dose	2014/15 Single dose	2015/16 Single dose
Peldon	27/08/09	22/09/09	01/09/11	14/08/12	None applied	28/07/14	13/08/15
Great Carlton	25/08/09	02/09/09	30/08/11	18/09/12	None applied	04/09/14	04/09/15
Cholsey	28/08/09	07/10/09	29/08/11	18/09/12	None applied	16/09/14	10/09/15
Weston	01/09/09	18/09/09	06/09/11	16/08/12			
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			

3.5. Olsen P Analysis

Soil Sampling Procedure

In 2009, 2010 and 2011 each of the 18 large plots was soil sampled for Olsen P while in 2012, 2013, 2014, 2015 and 2016 the 54 sub plots were each sampled separately. In both cases, 16 individual soil cores were taken randomly within each large or sub plot, using a gouge auger or similar. Soils were sampled to primary cultivation depth (*i.e.* 15, 20, 22 or 25cm) at that site. 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.

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 3.10). The target sampling time for subsequent years was spring (late Feb – early April).

In 2010, sampling at most sites was delayed due to cold and wet winter and spring conditions. In 2011, under exceptionally dry soil conditions, sampling at two sites had to be re-scheduled for 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 3.10. Sampling dates for Olsen P analysis

Site	2009	2010	2011	2012	2013	2014	2015	2016
Peldon	06/05/09	12/05/10	11/04/11	24/04/12	21/02/13	27/03/14	01/04/15	20/04/16
Great Carlton	13/05/09	23/03/10	01/03/11	19/03/12	14/03/13	19/03/14	24/03/15	29/02/16
Cholsey	10/07/09	21/05/10	05/04/11	22/03/12	26/03/13	05/03/14	14/05/15	17/03/16
Weston	12/05/09	06/05/10	05/09/11	21/03/12	20/02/13			
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			

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) levels were determined. Most commercial laboratories use a volume of soil and known volume of extractant, with Olsen P results reported in mg P/litre. For this project, a known mass of soil and volume of extractant was used, so Olsen P results are reported as mg P/kg. However, for most mineral soils the results in mg/litre and mg/kg are very similar.

The Olsen method (Olsen *et al*., 1954) for determining readily plant-available P in soil is widely used worldwide and has been used in England and Wales by ADAS since 1971. However, the analysis does not have a precise endpoint; *i.e.* if the soil is extracted a second time with another portion of reagent more P is extracted. Consequently, when a single extraction is used as in routine soil analysis, the amount of P extracted will be influenced by, for example, method of shaking, vigour and time, temperature, contact time with extracting solution, type of filter papers used, length of time for filtering and portion of the filtrate taken for analysis. The protocol used in a specific laboratory will give consistent results but minor modifications in the protocol used in different laboratories will lead to small differences in the amount of Olsen P reported in the soil. For these reasons it is important when changes in Olsen P over time are being followed, as a result of cropping and manuring, that soils should always be analysed by the same laboratory.

When a number of different laboratories are using the same analytical method they will exchange samples, analyse them and compare the results. The Professional Agricultural Analysis Group (PAAG) was established in the UK in 2009 to operate such a “ring test” of participating laboratories to ensure commonality among those in the Group, who all use the official English, Welsh and Northern

Irish methods for soil analysis. It is usual to ensure that the results for each laboratory are not greatly different from the mean of all the results. Such ring testing enables any systematic differences between laboratories to be identified and investigated.

For the further three years of field experiments undertaken from 2014 to 2016 at Peldon, Great Carlton and Cholsey, Olsen P analysis had to be carried out by NRM Laboratories, rather than by Rothamsted Research as for the first four years (2009-2013). These two laboratories carried out a standardisation exercise on a range of replicate samples from the first four years to ensure that their results were comparable. This was done so that the changes in Olsen P in the additional three years could be compared with those for the first four years. The standardisation exercise showed a good correlation between laboratories, with the rank order of samples very similar and a highly significant linear relationship (R^2 = 0.98). However, the relationship was not 1:1, with Olsen P levels reported by NRM Laboratories consistently around 25% less than those reported by Rothamsted Research. This systematic difference was similar to the results of previous ring testing organised by the Professional Agricultural Analysis Group (PAAG) in which the two laboratories had participated.

To present the data for the changes in Olsen P over the seven years of this project it was decided to transform the Olsen P data for each sample originally reported by Rothamsted Research (in the years 2010-2013) to the equivalent for NRM Laboratories, using the transformation:

$$y = (0.74 * x) + 0.46$$

Yield response curves, critical P values and all other analyses are reported here using the NRM equivalent Olsen P levels, unless stated otherwise. The implications of this for data interpretation are considered further in the Discussion (section 5.1).

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. Further assessments of seedbed quality were carried out at the Peldon and Great Carlton sites in 2014, 2015 and 2016. 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 subsequent years through to 2016, 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 Fitting

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 2012-2016. The number of individual values comprising the mean yield differed for each P Index, and varied between experiments and from year to year. Therefore, analysis of variance is not possible. A standard deviation was calculated for yield means comprising two or more individual values. In 2012 and subsequent years, yields for sub plots that had received fresh P fertiliser were calculated separately from those that had not.

In plots that received large P fertiliser treatments in autumn 2009, Olsen P levels had not fully equilibrated when measured in spring 2010. However, response curves were fitted to the yield and Olsen P data from 2011 for each large plot, and for 2012-2016 curves were fitted for the 36 Olsen P sub plots and separately 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/seed 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 £27/ha if wheat is valued at £135/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 £68/ha if wheat is valued at £135/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

For all cereal crops in 2014, 2015 and 2016, grain samples were retained from each plot and sent after harvest to a commercial laboratory for analysis of %P content. A change in the test procedure between 2014 and 2015 meant that the laboratory would have recorded slightly higher levels of P for the same P content from 2015 onwards. In the absence of a reliable conversion factor for the range of grain P contents produced in the experiments, it was decided not to attempt to convert the 2014 P contents to their 2015/16 equivalents. Therefore, over-year mean grain P contents for wheat (the only crop grown in 2014) have been calculated both with and without the 2014 values included.

The %P content of grain or seed was not measured in harvest years 2010 to 2013. Stored wheat grain samples were tested retrospectively for some sites from that period, but it was evident that grain P contents had declined with storage so the values were not considered reliable.

As measured values for cereals in harvest years 2014 to 2016 were much lower than the value (0.40% P, or 0.34% for grain at 85% dry matter), given in Table 4.11 in RB209 (AHDB, 2017) estimated values were used for 2010 to 2013 based on the mean values measured in wheat and barley for 2014 to 2016, which were as follows:

Winter wheat (soil P plots):	0.26% P	(0.22% for grain at 85% dry matter)
Winter wheat (fresh P plots):	0.30% P	(0.26% for grain at 85% dry matter)
Spring barley (soil P plots):	0.33% P	(0.28% for grain at 85% dry matter)
Spring barley (fresh P plots)	0.38% P	(0.32% for grain at 85% dry matter)

The values given in RB209 (AHDB, 2017) were used for oilseed rape and spring bean crops in 2010 to 2013, as these crops were not grown in the 2014 to 2016 period so no better estimates could be obtained:

Oilseed rape (all plots):	0.67% P	(0.61% for seed at 91% dry matter)
Spring field bean (all plots):	0.56% P	(0.48% P for seed at 86% dry matter)

For plots that received at least 100 kg P/ha in autumn 2009, but had no fresh P fertiliser thereafter, the overall P balance was calculated from the amount of P added less cumulative P offtake in grain or seed. Harvest 2009 yields (prior to application of the 2009 P treatments) were not recorded and therefore 2009 offtake was ignored.

3.10. Wheat Grain P Content and Curve Fitting

For wheat crops grown in the 2014 to 2016 period at Peldon, Great Carlton and Cholsey, linear relationships were fitted to the grain P content and soil Olsen P data, separately for the soil P only and fresh P plots. For two wheat crops where a meaningful estimate of the critical Olsen P level (to achieve 98% of maximum yield) was obtained, curves were fitted to the grain P content and soil Olsen P level, as a proportion of the critical P level, for the soil P only plots. The form of the asymptotic curve fitted was:

Grain P = a + b * (r^x)

Where *x* is the proportion of the critical P level and *a*, *b* and *r* are parameter estimates.

The relationship between grain P content and wheat yield was investigated for two wheat crops in 2016. Curves were fitted to the grain yield and grain P content, combining the results for soil P only and fresh P. The form of the asymptotic curve fitted was:

Yield = a + b * (r^x)

Where *x* is Grain P in % and *a*, *b* and *r* are parameter estimates.

3.11. Economic Analysis

The number of years required for the value of additional wheat yield obtained at Olsen P Index 1 or 2 (compared to Index 0 or 1) to exceed the initial cost of raising the Olsen P level from (mid Index) 0 to 1, 0 to 2 or 1 to 2 (in a single year), and then maintaining it (by replacing annual offtake), was determined for the four sites (Peldon, Great Carlton, Cholsey and Caythorpe) where wheat was the only or predominant crop grown.

The quantity of P_2O_5 required to raise Olsen P by 1 Index (Table 3.11) was calculated using the apparent % P availability values obtained from the first four years after initial P application (*i.e.* for the period 2009-2013). Wheat yields for each site were based on their mean yields at Index 0, 1 and 2 over the duration of the project. Offtakes of P_2O_5 per tonne at Indices of 0, 1 and 2 were based on the mean yields for each site and the mean grain P contents across all sites where this was measured.

Table 3.11. 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

Wheat yields were converted to a financial value for each site each year based on an average crop price of £135 per tonne. The initial cost of raising Olsen P by 1 Index, and annual cost of replacing P offtake was calculated using a P cost of £1.50 per kg (P_2O_5 cost of £0.65 per kg, equivalent to a TSP fertiliser price of about £300 per tonne). Cost of borrowing was added to the cost of the initial P fertiliser application at a rate of 2% per year. Cost of fertiliser application was not included in the calculation.

The net value was then determined by subtracting the overall P cost from the value of the wheat produced, at Indices of 0, 1 and 2, after a period of 1, 2, 3, 4 and 5 years, and the net benefit or cost relative to Index 0 was calculated to indicate how many years (based on consecutive wheat cropping) would have been needed to justify raising Olsen P to Index 1 (from 0) or 2 (from 0 or 1).

4. Results

4.1. Seedbed Conditions and Quality

The general condition of the seedbed after drilling at each of the sites for the seasons 2010 to 2016 is shown in Table 4.1.

Table 4.1. Seedbed conditions early after drilling

Site	2010	2011	2012	2013	2014	2015	2016
Peldon	Dry and very cloddy	Fine, firm seedbed	Wet but fine seedbed	Poor, wet cloddy seedbed	Wet seedbed	Wet but fine seedbed	Dry, firm seedbed
Great Carlton	Dry but fine seedbed	Fine, firm seedbed	Moist, firm seedbed	Wet, cloddy seedbed	Wet, firm seedbed	Good seedbed	Moist, firm seedbed
Cholsey	Fine seedbed	Fine, firm seedbed	Fine, firm seedbed	Fine seedbed	Wet, firm seedbed	Dry, firm seedbed	Dry but fine seedbed
Weston	Dry and cloddy	Very dry and hard	Coarse, firm seedbed	Firm 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			

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 4a. Additional soil structure scores (using the modified Peerlkamp method) for the Peldon and Great Carlton sites in 2014, 2015 or 2016 are provided in Appendix 3, Table 4b. Overall Seedbed quality (Sq) scores are shown for each site in Table 4.2 along with observations on soil structure and rooting. Values are calculated from scores relating to individual layers within the block (defined by changes in horizontal layers of differing structure).

Table 4.2. Seedbed quality (Sq)* assessment according to the Peerlkamp method

Site	Spring 2011	Spring 2013	Spring 2014	Spring 2015	Spring 2016
Peldon	-	Sq 2.3 (Good rooting, no evidence of compacted layer)	Sq 3.8 (Poor rooting, low macroporosity)	Sq 2.6 (Good rooting, no evidence of compacted layers)	Sq 2.4 (Good rooting, high macroporosity)
Great Carlton	Sq 3.7 (Relatively poor structure with roots restricted to pores or cracks between aggregates)	-	Sq 2.7 (Well structured soil, roots throughout soil)	Sq 3.6 (Poor structure with restricted root system	Sq 3.1 (Reasonable rooting, macropores visible)
Cholsey	-	Sq 2.4 (Well structured soil, roots throughout soil)			
Weston	-	Sq 4.6 (Poor rooting, saturated soil)			
Caythorpe	Sq 1.5 (Good seedbed structure with roots throughout profile)	-			
Cirenceste r	-	Sq 2.6 (Well structured shallow soil, stony below 15cm)			

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

4.2. Soil Olsen P

4.2.1. Measured Olsen P Levels (excluding fresh P plots)

A complete record of Olsen P levels within each large plot (2009 - 2011) or sub plot (2012 - 2016) 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 and final measured soil Olsen P levels

Initial (2009), interim (2013) and final (2016) soil Olsen P levels in the normal cultivated layer are summarised in Table 4.3, excluding sub plots that received fresh P fertiliser in autumn 2011 and subsequently. Only three sites were continued in 2014 - 2016, therefore 2013 values are the final levels for the other three sites. In 2009, all sites started with the majority of plots at either P Index 0 or the lower end of P Index 1. The experiment at Weston had to be repositioned after the initial soil sampling and analysis had been completed. Therefore, for 2009 an estimated initial Olsen P value of 3.9 mg/kg was assumed for each large plot, which was the average of the previously measured values (all within the range 3.0 - 4.8 mg/kg). At four sites there was substantial plot-to-plot variation in the initial Olsen P levels, including one plot at P Index 2 at Caythorpe. This existing variation was exploited to help create the wide range of initial Olsen P levels required in each experiment.

Table 4.3. Summary of initial and final levels of Olsen P at each site

Site	Depth of cultivated soil layer (cm)	Olsen P (mg/kg)						
		Spring/Summer 2009 All plots, pre-treatment		Treatment in autumn 2009	Spring 2013 Plot values		Spring 2016 Plot values	
		Mean	Range		Mean	Range	Mean	Range
Peldon	0-25	8.9	5.6 - 13.9	No P	7.0	5.3 - 9.3	7.2	4.3 - 13.3
				+ P	20.6	7.3 - 50.9	11.6	4.5 - 20.2
Great Carlton	0-22	10.6	7.9 - 13.6	No P	7.1	6.4 - 8.7	7.7	5.9 - 9.5
				+ P	15.0	6.7 - 33.8	12.3	7.5 - 17.0
Cholsey	0-20	5.3	3.9 - 6.4	No P	9.4	6.9 - 15.5	5.6	4.7 - 7.4
				+ P	13.5	6.8 - 28.0	7.7	4.5 - 13.9
Cay-thorpe	0-22	8.1	4.9 - 19.3	No P	8.5	6.7 - 11.4		
				+ P	16.4	7.9 - 24.9		
Weston	0-15	(3.9)	(3.0 - 4.8)	No P	13.1	7.6 - 18.7		
				+ P	16.3	7.3 - 41.1		
Ciren-cester	0-15	8.0	5.3 - 13.0	No P	13.5	10.2 - 18.5		
				+ P	15.7	5.1 - 27.4		

In 2013, the change in Olsen P levels compared to 2009 for plots that did not receive P in autumn 2009 varied between sites. At Peldon and Great Carlton, mean Olsen P levels were lower and the range of values was narrower (Table 4.3). At Caythorpe the mean Olsen P was little different, but the range was narrower. At Weston, Cirencester and Cholsey, mean Olsen P was higher and the range of values was wider. Mean Olsen P levels were higher in plots that had received P fertiliser in 2009 than in those that had not. However, the differential varied considerably between sites, with only small differences in the mean for Weston and Cirencester.

In 2016, mean Olsen P levels in plots that did not receive P in autumn 2009 were similar to those measured in 2013 for both Peldon and Great Carlton. However, levels were lower and the range of values was narrower compared to 2013 for Cholsey. For plots that had received Olsen P fertiliser in 2009, mean Olsen P levels were lower at all three sites in 2016 compared to 2013, with the smallest change at Great Carlton.

Year-to-year change in Soil Olsen P levels

Comparisons between single years can be misleading due to year-to-year variation. Mean Olsen P levels for each year from 2009 to 2016 for plots receiving different amounts of P fertiliser in 2009 are shown in Figs. 4.1 to 4.3 for Peldon, Great Carlton and Cholsey. Measured values for 2009 - 2011 are for each large plot, whereas those for 2012 - 2016 are the mean of the two sub plots that did not receive fresh P fertiliser in autumn 2011 and subsequently. Olsen P levels for the other three sites (Caythorpe, Weston and Cirencester) from 2009 to 2013 only are shown in Appendix 5 Figs. 1 to 3.

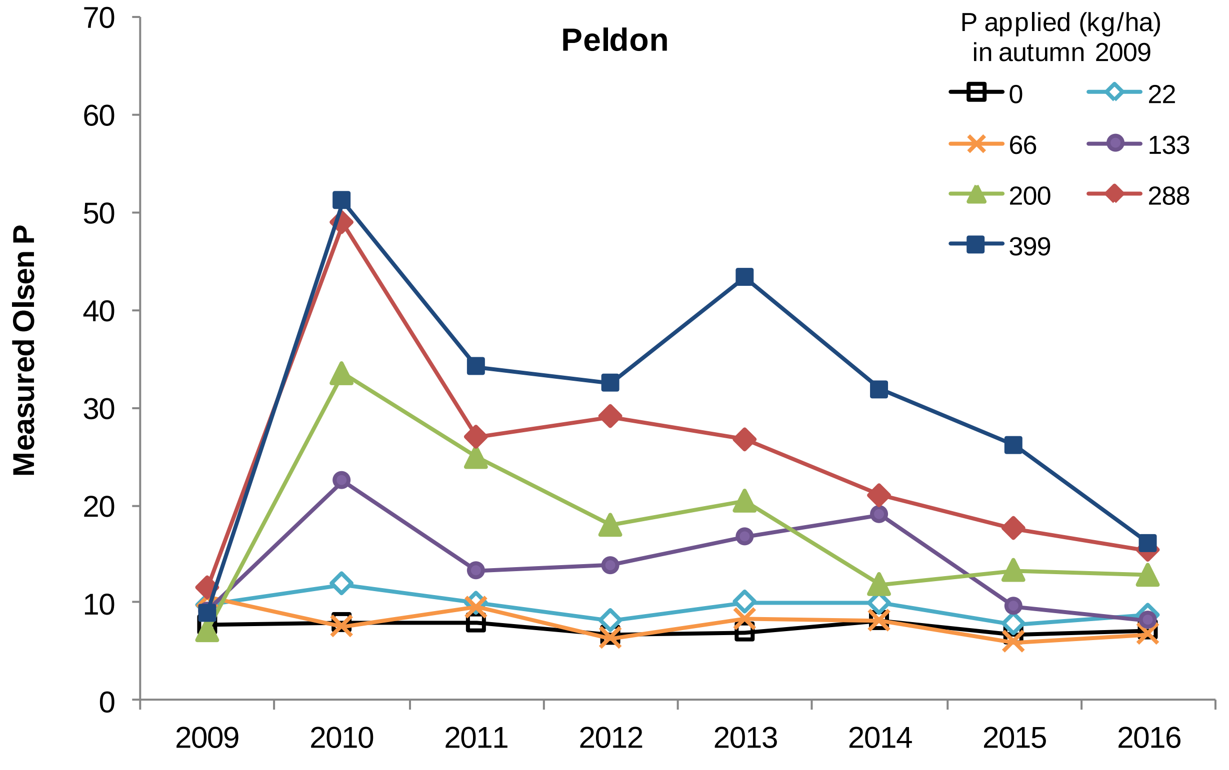


Fig. 4.1. Average measured Olsen P, mg/kg, at the Peldon site from 2009 to 2016, for plots receiving different amounts of P fertiliser in autumn 2009

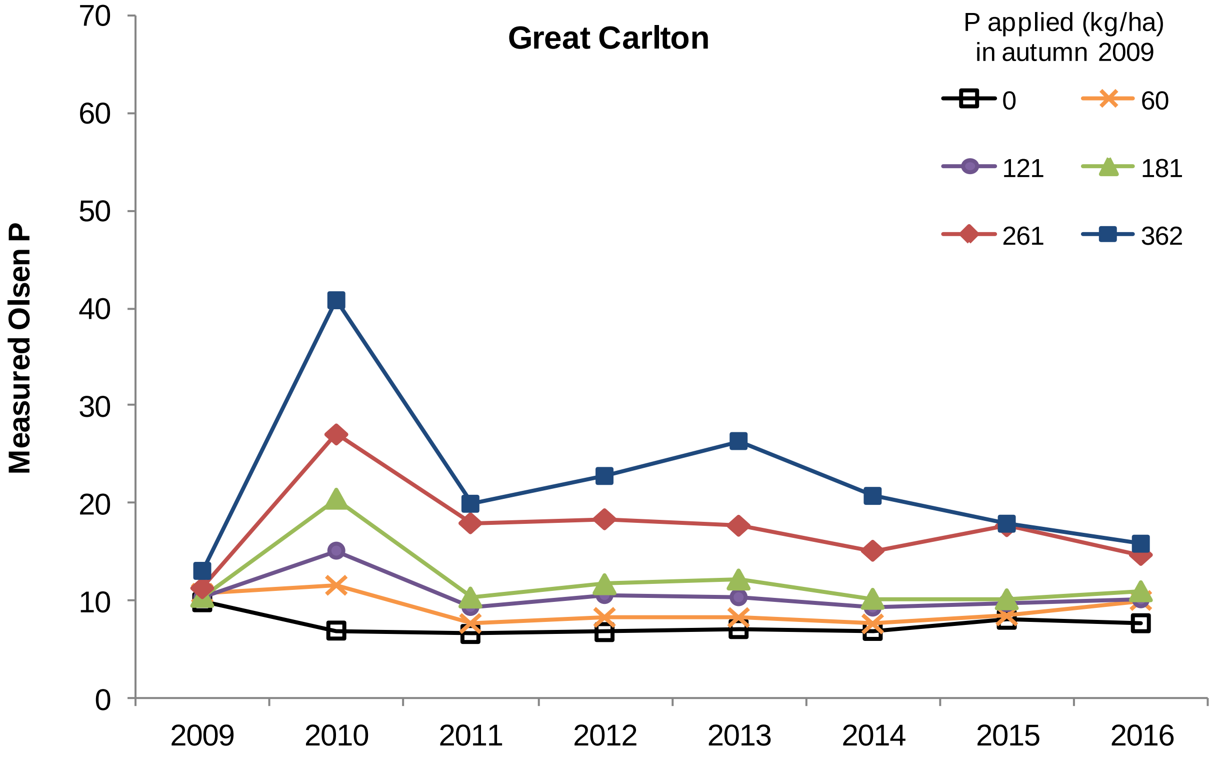


Fig. 4.2. Average measured Olsen P, mg/kg, at the Great Carlton site from 2009 to 2016, for plots receiving different amounts of P fertiliser in autumn 2009

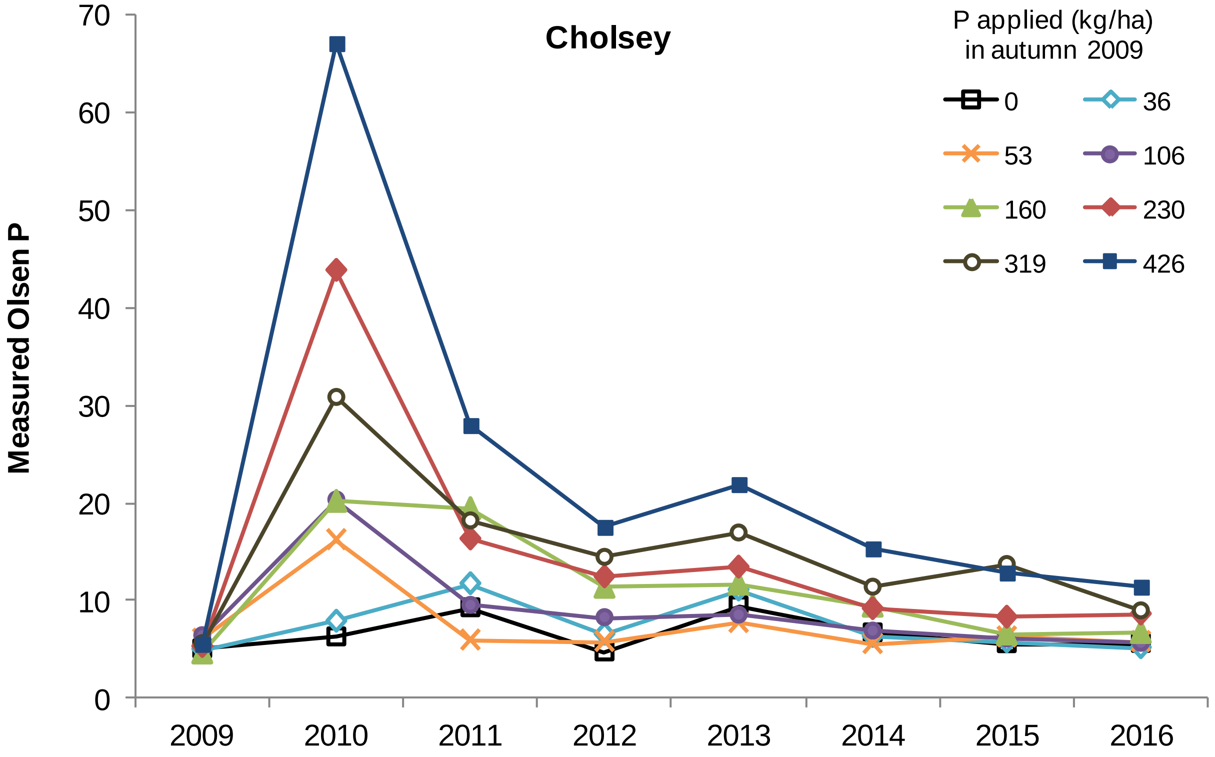


Fig. 4.3. Average measured Olsen P, mg/kg, at the Cholsey site from 2009 to 2016, for plots receiving different amounts of P fertiliser in autumn 2009

At Peldon, there was relatively little year-to-year change in Olsen P in plots that did not receive P fertiliser (see Fig. 4.4a). Plots that received P fertiliser in autumn 2009 showed an increase in 2010 as expected, large in the case of plots that received more than 100 kg P/ha. From 2011 to 2013 levels in the fertilised plots decreased only slightly, but from 2013 onwards there was a more obvious decline especially in plots that had received more than 100 P kg/ha (see Figs. 4.4b-d).

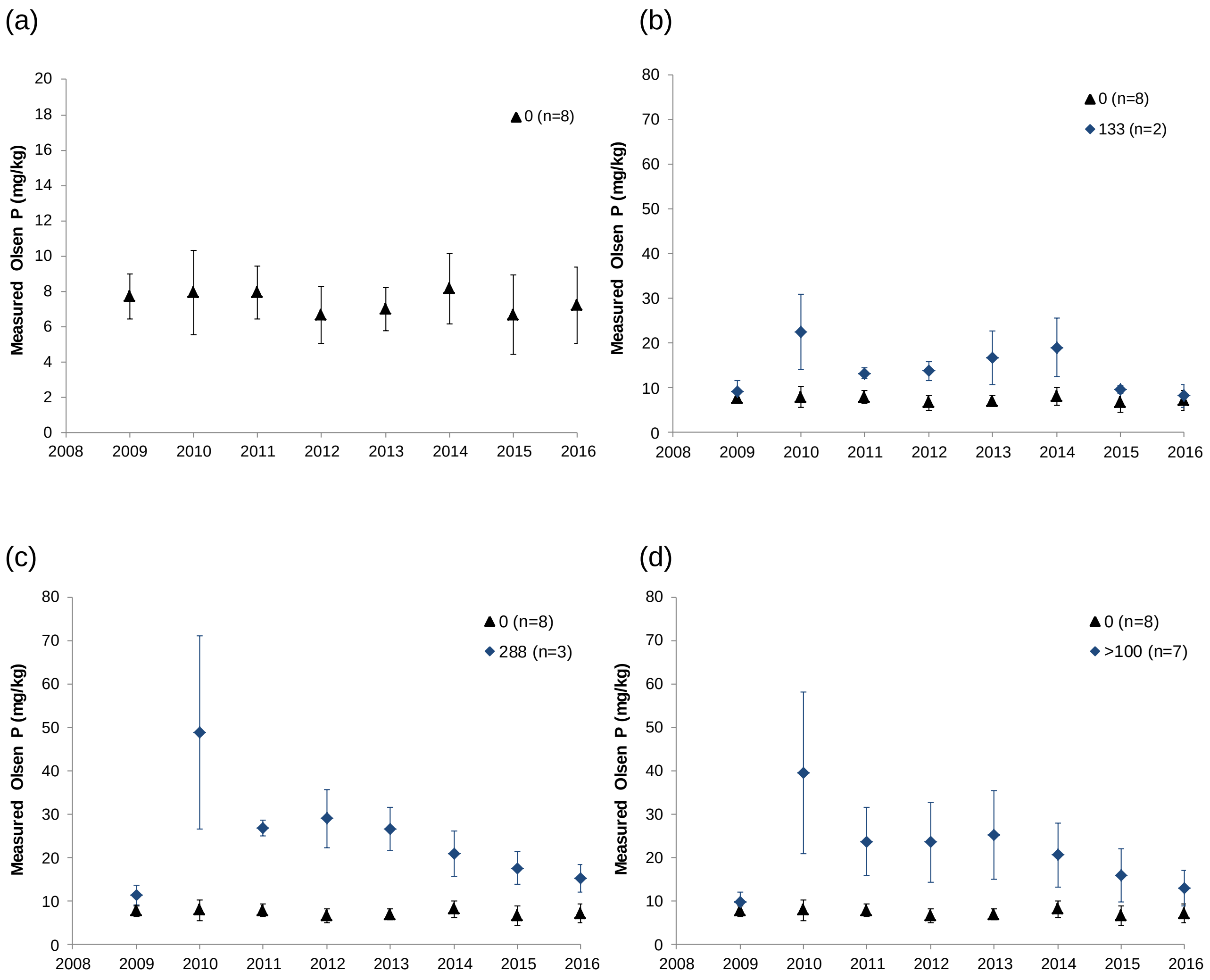


Fig. 4.4. Mean soil Olsen P level for plots not receiving any P fertiliser in autumn 2009 (a); plots receiving 133 kg/ha P fertiliser in autumn 2009 compared to plots receiving none (b); plots receiving 288 kg/ha P fertiliser in autumn 2009 compared to plots receiving none (c); and for the average of plots receiving >100 kg/ha P fertiliser in autumn 2009 compared to plots receiving none (d); for Peldon from spring 2009 until 2016. Error bars represent +/- 1 standard deviation on the mean (sample size (n) is defined in legend)

At Great Carlton there was an initial reduction in Olsen P between 2009 and 2010 in plots that did not receive P fertiliser (see Fig. 4.5a) but thereafter there was relatively little year-to-year change. The apparent higher value in 2009 may have been associated with an overall application of P fertiliser to the site in the months prior to the experiment starting in 2009. Plots that received P fertiliser in autumn 2009 showed an increase in 2010 as expected and had decreased by 2011. From 2011 to 2016 levels in the fertilised plots showed only a slight decrease (see Fig. 4.5b-d).

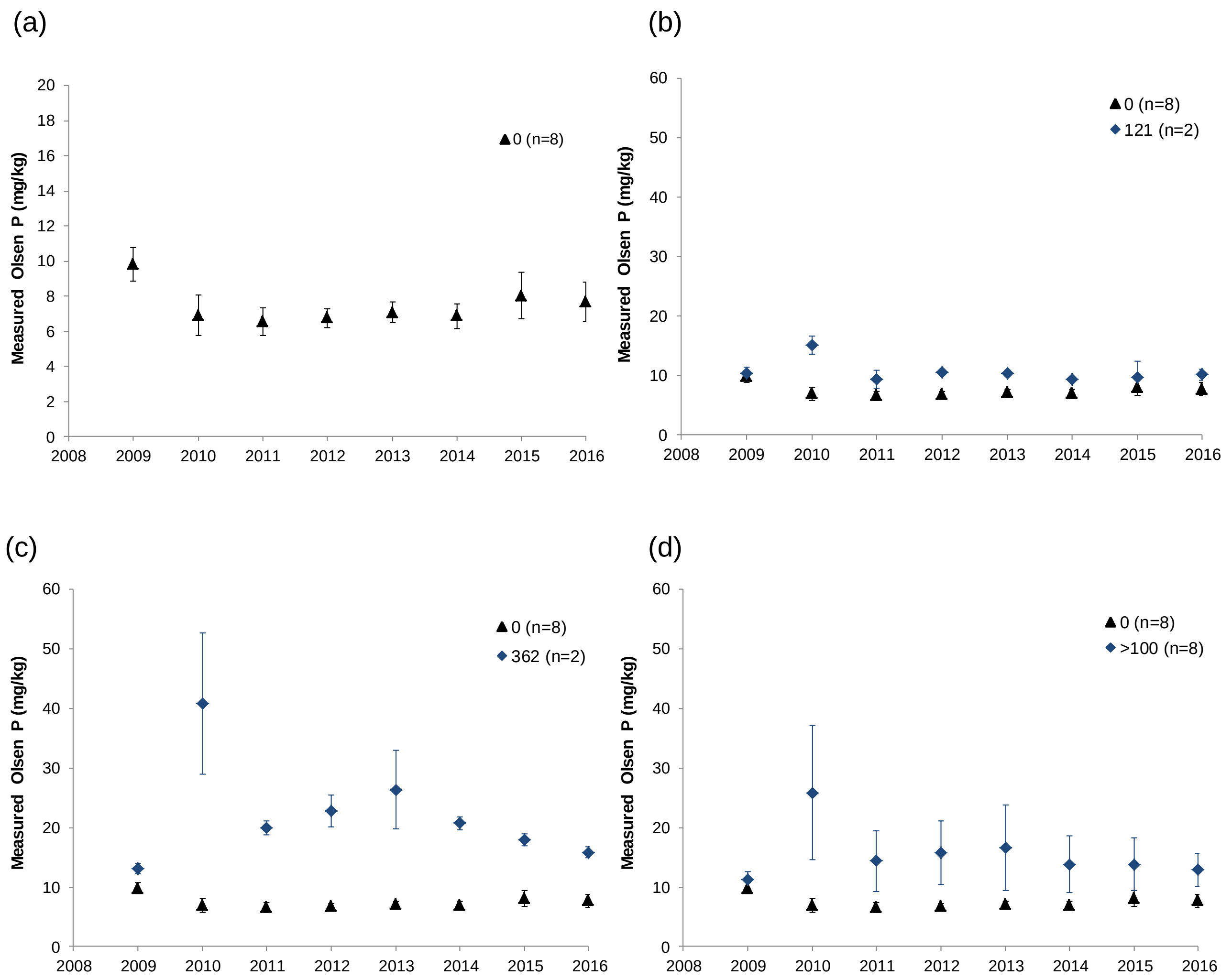


Fig. 4.5. Mean soil Olsen P level for plots not receiving any P fertiliser in autumn 2009 (a); plots receiving 121 kg/ha P fertiliser in autumn 2009 compared to plots receiving none (b); plots receiving 362 kg/ha P fertiliser in autumn 2009 compared to plots receiving none (c); and for the average of plots receiving >100 kg/ha P fertiliser in autumn 2009 compared to plots receiving none (d); for Great Carlton from spring 2009 until 2016. Error bars represent +/- 1 standard deviation on the mean (sample size (n) is defined in legend).

At Cholsey, there was greater year-to-year variation in Olsen P in plots that did not receive P fertiliser (see Fig. 4.6a), with particularly high values in 2011 and 2013 (but note in these years there was also more variation between unfertilised plots so the means should be treated with caution). Plots that received P fertiliser in autumn 2009 showed a large increase in 2010 but had substantially decreased by 2011. From 2011 to 2016 levels in the fertilised plots declined steadily (see Fig. 4.6b-d).

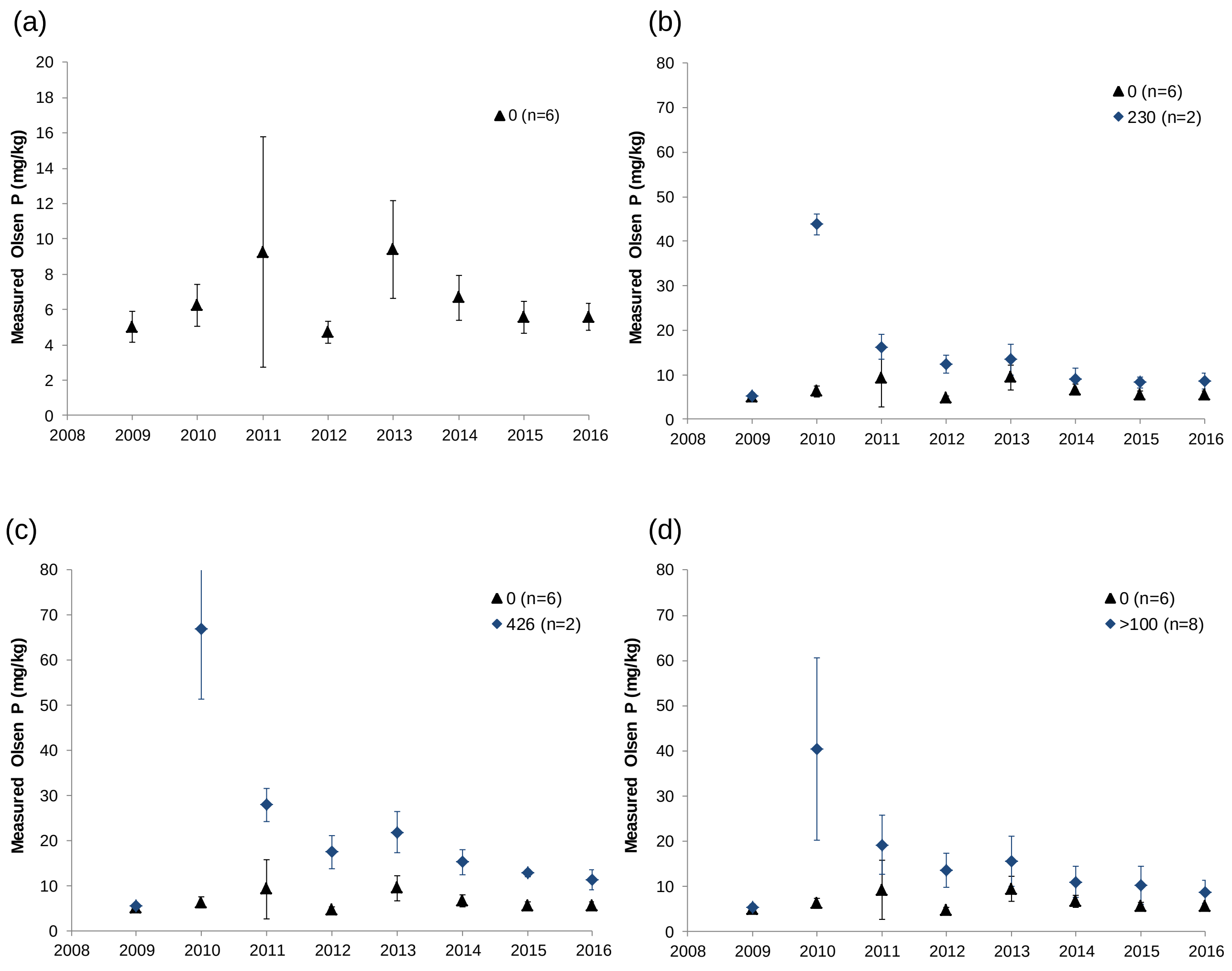


Fig. 4.6. Mean soil Olsen P level for plots not receiving any P fertiliser in autumn 2009 (a); plots receiving 230 kg/ha P fertiliser in autumn 2009 compared to plots receiving none (b); plots receiving 426 kg/ha P fertiliser in autumn 2009 compared to plots receiving none (c); and for the average of plots receiving >100 kg/ha P fertiliser in autumn 2009 compared to plots receiving none (d); for Cholsey from spring 2009 until 2016. Error bars represent +/- 1 standard deviation on the mean (sample size (n) is defined in legend).

Caythorpe showed similar patterns to Peldon over the period 2009-2013; 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. In addition, crop yields in 2012 tended to be low, and especially so at Caythorpe, such that P offtake was unusually low.

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.

At Cirencester, 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.

Effect of P fertiliser amount applied on measured soil Olsen P Levels

In Figs 4.7 to 4.9, measured soil Olsen P levels each year are presented according to the amount of P fertiliser applied in autumn 2009, for Peldon (Fig. 4.7), Great Carlton (Fig. 4.8) and Cholsey (Fig, 4.9). After 2010, when the effect of the large initial P applications in 2009 was evident at all three sites, the response of soil Olsen P to amount of fertiliser P applied was greatest at Peldon and smallest at Cholsey.

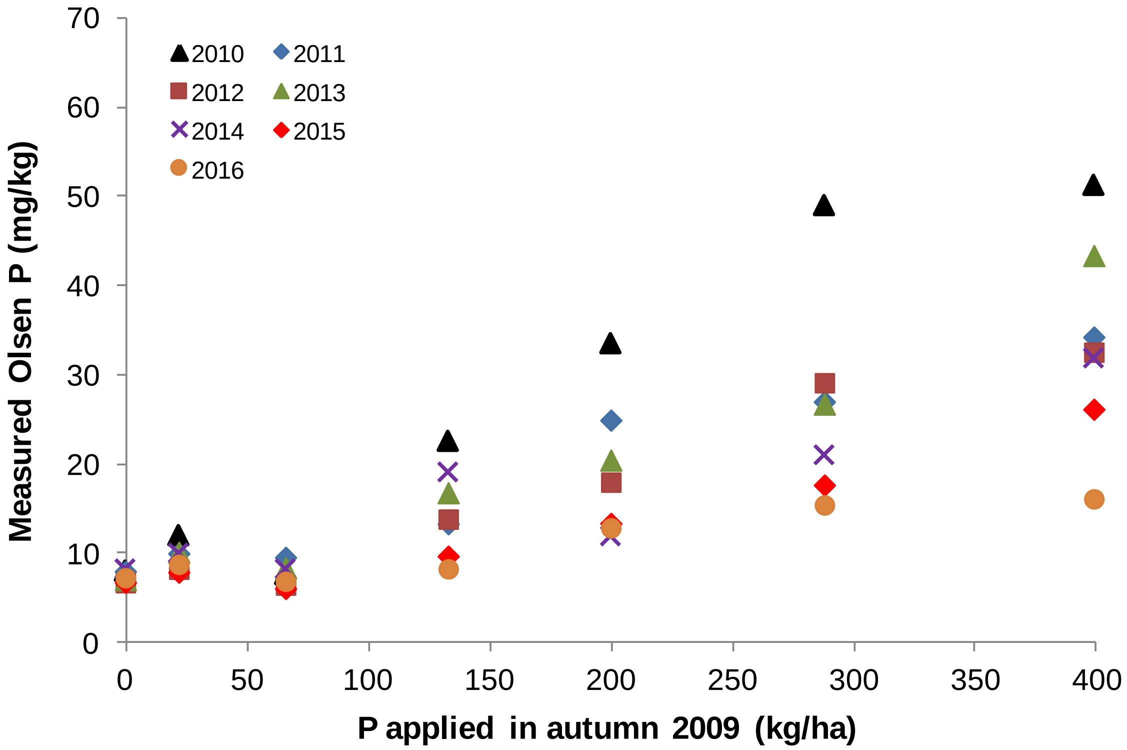


Fig. 4.7. Averaged measured Olsen P, mg/kg, each year at Peldon, for each amount of P fertiliser applied in autumn 2009

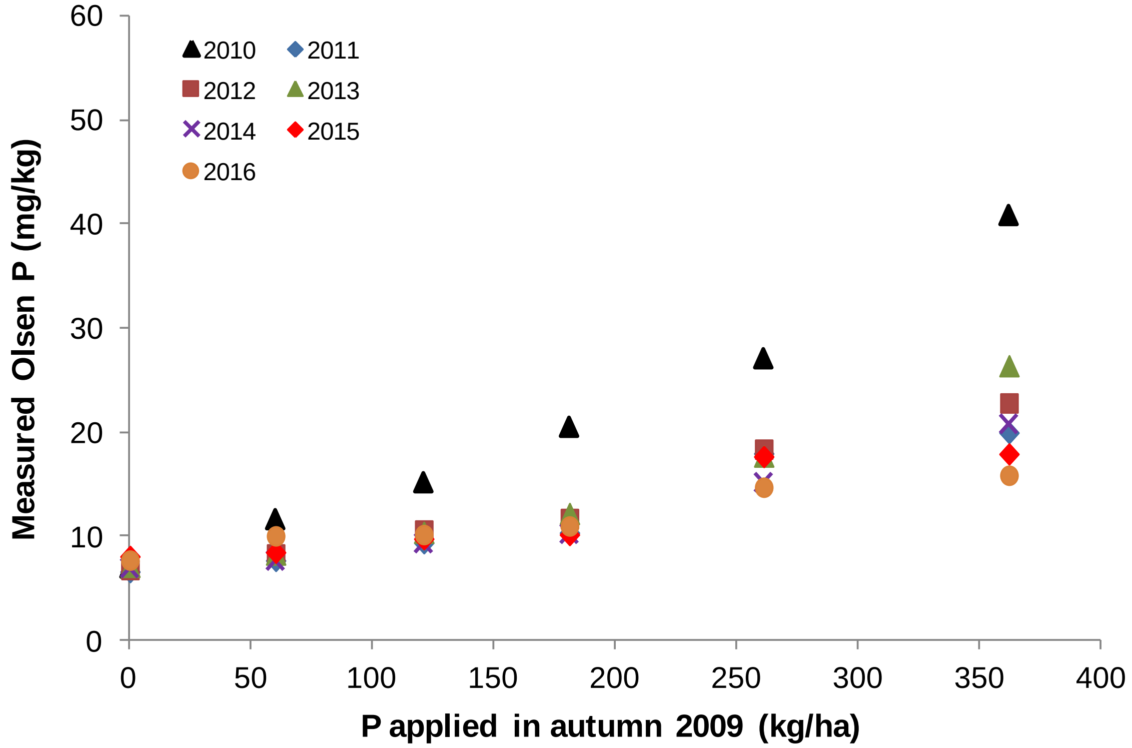


Fig. 4.8. Averaged measured Olsen P, mg/kg, each year at Great Carlton, for each amount of P fertiliser applied in autumn 2009

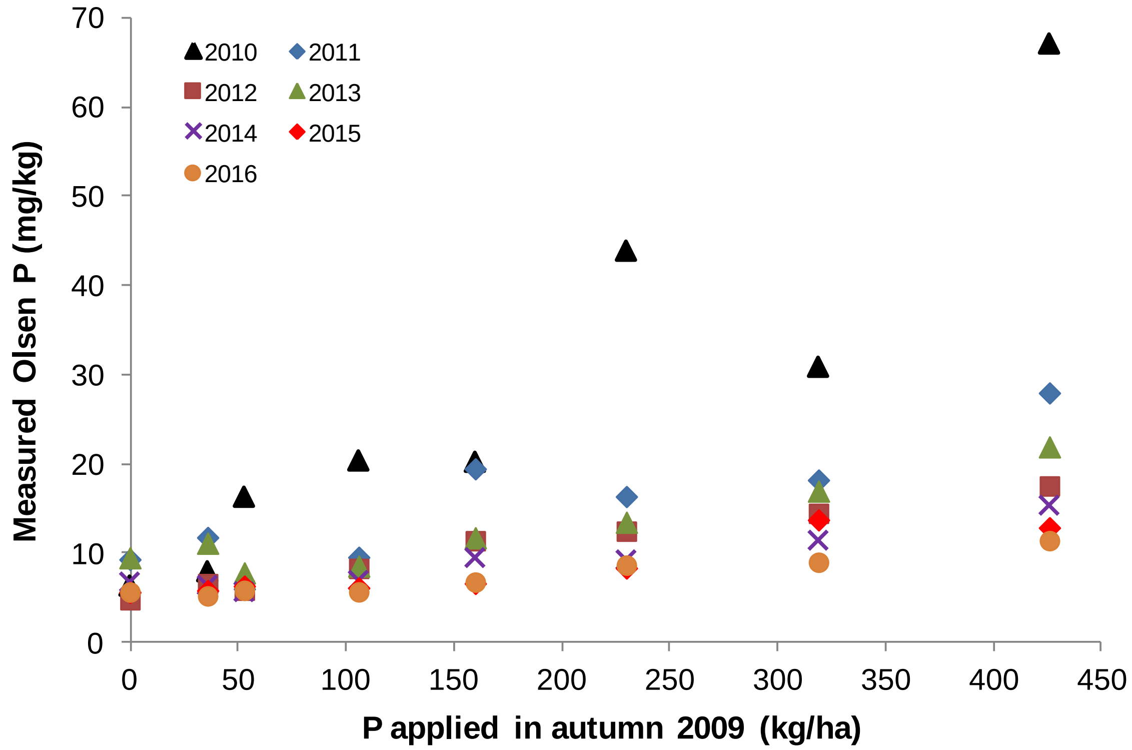


Fig. 4.9. Averaged measured Olsen P, mg/kg, each year at Cholsey, for each amount of P fertiliser applied in autumn 2009

Soil Olsen P levels below cultivated depth

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 6 mg/kg) in plots that had received P. At Caythorpe Olsen P levels averaged 3 mg/kg in untreated plots and 5 mg/kg in P treated plots. Only P treated plots were tested at Cholsey, and Olsen P levels were 4 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 3–8 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 8–14 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 5.9 mg/kg in 2012 and 5.8 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 at 15-30cm depth averaged 6.3 mg/kg in 2012 and 6.7 mg/kg in 2013.

4.2.2. Relationship between Target and Measured Olsen P Levels

The relationship between the target Olsen P levels in 2010 and the measured (actual) Olsen P levels each year are shown in Figs. 4.10 to 4.12 for Peldon, Great Carlton and Cholsey respectively from 2010 to 2016, and in Appendix 5 Figs. 4 to 6 for Caythorpe, Weston and Cirencester from 2009 to 2013. Measured values for 2010 and 2011 are for each large plot, whereas those for 2012 to 2016 are the mean of the two sub plots that did not receive fresh P fertiliser in autumn 2011 or subsequently. The 2010 target Olsen P level 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 partly to the amount of P removed in the harvested crops.

At Peldon, in spring 2010 measured Olsen P levels in plots that had received P the previous autumn were typically about 70% higher than the target levels, indicating that the added P had not yet equilibrated. By spring 2011, measured levels were much closer to the 2010 target, although still marginally higher. Between 2011 and 2013 the relationship between measured and target Olsen P showed little change, suggesting that the added P had equilibrated, but from 2014 through to 2016 measured levels continued to decline below the 2010 target levels.

At Great Carlton and Caythorpe, measured levels were about 10% above the target levels in spring 2010, but had largely equilibrated at slightly below the 2010 target levels from 2011. At Great Carlton measured levels continued to decline gradually up to 2016, by which time they were typically about half the 2010 target levels. At Cholsey, measured Olsen P levels in spring 2010 were around double the target levels. By spring 2011 measured levels were much closer to the 2010 target but, other than a slight rise in 2013, they then declined up to 2016 by which time they were typically only about a third of the 2010 target levels.

At Weston, there was no apparent relationship between measured and expected Olsen P after 2010. At Cirencester measured levels were already slightly below the target in spring 2010, and then fell further by 2011 when there was little relationship with the 2010 target levels. Measured levels were similar in 2012 but in 2013 there was a slight increase.

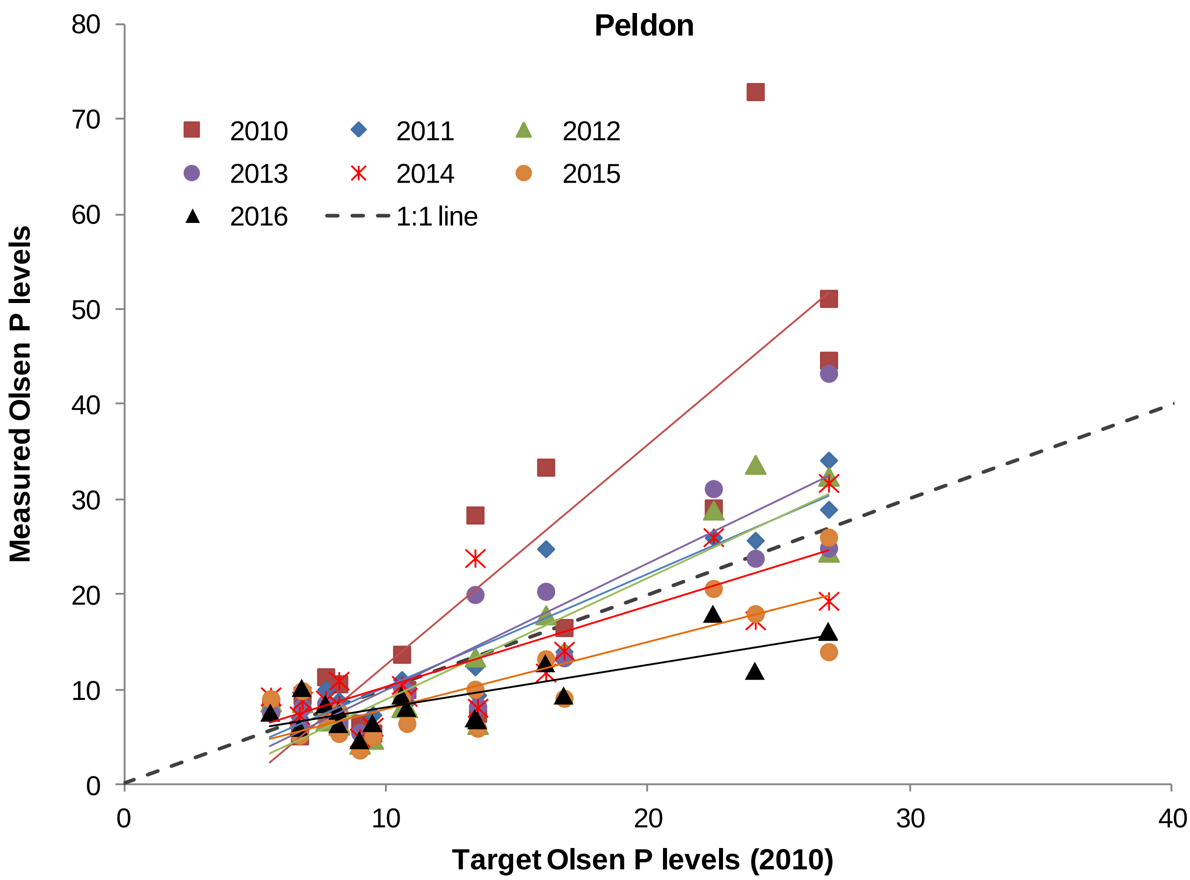


Fig. 4.10. Measured Olsen P, mg/kg, compared to 2010 target levels at the Peldon site

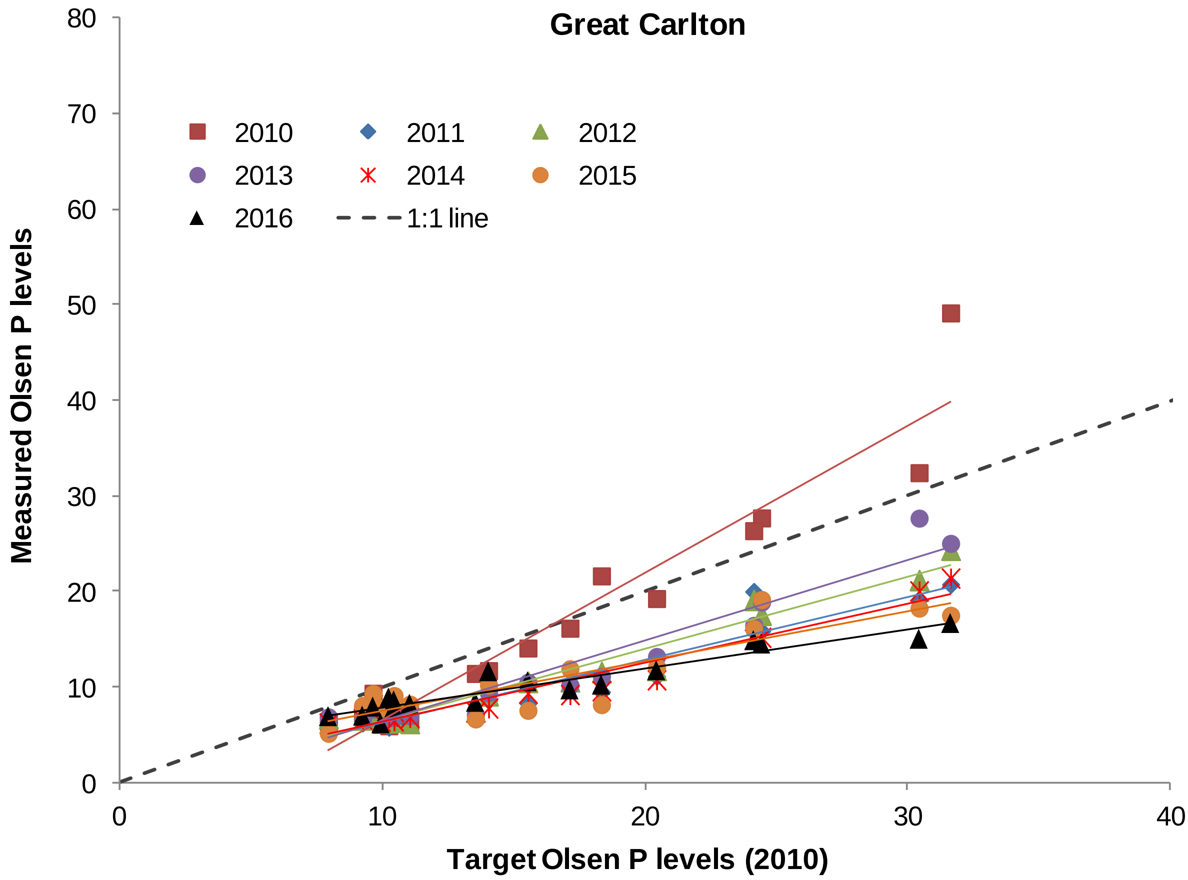


Fig. 4.11. Measured Olsen P, mg/kg, compared to 2010 target levels at the Great Carlton site

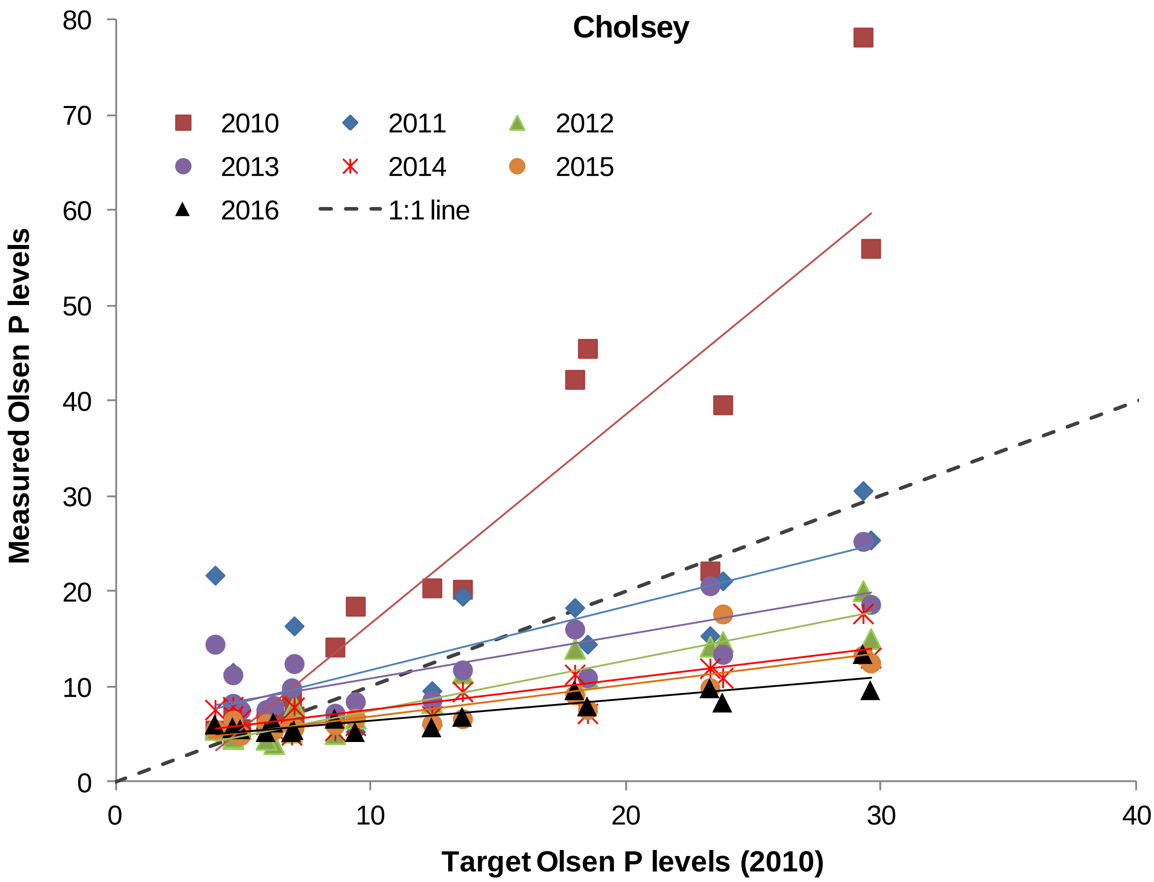


Fig. 4.12. Measured Olsen P, mg/kg, compared to 2010 target levels at the Cholsey site

4.2.3. Apparent Availability of P Fertiliser Applied in Autumn 2009

Table 4.4 shows the apparent availability of the P fertiliser applied in autumn 2009 (as an average for all plots that received an initial application of at least 100 kg/ha P) in each of the subsequent four years (for five sites, Weston has been excluded) or seven years (for three sites), but excluding the fresh P sub plots from 2012 onwards. 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 cumulative additional P offtake (through higher yield) compared to plots that did not receive any P fertiliser.

Table 4.4. 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	2014	2015	2016	2014-16 Mean
Peldon	39	18	20	22	20	16	9	5	10
Great Carlton	22	8	10	10	9	7	5	5	6
Cholsey	32	9	9	5	7	3	4	3	3
Caythorpe	16	13	9	12	11				
Cirencester	9	1	0	3	1				
5-Site Mean	**24**	**10**	**9**	**10**	**10**				

In 2010, (about six months after the P fertiliser was applied) initial P availability, as assessed by the change in Olsen P, ranged from 9 to 39%. 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. At Peldon, availability decreased from 39% in 2010 to 18% in 2011, then remained at a similar percentage in 2012 and 2013 (at a higher level than the 15% assumed when initial P treatment application rates were calculated) before decreasing progressively through to 2016. At Great Carlton, availability had decreased to around 8% by 2011, but then showed little further decline through to 2016. At Cholsey, availability had fallen to less than 10% by 2011, and continued to decrease down to less than 5% by 2014. At Caythorpe availability remained within a fairly narrow range between 2011 and 2013, averaging about 11%, but at Cirencester very little of the applied P remained available after 2010.

Although across all five sites, average P availability was around 10% in 2011 to 2013 (slightly less than the 15% that had been assumed when determining the initial P fertiliser treatment rates). The higher percentage P availability at Peldon is interesting and suggests that there is an inherent soil factor affecting the retention of added P extractable by the Olsen reagent that 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. Similarly, the very low percentage P availability at Cirencester suggests that applying large amounts of P fertiliser in any one year might not be an appropriate strategy for all soils.

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 for five sites in 2013 (Weston has been excluded) and for three sites in 2016 are shown in Table 4.5. The average change in Olsen P from 2011 to 2013 or from 2011 to 2016 is also shown, along with the calculated % availability of the fresh P fertiliser applied in the autumns of 2011 and 2012, and at three sites the autumns of 2014 and 2015 also (no fresh P was applied in autumn 2013).

The apparent availability in 2013 of fresh P fertiliser applied in autumns 2011 and 2012 varied between 11 and 20% over the five sites, but with the average of 15% close to what was assumed in the calculations. At this stage there was little similarity between the apparent % availabilities for the plots that had only received P in autumn 2009, and those that received fresh P in autumn 2011 and 2012. However, by 2016 the apparent availabilities of P fertiliser applied to the fresh P plots at Peldon, Great Carlton and Cholsey showed a similar pattern to the apparent availabilities of P fertiliser applied in autumn 2009 only (see Table 4.4)

Table 4.5. 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	2013 average	Change 2013-2011	% available	2016 average	Change 2016-2011	% available
Peldon	14.4	20.1	5.7	11	24.4	10.0	10
Great Carlton	10.2	22.0	11.8	20	19.7	9.5	8
Cholsey	13.6	21.9	8.4	13	19.8	6.2	5
Caythorpe	11.6	21.0	9.4	18			
Cirencester	9.9	20.9	11.1	12			
Mean				**15**			

4.3. Yield Response to Olsen P

4.3.1. Winter Wheat: Mean Yields at each P Index

Twenty two wheat crops were grown in total over the six sites and four or seven years. Mean grain yields at each Olsen P Index, and the standard deviation for each mean, are shown in Figs 4.13a-d. As the number of plot values comprising each yield mean varies, not just between sites and years, but also within an experiment (precluding analysis of variance), results from individual experiments should be treated with caution. At Cholsey in 2016 and Cirencester in 2012 only P Indices of 0 and 1 were represented so these crops have been excluded. In some cases there were no plots at a P Index of 3 or above. A 20 site year mean is therefore shown for yields at P Indices of 0, 1 and 2 only, and a 14 site year mean for yields at P Indices of 0, 1, 2 and 3 (in some experiments represented by only a single plot). Largest grain yields were obtained in 2010 and 2012 at Peldon, in 2014 at Great Carlton and 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.

Table 4.6 shows the mean decrease or increase in winter wheat yield at P Indices of 0 and 1 relative to that at P Index 2. All soils at Index 0 gave smaller yields than at Index 2, with the penalty ranging from about 0.7 t/ha to 2.5 t/ha.18 out of 20 crops gave a lower yield at Index 1 than at Index 2, with the penalty ranging from about 0.1 t/ha to 1.9 t/ha. Averaged over 20 site years, compared to an Olsen P Index of 2, the mean yield penalty at P Index 0 was about 1.4 t/ha and the mean yield penalty at P Index 1 was about 0.5 t/ha. Averaged over just the 14 site years, the yield penalties at P Index 0 and 1 were much the same, and the mean yield advantage at P Index 3 (or higher) compared to Index 2 was about 0.25 t/ha (Fig 4.13d).

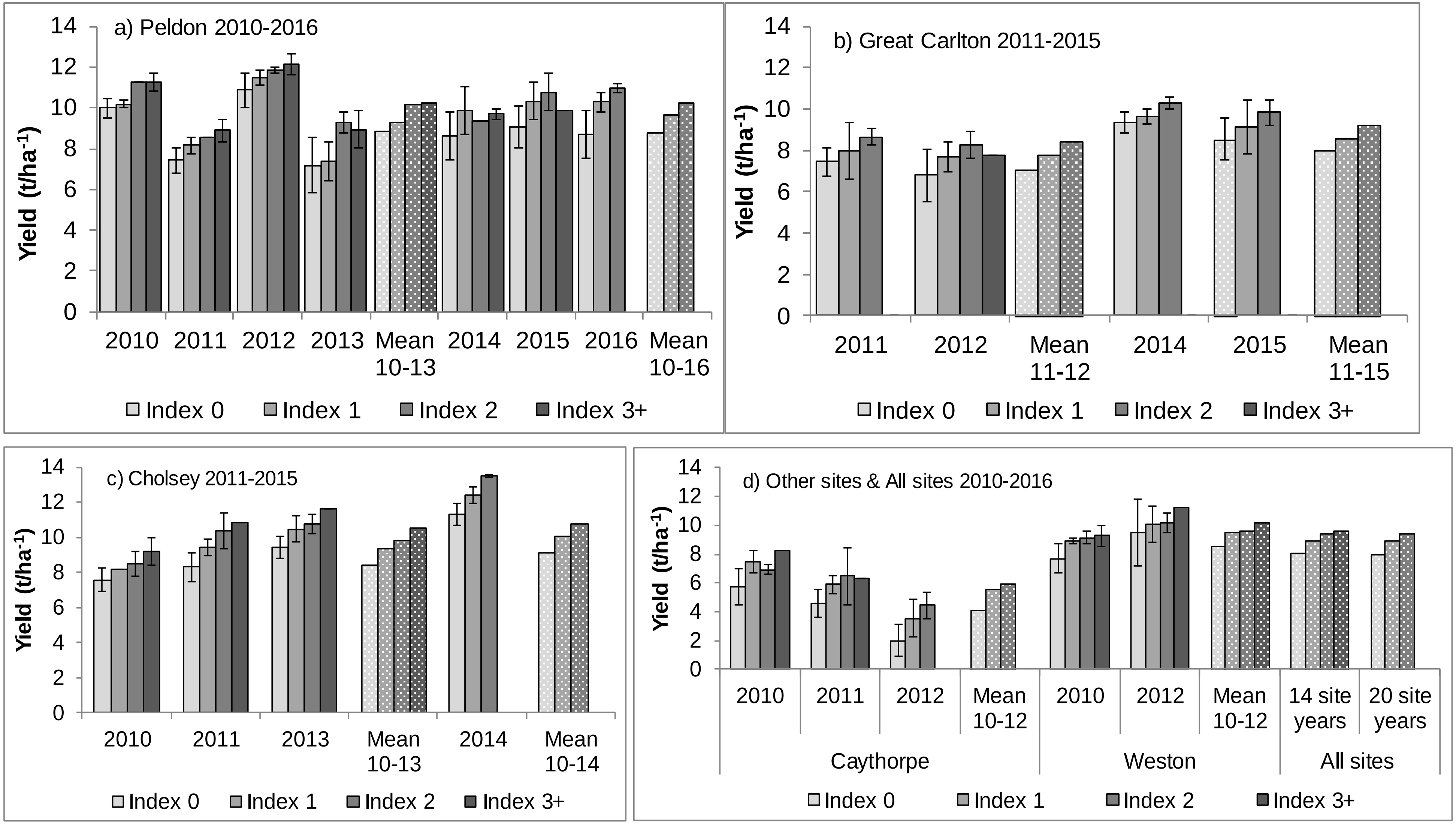


Fig. 4.13. Effect of P Index on mean wheat grain yield for a Peldon 2010-2016, b Great Carlton 2011-2015, c Cholsey 2011-2015, d Other sites & All sites 2010-2016. Error bars refer to the standard deviation on mean.

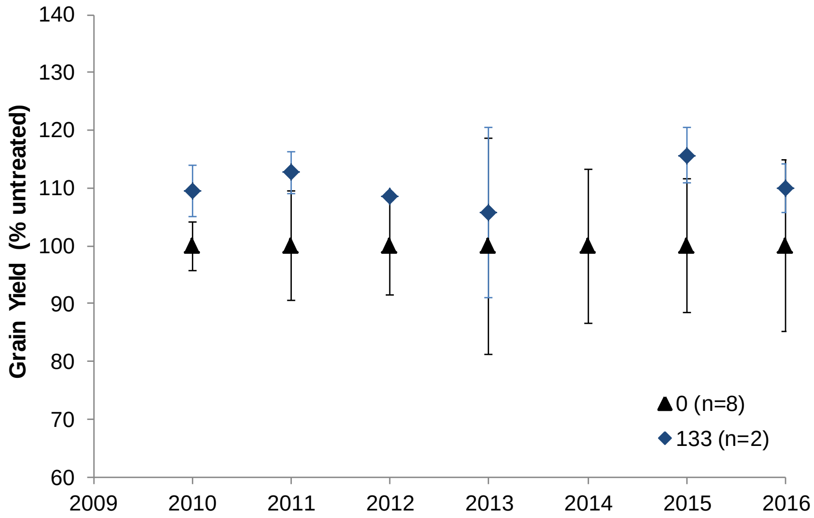
Table 4.6. Increase or decrease in wheat grain yield compared to a P Index of 2

Site	Year	Yield increase (+) or decrease (-) vs Index 2 (t/ha)	
		Index 0	Index 1
Peldon	2010	-1.27	-1.10
	2011	-1.11	-0.38
	2012	-0.98	-0.36
	2013	-2.08	-1.89
	2014	-0.73	+0.51
	2015	-1.71	-0.46
	2016	-2.25	-0.68
	Mean	-1.45	-0.62
Great Carlton	2011	-1.19	-0.67
	2012	-1.49	-0.61
	2014	-0.94	-0.65
	2015	-1.26	-0.68
	Mean	-1.22	-0.65
Cholsey	2010	-0.94	-0.32
	2011	-2.06	-0.94
	2013	-1.31	-0.28
	2014	-2.22	-1.14
	Mean	-1.63	-0.67
Caythorpe	2010	-1.14	+0.57
	2011	-1.85	-0.57
	2012	-2.45	-0.89
	Mean	-1.81	-0.30
Weston	2010	-1.45	-0.20
	2012	-0.69	-0.11
	Mean	-1.07	-0.15
Mean 20 site years		**-1.46**	**-0.54**

4.3.2. Winter Wheat: Mean Yields by 2009 P Treatment

Figures 4.14-4.16 show mean yields for plots receiving no P fertiliser in autumn 2009, compared to the mean yields for selected amounts of P fertiliser applied in autumn 2009, for Peldon (Fig. 4.14), Great Carlton (Fig. 4.15) and Cholsey (Fig. 4.16). Yields are presented as a % of the mean of plots receiving no P fertiliser, so the relative responses can be compared across years. At Peldon, yield differences were evident for both amounts of P fertiliser through to 2016. Their relative advantage over plots receiving no P fertiliser varied from year to year, but was not decreasing with time.

(a) 0 and 133 kg /ha P applied in autumn 2009



(b) 0 and 288 kg /ha P applied in autumn 2009

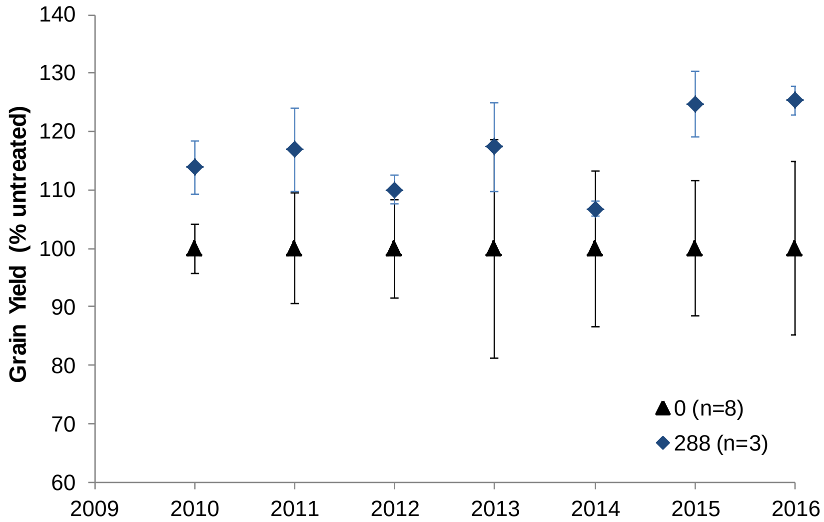
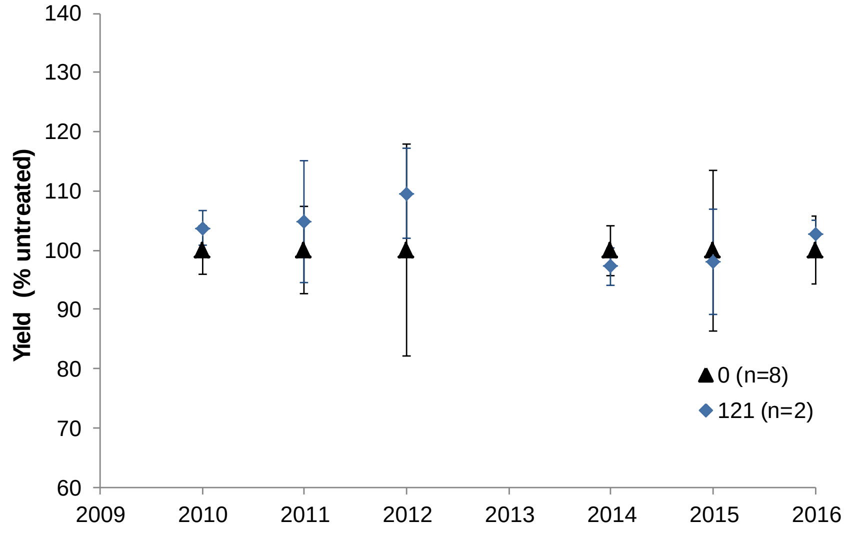


Fig. 4.14. Mean grain yield (as a % of the mean of plots not receiving any P fertiliser in autumn 2009) for plots receiving 133 kg/ha P fertiliser in autumn 2009 compared to plots receiving none (a); and for plots receiving 288 kg/ha P fertiliser in autumn 2009 compared to plots receiving none (b); for Peldon from spring 2009 until 2016. Error bars represent +/- 1 standard deviation on the mean. There was no yield value obtained for the 133 kg/ha P fertiliser treatment in 2014 (sample size (n) is defined in legend).

At Great Carlton, yield differences were evident for both amounts of P fertiliser until 2012, but from 2014 to 2016 were only apparent for the higher amount of P applied. Their relative advantage over plots receiving no P fertiliser again varied from year to year, but was generally smaller after 2013.

(a) 0 and 121 kg /ha P applied in autumn 2009



(b) 0 and 362 kg /ha P applied in autumn 2009

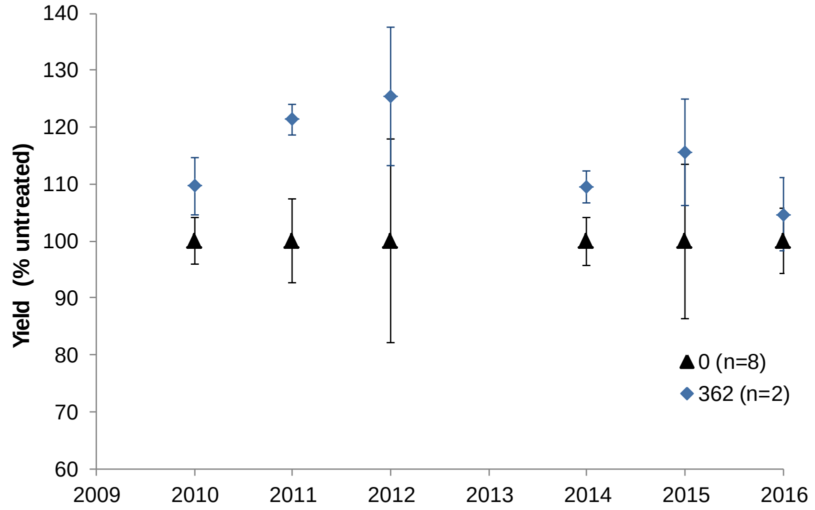
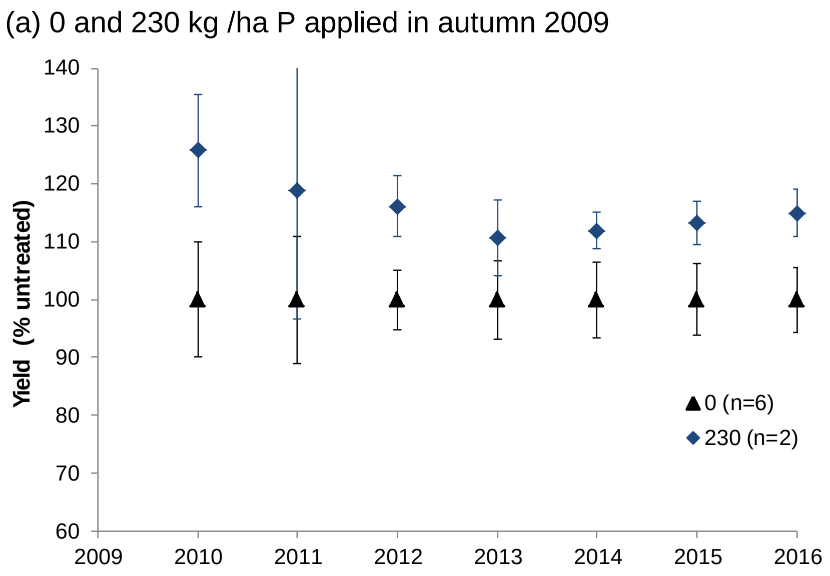


Fig. 4.15. Mean grain yield (as a % of the mean of plots not receiving any P fertiliser in autumn 2009) for plots receiving 121 kg/ha P fertiliser in autumn 2009 compared to plots receiving none (a); and for plots receiving 362 kg/ha P fertiliser in autumn 2009 compared to plots receiving none (b); for Great Carlton from spring 2009 until 2016. Error bars represent +/- 1 standard deviation on the mean (sample size (n) is defined in legend). There was no yield data for 2013 due to a crop failure.

At Cholsey, yield differences were evident for both amounts of P fertiliser right through to 2016, although the lower of the two amounts shown here is larger than at the other two sites. The relative advantage over plots receiving no P fertiliser varied from year to year, but tended to decrease between 2010 and 2013.



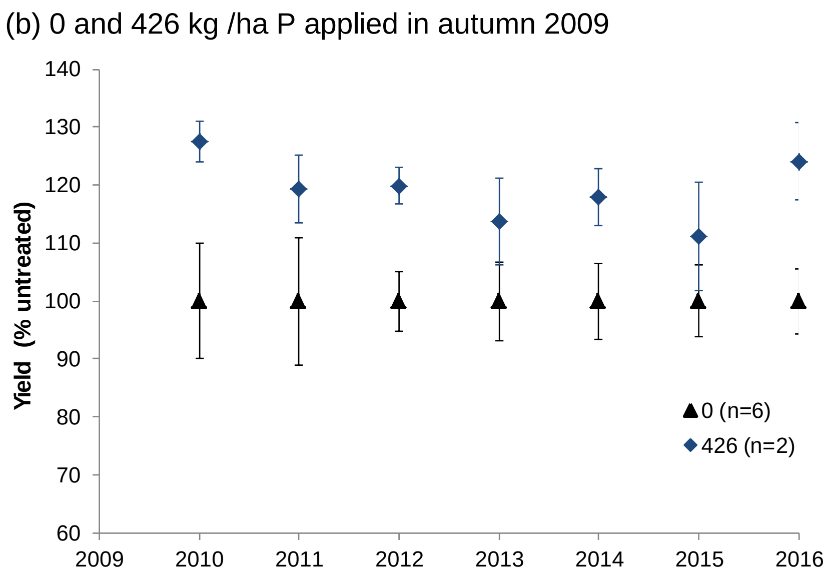


Fig. 4.16. Mean grain yield (as a % of the mean of plots not receiving any P fertiliser in autumn 2009) for plots receiving 230 kg/ha P fertiliser in autumn 2009 compared to plots receiving none (a); and for plots receiving 426 kg/ha P fertiliser in autumn 2009 compared to plots receiving none (b); for Cholsey from spring 2009 until 2016. Error bars represent +/- 1 standard deviation on the mean (sample size (n) is defined in legend).

4.3.3. Winter Oilseed Rape: Mean Yields at each P Index

Four of the five oilseed rape crops grown were harvested, one in each year across four of the sites. Mean yields at each P Index, and the standard deviation for each mean, are shown in Fig. 4.17. Seed yields were moderate at Cholsey in 2012, but relatively high in other cases. At Weston there was no apparent relationship between P Index and seed yield. At Great Carlton and Cholsey, yields were lower at P Index 0 than at P Index 2, with yield penalties of 0.24 t/ha and 0.56 t/ha respectively (Table 4.7). At Cirencester only P Indices 0 and 1 were represented.

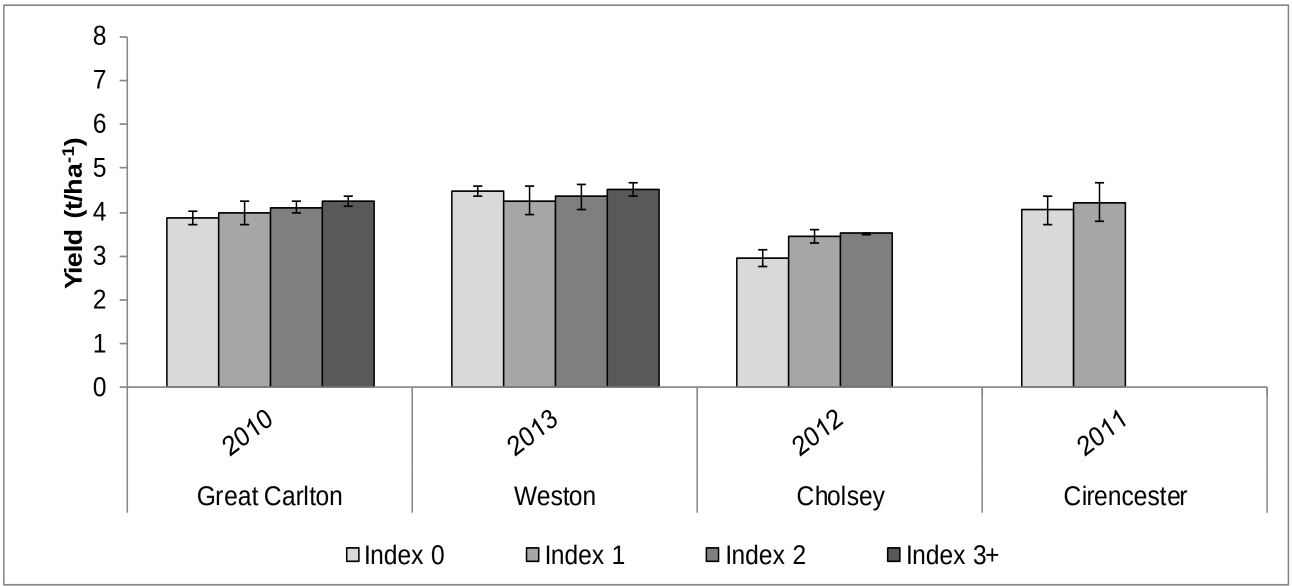


Fig 4.17. Effect of P Index on mean winter oilseed rape seed yield. Error bars refer to the standard deviation on mean.

Table 4.7. 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	-0.24	-0.12	+0.13
Weston	2013	+0.14	-0.08	+0.16
Cholsey	2012	-0.56	-0.05	-

4.3.4. Winter and Spring Barley: Mean Yields at each P Index

There were four barley crops in total: spring barley at Cirencester in 2010 and 2013, spring barley at Caythorpe in 2013, and winter barley at Great Carlton in 2016. Mean grain yields at each P Index, and the standard deviation for each mean, are shown in Fig 4.18. Yield penalties at Index 0 and 1 compared to Index 2 are shown in Table 4.8. Yields were low and variable at Cirencester in 2013. Mean yields showed no clear relationship with P Index, with better than expected yields at P Index 0.

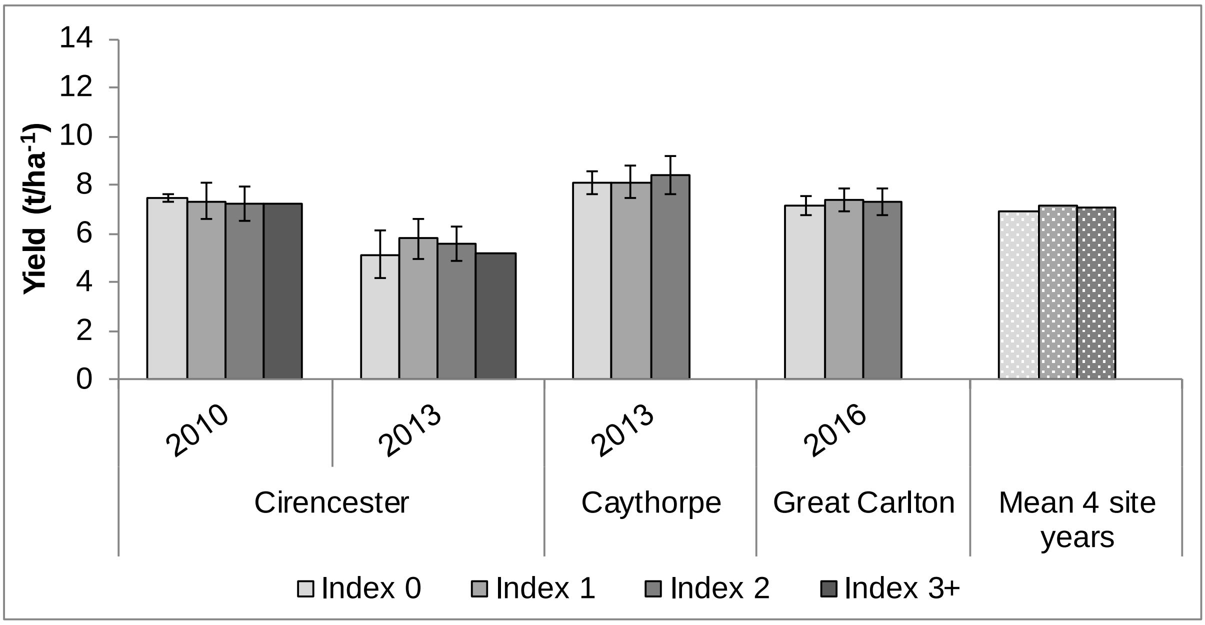


Fig 4.18. Effect of P Index on mean barley grain yield. Error bars refer to the standard deviation on mean.

Table 4.8. Increase or decrease in barley yield compared to a P Index of 2

Site	Year	Yield increase (+) or decrease (-) vs Index 2 (t/ha)	
		Index 0	Index 1
Cirencester	2010	+0.26	+0.12
	2013	-0.42	+0.23
Caythorpe	2013	-0.31	-0.29
Great Carlton	2016	-0.18	+0.10
Mean 4 site years		**-0.16**	**+0.04**

4.3.5. Other Crops

Winter Oats

The only winter oat crop was Cholsey in 2015. All but one plot were at either Index 0 or 1. Yields averaged 7.70 t/ha at Index 0 and 7.92 t/ha at Index 1, a difference of 0.22 t/ha (see also Table 4.20).

Spring Beans

The only spring bean crop was at Weston in 2011. Seed yields were very low due to severe spring drought. Yields averaged 1.4 t/ha at P Index 0 or 1, and 1.9 t/ha at P Index 2.

4.4. Yield Response to Fresh P

4.4.1. Winter Wheat

Data on wheat yield response to fresh P fertiliser were obtained for fourteen crops (Figs 4.19a-d). For each site yields with fresh P are shown at Olsen P Indices of 1, 2 and 3 as measured in the fresh P plots. The majority of experiments had no plots at P Index 0 (when measured in the fresh P plots) as a result of the large applications of P fertiliser each autumn. At Cholsey in 2014 and Weston in 2014 only P Indices of 1 and 2 were represented so these crops have been excluded from the 12 site year mean. Compared to P Index 2, the mean yield penalty at Index 1 was only about 0.25 t/ha (but note that the yield penalties at Index 0 in the two excluded experiments were much greater). The mean yield advantage at P Index of 3 (or higher) compared to Index 2 was about 0.4 t/ha.

In Table 4.9 mean grain yields at P Indices of 1 and 2 for plots receiving fresh P are compared with mean grain yields at P Indices of 1 and 2 for plots that only received P in autumn 2009. Yields are the mean of 12 site years for which P Indices of 1 and 2 were represented in both the fresh P and non-fresh P plots. At Index 2, there was no overall yield difference between plots that received fresh P and those that did not. At Index 1, there was a small yield advantage (about 0.2 t/ha) to plots that had received fresh P.

Table 4.9. Wheat grain yield comparison between soil P only and fresh P plots at P Index 1 and 2

	Yield (t/ha) at each P Index	
	Index 1	Index 2
Soil P only plots	9.36	9.96
Plots receiving fresh P	9.58	9.96
Yield difference (t/ha)	**+0.22**	**0.00**

Mean of 12 site years: Peldon 2012, 2013, 2014, 2015, 2016; Great Carlton 2012, 2014, 2015; Cholsey 2013, 2014; Caythorpe 2012; and Weston 2012

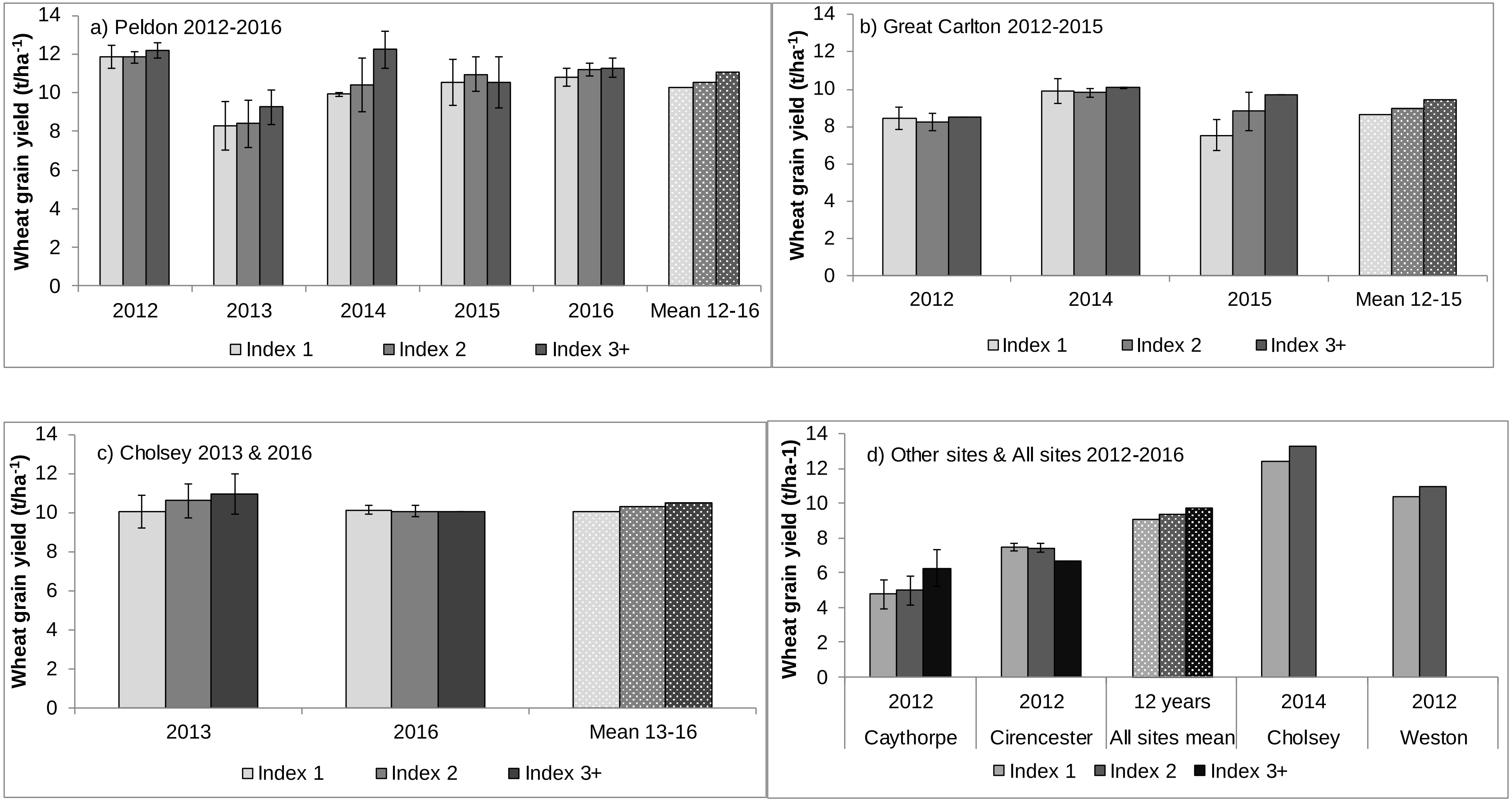


Fig 4.19. Wheat grain yield with fresh P fertiliser for plots at Olsen P Index 1, 2 or 3+. Error bars refer to the standard deviation on mean.

The yield of each fresh P sub-plot was compared to the average yield of the two sub plots without fresh P that were part of the same large plot, and the yield increase or decrease with fresh P was calculated. This was only done for 2012 and 2013, because after that the difference in measured Olsen P levels between plots that received fresh P and those that did not had become large. Table 4.10 shows the yield increase or decrease with fresh P relative to the yield without fresh P, at soil P Indices of 0, 1 and 2 as measured in the sub plots that did not receive fresh P (to make clear any benefit of fresh P). Yield responses to fresh P at Caythorpe in 2012 were abnormally large, due to the very low yields achieved under waterlogged conditions in plots that did not receive fresh P. Yield increases with fresh P ranged from 0.24 to 1.60 t/ha at Index 0. Four crops showed an increase of more than 0.5 t/ha at Index 1, and two crops showed an increase of more than 0.5 t/ha at Index 2. 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 0.5 t/ha at Index 1 was sufficient to raise yields to the level achieved with soils maintained at Index 2.

Table 4.10. Wheat grain yield response to fresh P fertiliser compared to soil P plots at Index 0, 1 or 2

Site	Year	Increase (+) or decrease (-) in yield at each P Index		
		Index 0	Index 1	Index 2
Peldon	2012	+0.91	+0.02	+0.04
	2013	+1.18	+0.65	+0.52
Great Carlton	2012	+1.60	+0.80	+0.11
Cholsey	2013	+0.69	+0.66	+0.03
Caythorpe	2012	+2.79	+1.54	+1.09
Weston	2012	+0.24	-0.25	+0.08
Mean 6 site years		**+1.24**	**+0.57**	**+0.31**

4.4.2. Winter Oilseed Rape

Data on oilseed rape yield response to fresh P fertiliser were obtained for two crops. Seed yields at Olsen P Indices of 0, 1, 2 and 3+ (as measured in the fresh P plots) are shown in Fig 4.20. There were no meaningful differences in yield between P Indices.

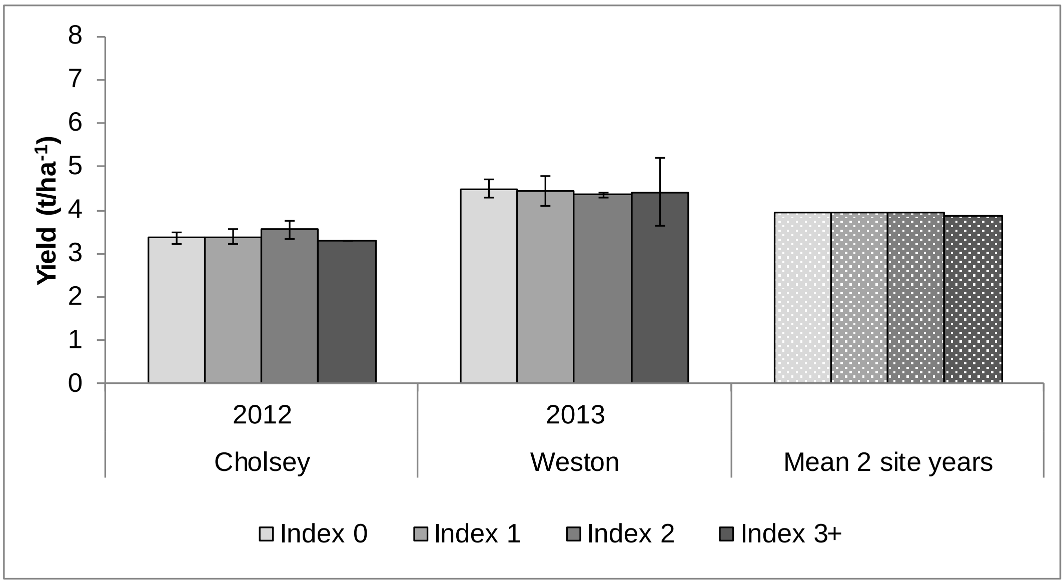


Fig 4.20. Winter oilseed rape seed yield with fresh P fertiliser for plots at Olsen P Index 1, 2 or 3+. Error bars refer to the standard deviation on mean.

In Table 4.11 seed yields at P Indices of 0, 1 and 2 for plots receiving fresh P are compared with seeds yields at P Indices of 0, 1 and 2 for plots that only received P in autumn 2009. There were no consistent differences in yield between fresh P and soil P only plots, when compared at the same Olsen P Index. There was perhaps an indication of a yield advantage to fresh P at P Index 0 at Cholsey, where the difference was similar to the yield penalty seen at P Index 0 compared to Index 1 in the soil P only plots.

Table 4.11. Oilseed rape yield comparison between soil P only and fresh P plots at P Index 0, 1 and 2

	Yield (t/ha) at each P Index					
	Cholsey			Weston		
	Index 0	Index 1	Index 2	Index 0	Index 1	Index 2
Soil P only plots	2.96	3.46	3.51	4.49	4.27	4.35
Plots receiving fresh P	3.37	3.39	3.55	4.49	4.46	4.36
Yield difference (t/ha)	**+0.41**	**-0.07**	**+0.04**	**0.00**	**+0.21**	**-0.01**

4.4.3. Winter and Spring Barley

Data on winter or spring barley yield response to fresh P fertiliser were obtained for three crops. Grain yields at Olsen P Indices of 1, 2 and 3+ (as measured in the fresh P plots) are shown in Fig 4.21. There were no plots at P Index 0. At all sites, yields appeared to decrease as Olsen P increased above Index 1.

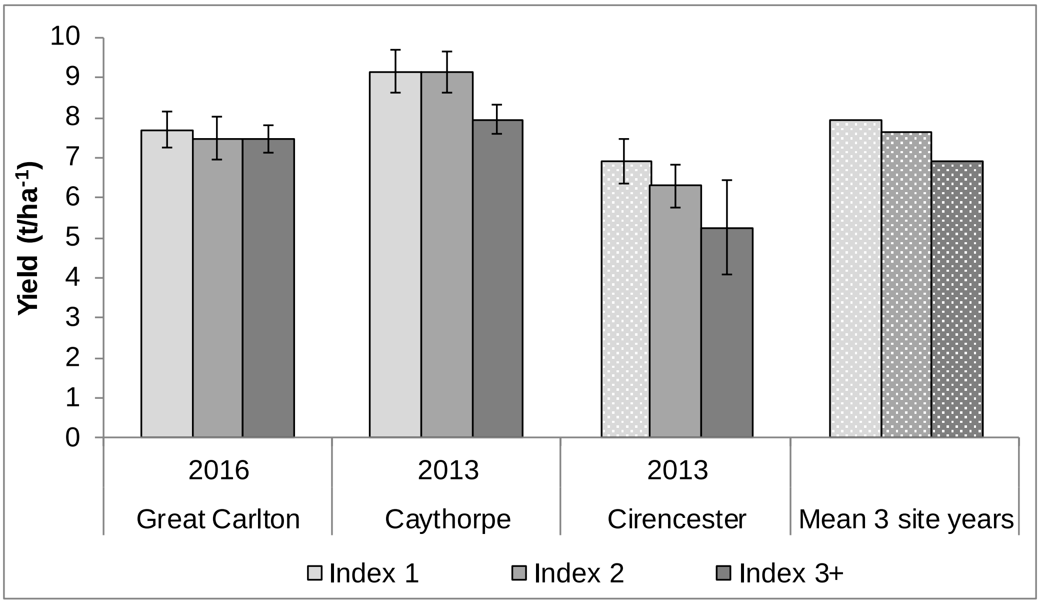


Fig 4.21. Barley grain yield with fresh P fertiliser for plots at Olsen P Index 1, 2 or 3+. Error bars refer to the standard deviation on mean.

In Table 4.12 grain yields at P Indices of 1 and 2 for plots receiving fresh P are compared with yields at P Indices of 1 and 2 for plots that only received P in autumn 2009. Fresh P plots were higher yielding than soil P only plots, when compared at the same Olsen P Index. The advantage to fresh P was seen at all 3 sites, but was largest for the two spring barley crops (Caythorpe 2013 and Cirencester 2013).

Table 4.12. Spring barley yield comparison between soil P only and fresh P plots at P Index 1 and 2

	Yield (t/ha) at each P Index	
	Index 1	Index 2
Soil P only plots	7.10	7.09
Plots receiving fresh P	7.92	7.64
Yield difference (t/ha)	**+0.82**	**+0.55**

Mean of 3 site years

The yield of each fresh P sub-plot was compared to the average yield of the two sub plots without fresh P that were part of the same large plot, and the yield increase or decrease with fresh P was calculated. This was only done up to 2013, because after that the difference in measured Olsen P levels between plots that received fresh P and those that did not had become large. Table 4.13

shows the yield increase or decrease with fresh P relative to the yield without fresh P, at soil P Indices of 0, 1 and 2 as measured in the sub plots that did not receive fresh P (to make clear any benefit of fresh P). Although neither site had shown a consistent yield benefit to increasing Olsen P, both showed a benefit from fresh P, averaging about 0.6 t/ha when compared to soil P plots at Index 1 and 0.9 t/ha when compared to soil P plots at Index 0.

Table 4.13. Barley yield response to fresh P fertiliser compared to soil P plots at Index 0, 1 or 2

Site	Year	Increase (+) or decrease (-) in yield at each P Index		
		Index 0	Index 1	Index 2
Caythorpe	2013	+1.16	+0.48	-0.13
Cirencester	2013	(+0.73)	+0.66	+0.26
Mean 3 site years		+0.94	+0.57	+0.07

( ) Value based only on 1 plot

4.4.4. Other Crops

Winter Oats

Data on winter oat grain yield response to fresh P fertiliser were obtained for one crop, at Cholsey in 2015. Yields at Olsen P Indices of 0, 1, 2 (as measured in the fresh P plots) are shown in Table 4.14. These are also compared to the yields of plots that only received P in autumn 2009.

Table 4.14. Winter oat yield with fresh P fertiliser for plots at Olsen P Index 0, 1 or 2, and in comparison to the yield of soil P only plots

Site	Mean yield (t/ha) with fresh P			Standard deviation on mean		
	Index 0	Index 1	Index 2	Index 0	Index 1	Index 2
Soil P only plots	7.70	7.92	(7.62)	0.554	0.598	-
Plots receiving fresh P	8.61	8.59	8.24	0.120	0.106	0.451
Yield difference (t/ha)	**+0.91**	**+0.67**	**+0.62**			

( ) Value based only on 1 plot

With only one site results have to be treated with caution, but there was no apparent positive response to Olsen P Index in plots treated with fresh P fertiliser. However higher yields were recorded for plots treated with fresh P than for soil P only plots, at the same P Index.

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. Further response curves were fitted in 2014, 2015 and 2016 for Peldon, Great Carlton and Cholsey. For 2011 the relationship was based on yield and Olsen P data from the 18 large plots. For 2012 and subsequent years, separate response curves were fitted for those sub plots that received no P fertiliser after autumn 2009, and those that received fresh P in autumn 2011 onwards, using the yield and Olsen P values measured in the respective plots.

4.5.1. Winter Wheat

Estimates of the fitted maximum (plateau) yield and critical Olsen P levels associated with 95% or 98% of maximum yield for wheat crops that received no P fertiliser after autumn 2009 are shown in Table 4.15. Meaningful estimates were obtained for twelve crops in total that had an adequate range of Olsen P levels in the soil P plots. The critical P values for Caythorpe in 2011 and Cholsey in 2011, 2013 and 2016 had large standard errors and should be treated with caution. Levels of Olsen P associated with 95% of maximum yield ranged from 6.9 mg/kg (Index 0) to 17.8 mg/kg (Index 2), and for 98% of maximum yield the range was 8.5 mg/kg (Index 0) to 24.4 mg/kg (Index 2). Over the ten wheat crops with relatively low standard errors, average critical P levels were around 11 mg/kg for 95% of maximum yield and 15 mg/kg for 98% of maximum yield, which are between the mid to upper half of P Index 1.

Peldon was the only site for which it was possible to fit response curves and obtain meaningful estimates for all years. Wheat yield responses to Olsen P at Peldon over the six successive crop years are shown in Figs. 4.22a-f for crops that received no P fertiliser after autumn 2009. The yield response plateaued at a lower level of Olsen P in 2012 through 2015 than in 2011. In 2016, yield did not plateau within the more limited range of Olsen P levels that remained. Response curves for other site years that gave meaningful estimates are shown in Figs 4.23a-f. Remaining response curves are shown in Figs 7a-e in Appendix 6.

Table 4.15. Fitted maximum wheat yield and Olsen P to achieve 95% and 98% of maximum yield for crops that received no P fertiliser after autumn 2009

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)	8.86	0.22	13.8	2.80	18.6	4.47	70
	2012	Sub plots (36)	11.84	0.18	6.9	0.50	8.5	0.83	71
	2013	Sub plots (36)	8.67	0.28	9.9	1.56	12.0	2.32	47
	2014	Sub plots (36)	10.07	0.38	9.8	1.90	12.2	2.82	46
	2015	Sub plots (36)	10.74	0.28	10.2	1.79	13.6	2.71	62
	2016	Sub plots (36)	11.44	0.78	15.9	5.78	21.5	8.34	60
Great Carlton	2011	Large plots (18)	8.64	0.35	10.2	2.91	13.1	4.73	50
	2012	Sub plots (36)	8.22	0.35	10.6	2.82	13.2	4.42	35
	2014	Sub plots (36)	n/a	n/a	n/a	n/a	n/a	n/a	n/a
	2015	Sub plots (36)	n/a	n/a	n/a	n/a	n/a	n/a	n/a
Cholsey	2011	*Large plots (18)*	*11.25*	*1.68*	*42.2*	*39.77*	*60.5*	*57.0*	*67*
	2013	*Sub plots (36)*	*11.33*	*0.78*	*17.1*	*10.30*	*24.4*	*16.37*	*38*
	2014	Sub plots (36)	n/a	n/a	n/a	n/a	n/a	n/a	n/a
	2016	*Sub plots (36)*	*10.49*	*1.58*	*15.2*	*13.48*	*21.2*	*19.57*	*49*
Caythorpe	2011	*Large plots (18)*	*7.79*	*1.92*	*29.3*	*29.04*	*39.3*	*40.08*	*52*
	2012	Sub plots (36)	4.54	0.47	17.8	4.32	21.9	5.79	59
Weston	2012	Sub plots (36)	10.50	0.45	8.5	2.92	10.5	4.19	44
Cirencester	2012	Sub plots (36)	n/a	n/a	n/a	n/a	n/a	n/a	n/a

n/a = no estimate obtained for these parameters

Figures in italics had large standard errors and should be treated with caution

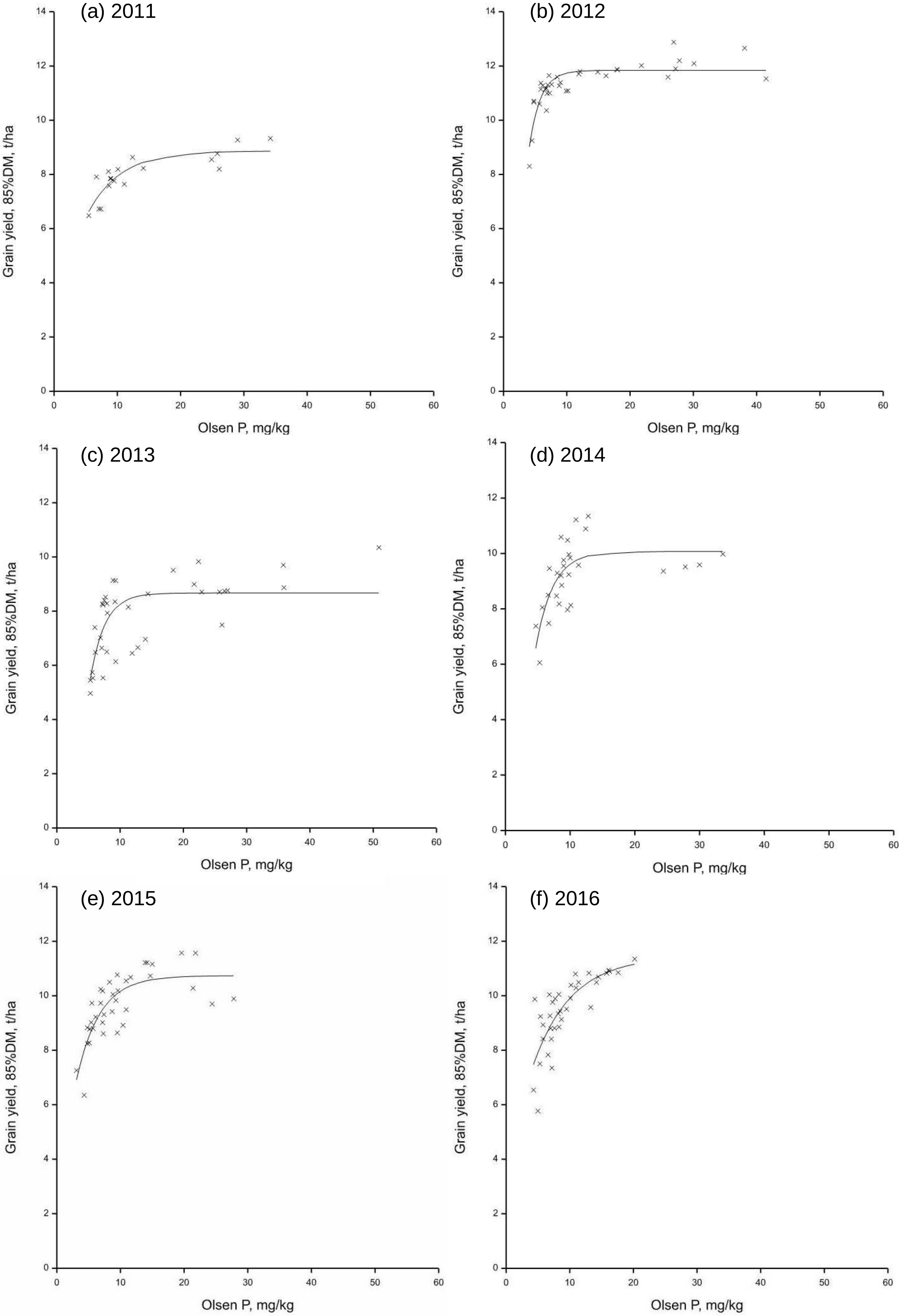


Fig. 4.22. Fitted yield response curves for Peldon wheat (a 2011, b 2012, c 2013, d 2014, e 2015, f 2016)

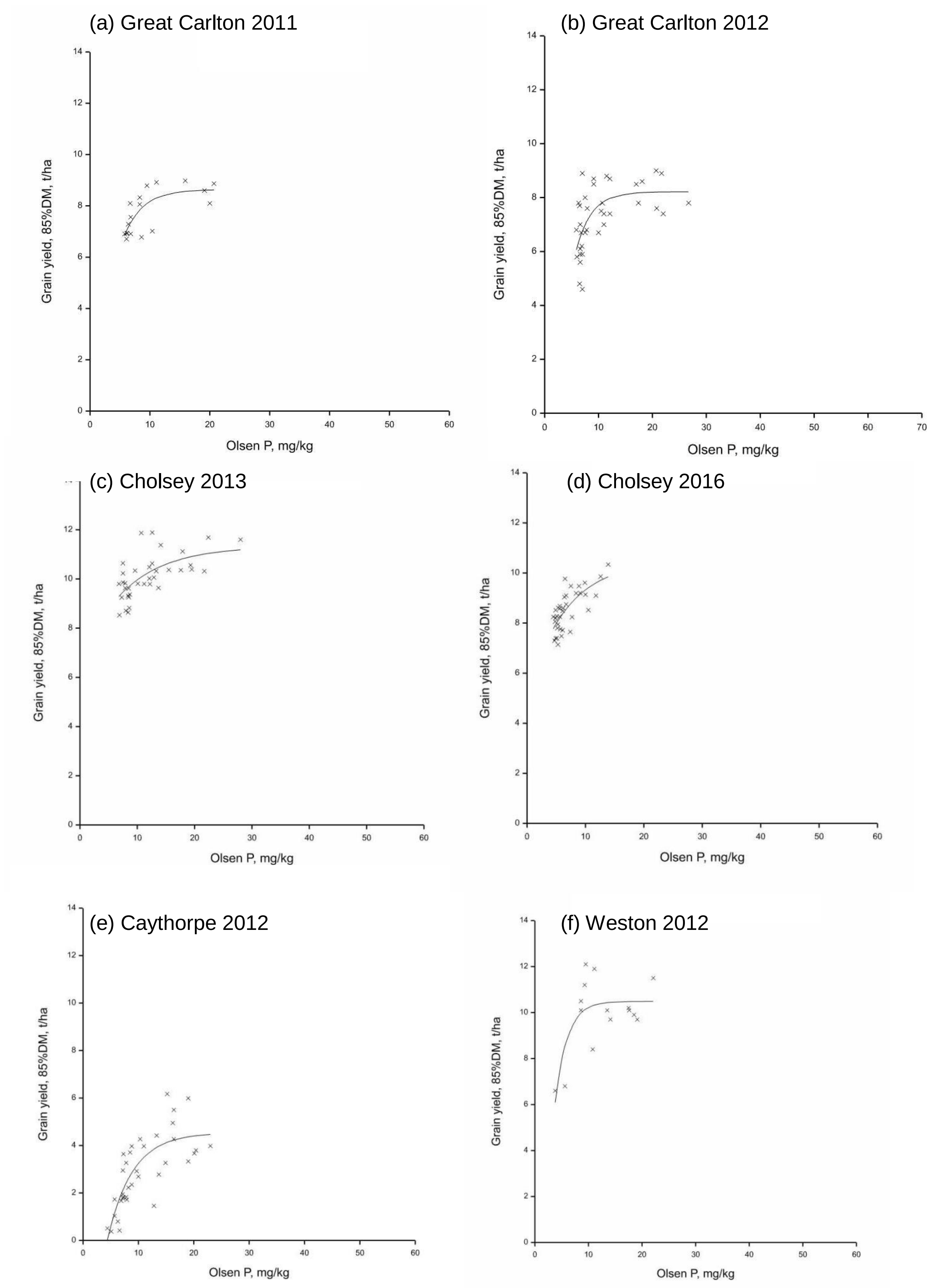


Fig. 4.23. Fitted yield response curves for wheat crops other than at Peldon (a Great Carlton 2011, b Great Carlton 2012, c Cholsey 2013, d Cholsey 2016, e Caythorpe 2012, f Weston 2012)

Wheat yield responses to Olsen P at Peldon for crops that had received fresh P fertiliser in the autumns of 2011, 2012, 2014 and 2015 are shown in Figs. 4.24a-d. Response curves for five other sites are shown in Figs.4.25a-e. In most cases yield responses were flatter where fresh P fertiliser had been applied compared to where it had not, but Great Carlton 2015 and Weston 2012 were notable exceptions (Fig 4.25b&e). In most cases it was not possible to obtain a meaningful estimate of the fitted maximum (plateau) yield and/or critical Olsen P levels associated with 95% or 98% of maximum yield. However, they were obtained for two wheat crops (Peldon 2015 and Great Carlton 2015) that had an adequate range of Olsen P levels in the fresh P plots (Table 4.16).

Table 4.16. Fitted maximum wheat yield and Olsen P to achieve 95% and 98% of maximum yield for crops that received fresh P fertiliser

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	2012	Sub plots (18)	12.73	3.73	n/a	n/a	n/a	n/a	n/a
	2013	*Sub plots (18)*	*9.19*	*1.21*	*19.8*	*27.62*	*27.9*	*48.76*	n/a
	2015	Sub plots (18)	10.70	0.27	9.0	1.38	11.5	2.07	75
	2016	Sub plots (18)	n/a	n/a	n/a	n/a	n/a	n/a	n/a
Great Carlton	2012	Sub plots (18)	8.43	0.15	6.6	n/a	7.1	n/a	n/a
	2015	Sub plots (18)	9.69	0.49	20.0	3.90	24.6	5.72	68
Cholsey	2013	*Sub plots (18)*	*11.09*	*0.83*	*25.2*	*15.18*	*33.5*	*31.27*	*6*
	2016	Sub plots (18)	10.20	0.15	36.4	n/a	35.1	n/a	n/a
Caythorpe	2012	Sub plots (18)	n/a	n/a	n/a	n/a	n/a	n/a	n/a
Weston	2012	*Sub plots (18)*	*10.76*	*0.93*	*10.1*	*7.16*	*13.8*	*10.76*	*15*
Cirencester	2012	Sub plots (18)	n/a	n./a	n/a	n/a	n/a	n/a	n/a

n/a = no estimate obtained for these parameters

Figures in italics had large standard errors and should be treated with caution

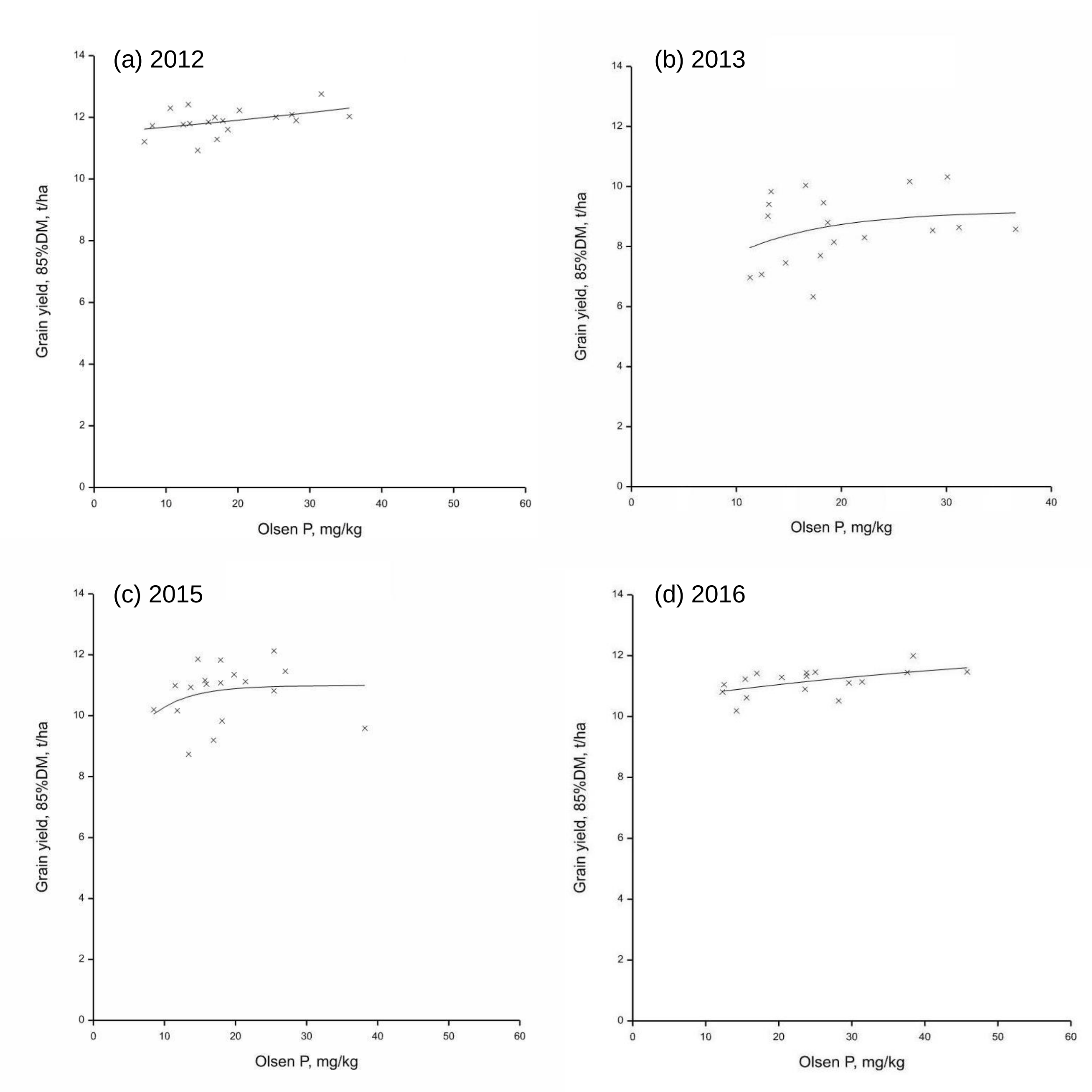


Fig. 4.24. Fitted yield response curves for Peldon wheat crops receiving fresh P fertiliser (a 2012, b 2013, c 2015, d 2016)

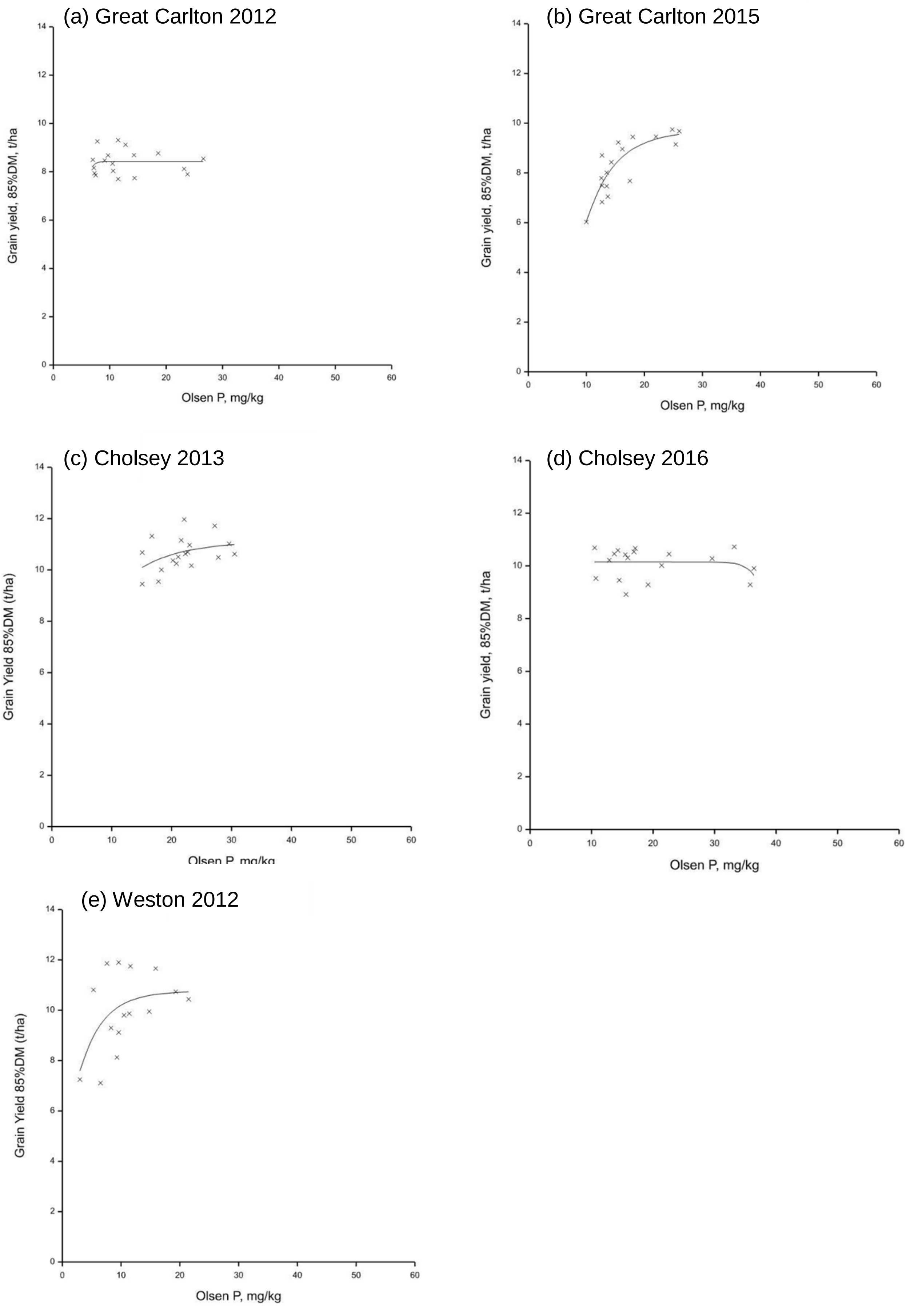


Fig. 4.25. Fitted yield response curves for other wheat crops receiving fresh P fertiliser (a Great Carlton 2012, b Great Carlton 2015, c Cholsey 2013, d Cholsey 2016, e Weston 2012)

4.5.2. Winter Oilseed Rape

Seed yield responses to Olsen P for oilseed rape crops at Cirencester in 2011 and Cholsey in 2012 that received no P fertiliser after autumn 2009 are shown in Figs. 4.26a and 4.26b respectively. Seed yield was more responsive to Olsen P and appeared to plateau at a higher Olsen P level at Cholsey than at Cirencester. Seed yield did not respond to Olsen P at Weston in 2013, and there was no response to Olsen P at Cirencester or Cholsey when fresh P fertiliser was applied. Reasonable estimates of the fitted maximum yields were obtained for all crops (Table 4.17). 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 this or any of the oilseed rape crops.

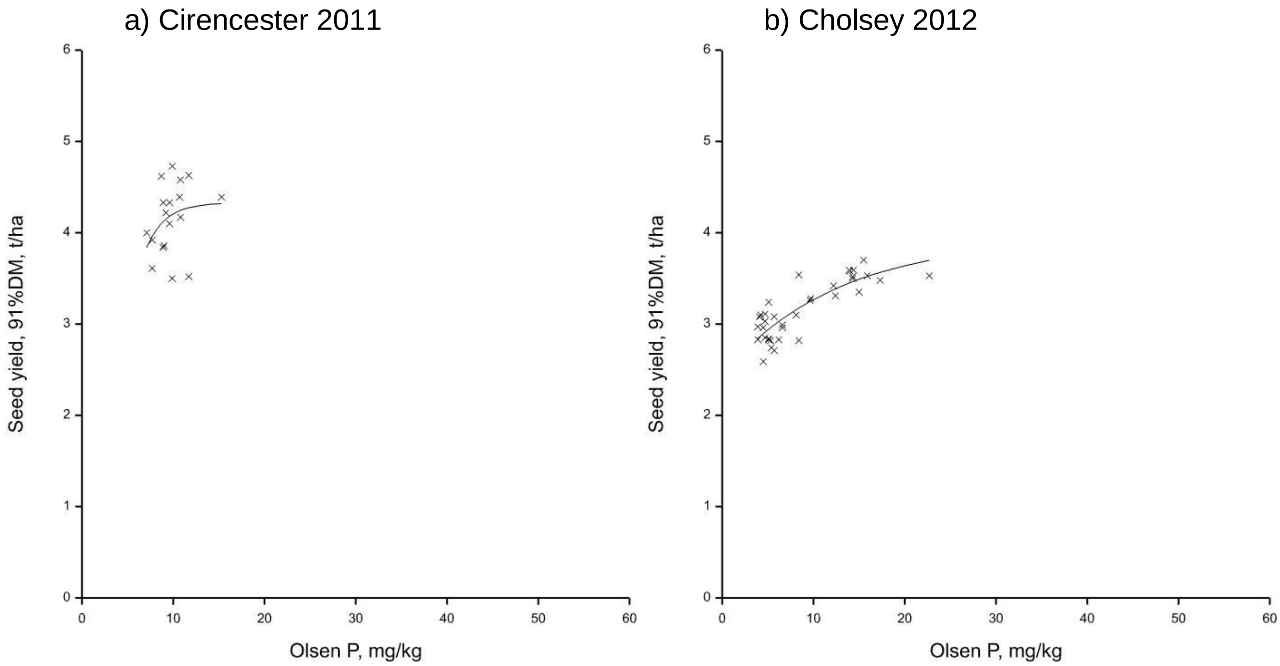


Fig. 4.26. Fitted yield response curves for oilseed rape (a Cirencester 2011, b Cholsey 2012)

Table 4.17. Fitted maximum oilseed rape yield and Olsen P to achieve 95% and 98% of maximum yield for crops that received no P fertiliser after autumn 2009

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.	
Cholsey	2012	*Sub plots (36)*	*3.93*	*0.51*	*33.2*	*32.96*	*48.5*	*47.46*	*68*
Cirencester	2011	*Large plots (18)*	*4.57*	*0.53*	*14.24*	*9.10*	*18.20*	*15.51*	*13*

Figures in italics had large standard errors and should be treated with caution

4.5.3. Winter and Spring Barley

Yield responses to Olsen P for spring barley at Caythorpe in 2013 and winter barley at Great Carlton in 2016 that received no P fertiliser after autumn 2009 are shown in Figs. 4.27a and 4.27b respectively. There was a small yield increase with Olsen P in the spring barley but not in the winter barley, and no clear plateau in either crop. In both cases, when fresh P fertiliser was applied, yield appeared to decrease as Olsen P increased. It was not possible to obtain meaningful estimates of the critical P levels associated with 95% or 98% of the maximum yield for any of the barley crops (Table 4.18).

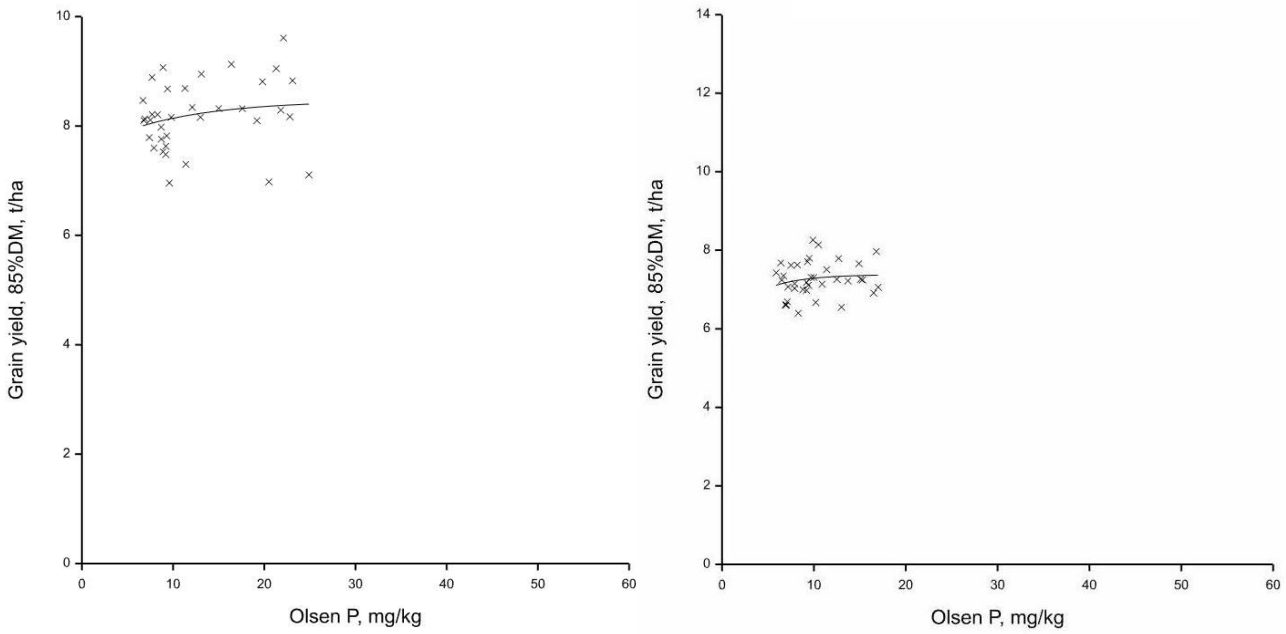


Fig. 4.27. Fitted yield response curves for a) spring barley at Caythorpe in 2013 and b) winter barley at Great Carlton in 2016

Table 4.18. Fitted maximum barley yield and Olsen P to achieve 95% and 98% of maximum yield for crops that received no P fertiliser after autumn 2009

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.	
Great Carlton	2016	Sub plots (36)	n/a	n/a	n/a	n/a	n/a	n/a	n/a
Caythorpe	2013	*Sub plots (36)*	*8.46*	*0.87*	*9.29*	*48.76*	*20.8*	*131.30*	*n/a*
Cirencester	2013	Sub plots (36)	n/a	n/a	n/a	n/a	n/a	n/a	n/a

n/a = no estimate obtained for these parameters

Figures in italics had large standard errors and should be treated with caution

4.6. P Content of Grain and Seed

4.6.1. Measured P Contents 2014 to 2016

For harvest years 2014 to 2016, %P contents in grain were measured for all crops. Results (at 100% dry matter, as reported by the laboratory) for seven crops of wheat are shown in Tables 4.19 and 4.20 for soil P only plots and for plots that received fresh P respectively, and for one crop each of winter barley and winter oats in Tables 4.21 and 4.22 respectively.

Table 4.19 % P content (100% dm) of wheat grain from harvests 2014-16 for soil P only plots at each P Index

Site	Year	Mean % P content (at 100% dm)			Standard deviation on mean		
		Index 0	Index 1	Index 2	Index 0	Index 1	Index 2
Peldon	2014	0.23	0.24	0.27	0.018	0.023	0.032
	2015	0.25	0.27	0.30	0.013	0.014	0.017
	2016	0.24	0.29	0.35	0.029	0.027	0.014
	15-16 Mean	0.24	0.28	0.32			
Great Carlton	2014	0.21	0.27	0.26	0.023	0.020	0.024
	2015	0.21	0.23	0.26	0.020	0.018	0.015
Cholsey	2014	0.22	0.27	0.33	0.039	0.044	0.018
	2016	0.24	0.32	-	0.030	0.027	-
Mean 4 sites exc. 2014		**0.24**	**0.28**	**0.30**			
Mean 7 site years		**0.23**	**0.27**	**0.29**			

For soil P only plots (Table 4.19), there was some variation between sites and seasons. At Peldon and Cholsey, mean grain P contents were lower in 2014 than in 2015 / 2016 for plots within the same Olsen P Index. However, this was not the case at Great Carlton. It is not known whether or not the change in the laboratory testing procedure between 2014 and 2015 might have contributed to the differences observed at Peldon and Cholsey. The inclusion or not of the 2014 grain P data made only a small difference to the over-year mean grain P contents.

Regardless of the year, grain P contents were consistently lower at an Olsen P Index of 0 than at Index 1, and in most cases lower at Index 1 than at Index 2. Even at Index 2, mean grain P contents were lower than the value of 0.4% P in grain dry matter used to derive the kg P_2O_5 offtake per tonne of cereal grain given in RB209. At Index 0, mean grain P contents were only around 60% of this value. For fresh P treated plots (Table 4.20), grain P contents tended to be marginally higher than for soil P only plots at the same Index, but showed a similar relationship with Olsen P Index. Even for plots treated with fresh P and at an Olsen P Index of 3 or higher, grain P contents were less than 0.4%.

Table 4.20 % P content (100% dm) of wheat grain from harvests 2014-16 for fresh P plots at each P Index

Site	Year	Mean % P content (at 100% dm)			Standard deviation on mean		
		Index 1	Index 2	Index 3+	Index 1	Index 2	Index 3+
Peldon	2014*	0.25	0.26	0.26	0.033	0.022	0.018
	2015	0.28	0.30	0.33	0.010	0.016	0.008
	2016	0.35	0.36	0.37	0.002	0.021	0.026
	15-16 Mean	0.31	0.33	0.35			
Great Carlton	2014*	0.25	0.28	0.27	0.027	0.029	0.023
	2015	0.27	0.26	(0.29)	0.018	0.016	-
Cholsey	2016	0.37	0.38	0.37	0.017	0.016	0.014
Mean 4 site excl. 2014		**0.29**	**0.31**	**0.32**			
Mean 6 site years		**0.30**	**0.31**	**0.32**			

( ) Value based only on 1 plot

* Note that no fresh P was applied in autumn 2013. Cholsey 2014 has been excluded as no grain P values were obtained for plots over Index 1

Although based on only a single crop, there were indications of a similar increase in grain P content with soil Olsen P Index for winter barley in 2016 (Table 4.21), with marginally higher values for fresh P than soil P only plots. For the same Olsen P Index, P contents in barley grain were higher than for wheat grain at the same site in the previous two years, and in fresh P plots at Index 3 or higher achieved 0.4%. Grain P contents in winter oats in 2015 (Table 4.22) were rather variable but tended to be lower in plots at an Olsen P Index of 0, and were again consistently lower than 0.4%.

Table 4.21 % P content (100% dm) of winter barley grain for soil P only and fresh P plots at each P Index (Great Carlton, 2016)

Plots	Mean % P content (at 100% dm)				Standard deviation on mean			
	Index 0	Index 1	Index 2	Index 3+	Index 0	Index 1	Index 2	Index 3+
Soil P only	0.31	0.34	0.37		0.031	0.034	0.016	
Fresh P		0.37	0.38	0.40		0.036	0.036	0.009

Table 4.22 % P content (100% dm) of winter oat grain for soil P only and fresh P plots at each P Index (Cholsey, 2015)

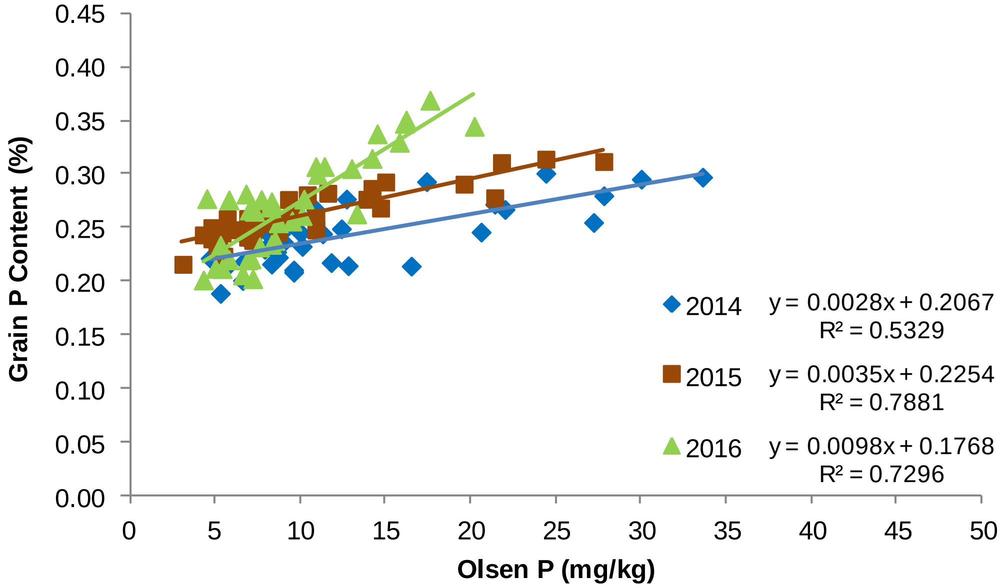
Plots	Mean % P content (at 100% dm)				Standard deviation on mean			
	Index 0	Index 1	Index 2	Index 3+	Index 0	Index 1	Index 2	Index 3+
Soil P only	0.20	0.23	(0.21)		0.030	0.035	-	
Fresh P	0.24	0.30	0.27	0.28	0.095	0.019	0.036	0.021

( ) Value based only on 1 plot

4.6.2. Relationship Between Soil Olsen P and Grain P Content of Wheat

For wheat crops grown between 2014 and 2016 at Peldon (Fig. 4.28), Great Carlton (Fig 4.29) and Cholsey (Fig. 4.30), the relationship between P content of harvested grain and the Olsen P level for each plot was examined (separately for the soil P only and fresh P plots). Grain P was clearly related to Olsen P for the soil P only plots. For Peldon and Cholsey, the slopes of the lines differed between 2014 (or 2015) and 2016. The slopes of the lines were similar between 2014 and 2015 at both Peldon and Great Carlton; however at Peldon grain P values were higher in 2015 than 2014 for the same level of Olsen P, whereas at Great Carlton they were about the same. In contrast, the relationships between grain P and Olsen P were generally weak for the fresh P plots.

(a) Soil P plots



(b) Fresh P plots

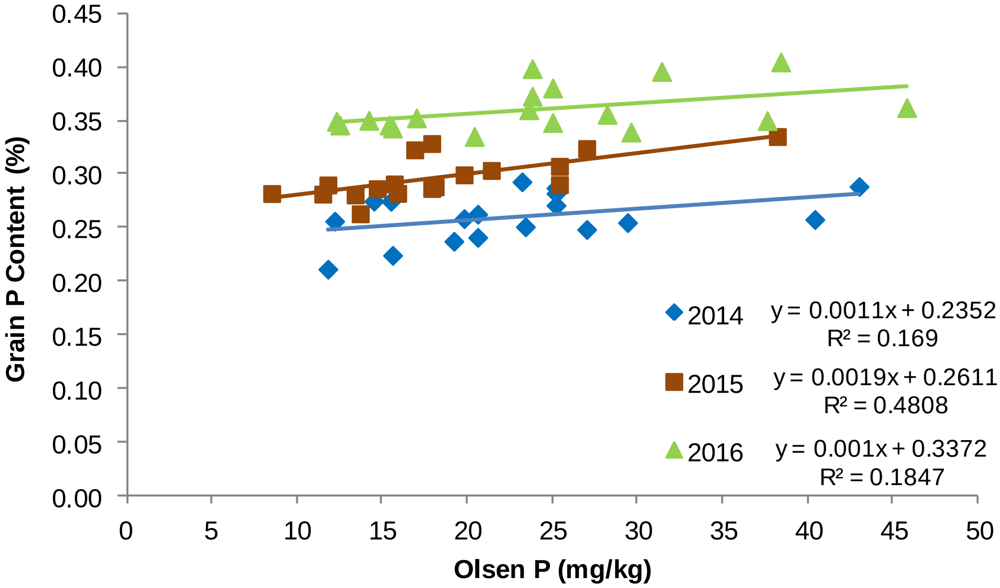
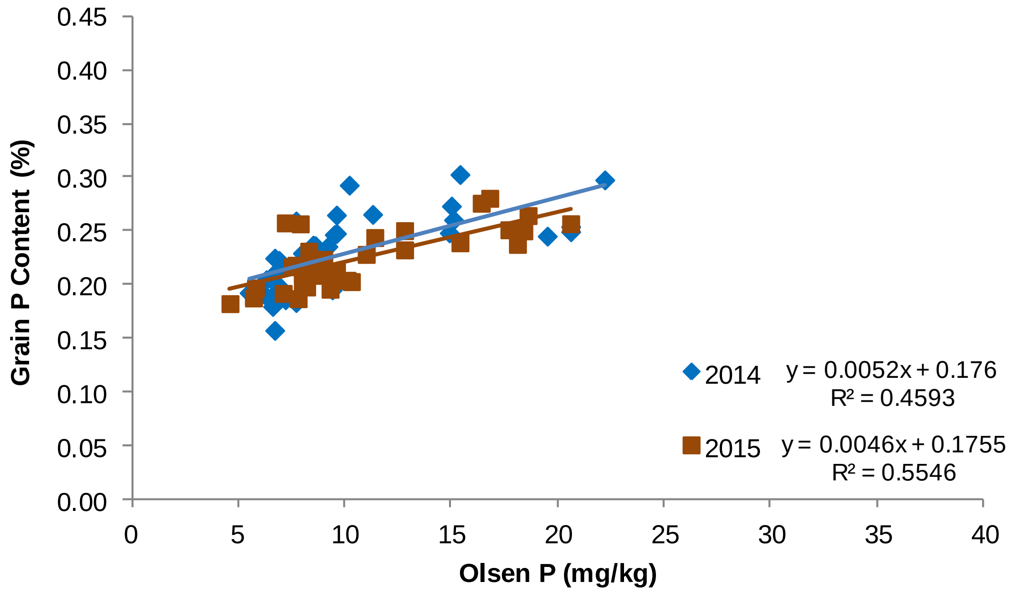


Fig. 4.28 Relationship between soil Olsen P and % P content of wheat grain for (a) soil P and (b) fresh P plots at Peldon for harvest 2014, 2015 and 2016 crops

(a) Soil P plots



(b) Fresh P plots

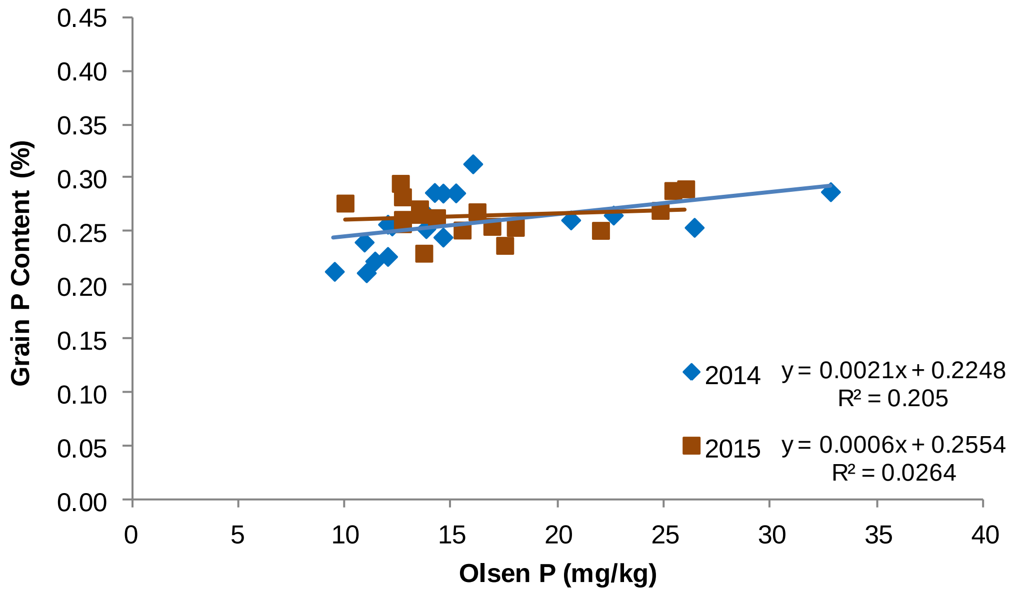
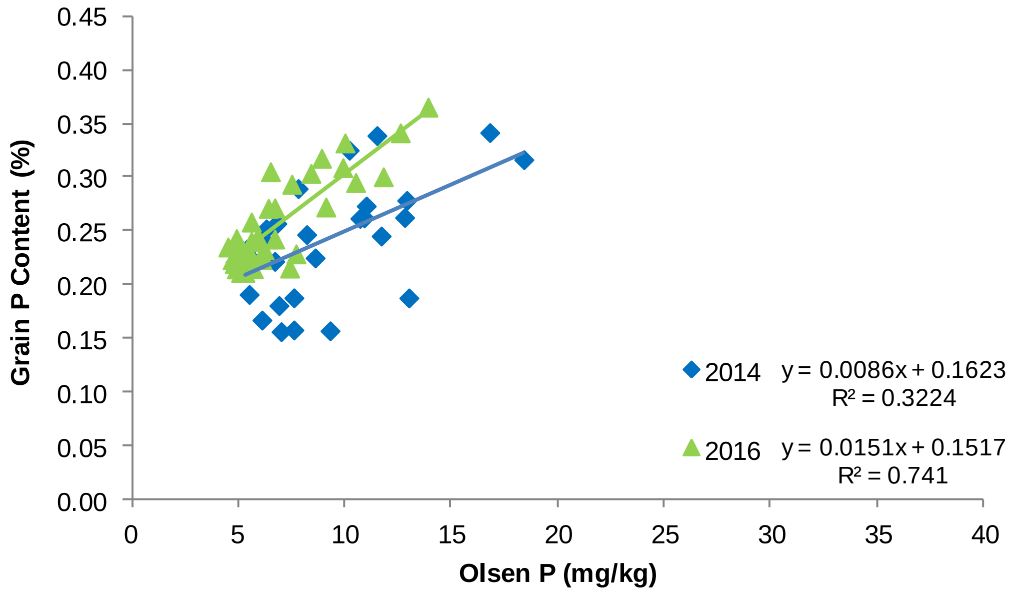


Fig. 4.29 Relationship between soil Olsen P and % P content of wheat grain for (a) soil P and (b) fresh P plots at Great Carlton for harvest 2014 and 2015 crops

(a) Soil P plots



(b) Fresh P plots

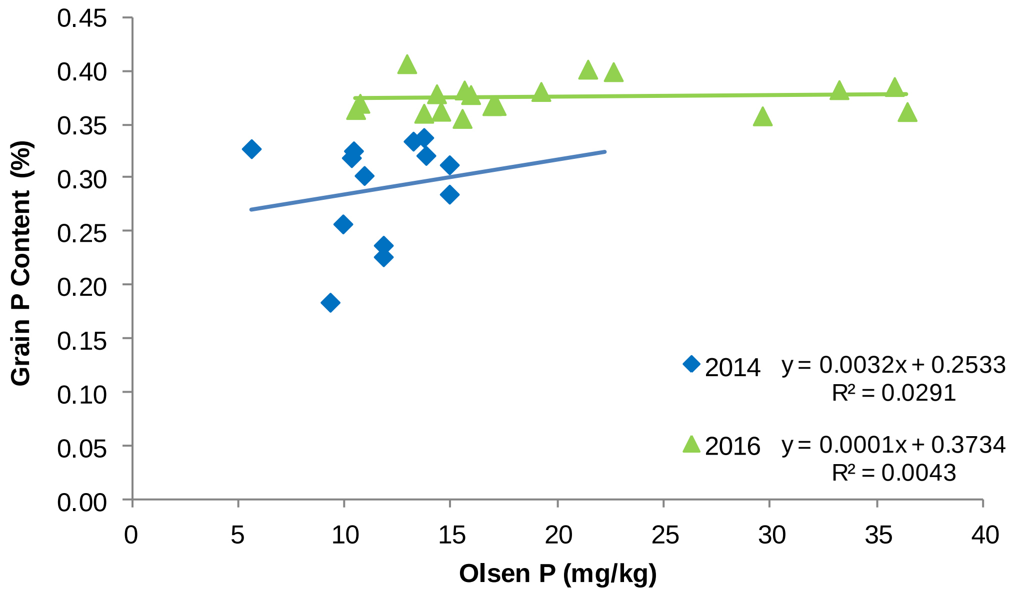


Fig. 4.30 Relationship between soil Olsen P and % P content of wheat grain for harvest 2014 and 2016 at Cholsey (includes soil P only plots and fresh P plots)

The relationship between the P content of grain from soil P only plots and the amount of P fertiliser that they had received in autumn 2009 was examined for wheat crops at Peldon, Great Carlton and Cholsey between 2014 and 2016 (see Appendix Figs 8a-8c). Wheat grain P content clearly reflected the amount of P fertiliser that had been applied.

For two wheat crops where a meaningful estimate of the critical Olsen P level (to achieve 98% of maximum yield) was obtained, namely Peldon in 2014 and 2015, the relationship between soil Olsen P level (as a proportion of the critical P level) and grain P content was investigated for the soil P only plots (Fig. 4.31). In both 2014 and 2015, grain P contents continued to rise well above that achieved at the critical Olsen P level. In addition, the grain P content at the critical Olsen P level for yield was higher in 2015 than in 2014.

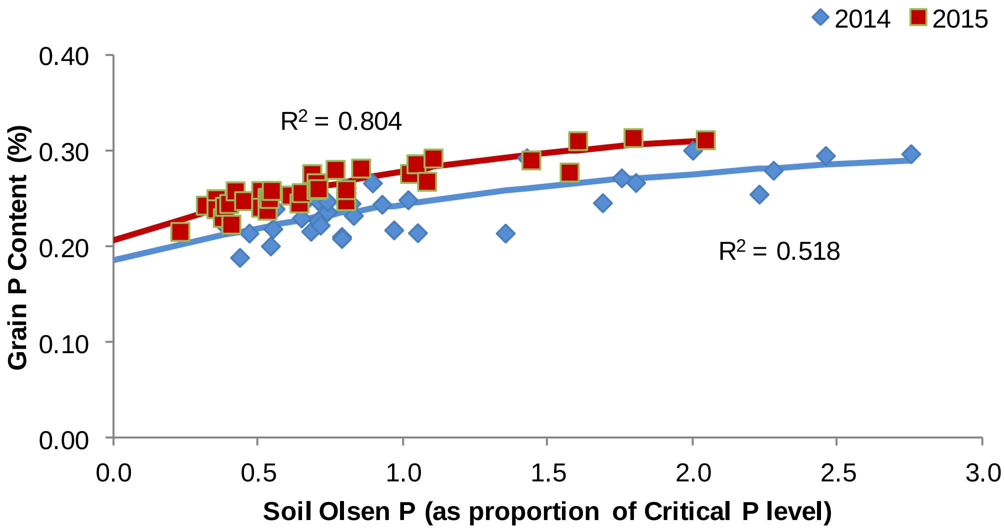


Fig. 4.31 Relationship between soil P level (as a proportion of the Critical P to achieve 98% maximum yield) and % P content of wheat grain for soil P only plots at Peldon for harvests 2014 and 2015

4.6.3. Wheat Grain P Content and Yield

For all seven wheat crops the relationship between grain P content and wheat yield was investigated for the soil P only and fresh P plots combined. At Great Carlton, there was no apparent relationship between wheat yield and grain P content in either 2014 or 2015. However, at Peldon and Cholsey there was evidence of a relationship, but this was strongest in 2016 at both sites (Fig. 4.32). In both cases, yields appeared to be plateauing as grain P content approached 0.4%.

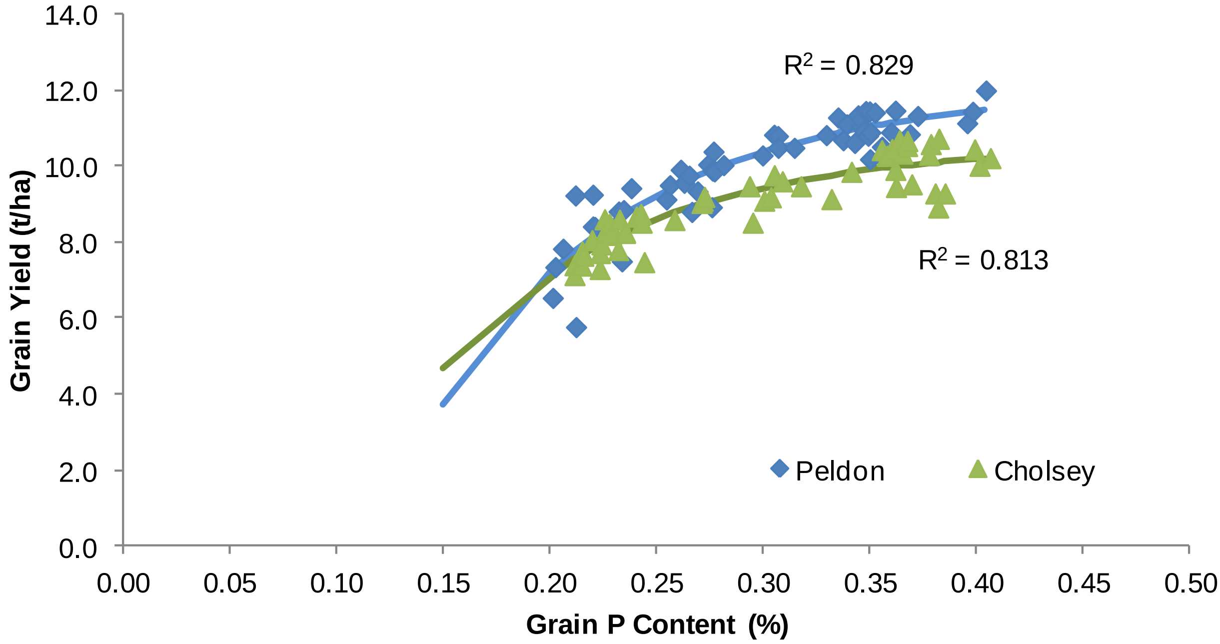


Fig. 4.32 Relationship between % P content of wheat and grain yield at Peldon and Cholsey in 2016

4.7. P Offtake

Calculated annual offtakes of P (and as P_2O_5) in grain or seed are shown in Appendix 8 Tables 13 (wheat, 85% dry matter), 14 (oilseed rape, 91% dry matter) and 15 (barley, 85% dry matter). Offtakes of P and P_2O_5 in fresh winter wheat (Table 4.23), winter barley and winter oat (Table 4.24) grain at 85% dry matter are shown below for the years 2014-2016 in which grain P contents were measured.

Table 4.23 P and P_2O_5 offtake (kg/t) in wheat grain (at 85% dm) from harvest 2014-16 for soil P only and fresh P plots at each P Index

Plots	Site	Year	P offtake (kg/t at 85% dm)				P_2O_5 offtake (kg/t at 85% dm)			
			Index 0	Index 1	Index 2	Index 3+	Index 0	Index 1	Index 2	Index 3+
Soil P only plots	Peldon	2014	1.9	2.0	2.3		4.4	4.7	5.2	
		2015	2.1	2.3	2.5		4.8	5.3	5.8	
		2016	2.1	2.5	3.0		4.7	5.7	6.8	
	Great Carlton	2014	1.8	2.3	2.2		4.0	5.2	5.1	
		2015	1.8	1.9	2.2		4.1	4.4	5.1	
	Cholsey	2014	1.8	2.3	2.8		4.2	5.3	6.4	
		2016	2.1	2.8	-		4.7	6.3	-	
Mean 4 site excl. 2014			**1.9**	**2.3**	**2.5**		**4.6**	**5.4**	**5.9**	
Mean 7 site years			**2.0**	**2.4**	**2.6**		**4.4**	**5.3**	**5.7**	
Fresh P plots	Peldon	2014		2.1	2.2	2.2		4.8	5.1	5.1
		2015		2.4	2.5	2.8		5.5	5.8	6.4
		2016		3.0	3.1	3.1		6.8	7.0	7.2
	Great Carlton	2014		2.1	2.4	2.3		4.9	5.5	5.3
		2015		2.3	2.2	2.5		5.2	5.1	5.7
	Cholsey	2016		3.2	3.2	3.2		7.3	7.4	7.2
Mean 4 site excl. 2014				**2.7**	**2.8**	**2.9**		**6.2**	**6.3**	**6.6**
Mean 6 site years				**2.5**	**2.6**	**2.7**		**5.7**	**6.0**	**6.1**

Table 4.24 Mean P and P_2O_5 offtake (kg/t) in winter barley grain (at 85% dm) from harvest 2016, and winter oat grain (at 85% dm) from harvest 2015, for soil P only and fresh P plots at each P Index

Crop	Plots	P offtake (kg/t at 85% dm)				P_2O_5 offtake (kg/t at 85% dm)			
		Index 0	Index 1	Index 2	Index 3+	Index 0	Index 1	Index 2	Index 3+
Winter Barley	Soil P only	2.6	2.9	3.1		6.0	6.7	7.2	
	Fresh P		3.1	3.2	3.4		7.2	7.3	7.8
Winter Oat	Soil P only	1.7	2.0	(1.8)		4.0	4.5	(4.1)	
	Fresh P	2.1	2.6	2.3	2.3	4.7	5.9	5.2	5.4

( ) Value based only on 1 plot

4.8. P Balance

Table 4.25 shows the overall P balance for all sites over the first 4 years, for plots that received at least 100 kg/ha P fertiliser in autumn 2009. The balance is based on P added in 2009 minus total P removed in the 3 crops harvested from 2010-12 (sub plots that received fresh P in autumn 2011 and 2012 have been excluded). Offtakes for wheat and barley are based on estimated grain P content values (for soil P only plots) as described in section 3.9. Offtakes for oilseed rape and spring beans are based on standard P content values. The increase in Olsen P from 2009 to spring 2013 is also shown, as mg/kg and kg/ha (calculated from cultivation depth and soil bulk density at each site).

Table 4.25. P balance and Olsen P increase (2009-13) for plots receiving >100 kg/ha P fertiliser in 2009

Site	P added	P offtake	P balance	Olsen P mg/kg		Incr. / dec. (-) in Olsen P	
	kg/ha	kg/ha	kg/ha	2009	2013	mg/kg	kg/ha
Peldon	133	69	64	9.1	16.7	7.6	25.4
	200	70	130	7.1	20.4	13.3	44.2
	288	71	217	11.5	26.7	15.2	50.5
	399	74	325	8.9	43.3	34.4	114.7
Mean	**247**	**71**	**176**	**9.8**	**25.3**	**15.5**	**51.6**
Great Carlton	121	57	64	10.3	10.3	0.0	0.0
	181	63	118	10.4	12.2	1.8	5.3
	261	63	198	11.3	17.7	6.4	19.3
	362	64	298	13.0	26.3	13.3	40.1
Mean	**231**	**62**	**169**	**11.2**	**16.6**	**5.4**	**16.2**
Cholsey	106	52	54	6.4	8.5	2.1	5.6
	160	67	93	4.6	11.7	7.1	18.8
	230	65	165	5.3	13.4	8.1	21.7
	319	61	258	5.6	16.9	11.3	30.2
	426	66	360	5.5	21.9	16.4	43.6
Mean	**277**	**63**	**214**	**5.5**	**15.6**	**10.1**	**26.9**
Caythorpe	130	38	92	12.9	17.4	4.6	14.8
	195	35	160	8.4	18.1	9.8	31.8
	282	42	240	8.2	20.3	12.1	39.5
	391	43	348	8.5	21.7	13.2	43.1
Mean	**229**	**39**	**190**	**9.6**	**19.1**	**9.4**	**30.8**
Weston	123	46	77	3.9	12.8	9.0	18.4
	178	52	126	3.9	14.1	10.2	21.0
	247	47	200	3.9	14.3	10.5	21.5
	329	51	278	3.9	16.9	13.0	26.9
Mean	**219**	**49**	**170**	**3.9**	**14.5**	**10.7**	**22.0**
Cirencester	111	63	48	8.9	16.1	7.2	13.3
	160	67	93	6.1	12.0	5.9	11.0
	221	63	158	7.9	21.3	13.4	24.8
	295	66	229	8.0	18.3	10.3	19.1
Mean	**187**	**64**	**122**	**7.9**	**17.5**	**9.6**	**17.7**

At all sites P balances were positive for plots receiving more than 100 kg/ha P fertiliser in 2009, ranging from around 50 to more than 250 kg/ha. The measured increase in Olsen P between 2009 and 2013 for a given P balance varied between sites, with the largest increases in Olsen P observed at Peldon.

Table 4.26 shows the same information as for Table 4.31, but over 7 years (2009 through to spring 2016), for the three sites (Peldon, Great Carlton and Cholsey) that continued for a further 3 years. Additional offtakes for 2014 and 2015 are based on measured % P contents.

Table 4.26. P balance and Olsen P increase or decrease (2009-16) for plots receiving >100 kg/ha P fertiliser in 2009

Site	P added	P offtake	P balance	Olsen P mg/kg		Incr. / dec. (-) in Olsen P	
	kg/ha	kg/ha	kg/ha	2009	2016	mg/kg	kg/ha
Peldon	133	128	5	9.1	8.2	-0.9	-3.1
	200	142	58	7.1	12.8	5.7	18.9
	288	140	148	11.5	15.4	3.9	12.8
	399	147	253	8.9	16.1	7.2	23.8
Mean	**247**	**138**	**109**	**9.8**	**13.1**	**3.2**	**10.7**
Great Carlton	121	92	29	10.3	10.1	-0.2	-0.5
	181	105	76	10.4	11.0	0.6	1.7
	261	106	155	11.3	14.7	3.4	10.3
	362	108	254	13.0	15.8	2.8	8.4
Mean	**231**	**103**	**128**	**11.2**	**12.9**	**1.6**	**5.0**
Cholsey	106	102	4	6.4	5.6	-0.8	-2.1
	160	137	23	4.6	6.7	2.1	5.6
	230	131	99	5.3	8.6	3.3	8.9
	319	129	190	5.6	8.9	3.4	8.9
	426	139	287	5.5	11.4	5.9	15.6
Mean	**277**	**130**	**147**	**5.5**	**8.8**	**3.3**	**8.8**

Mean P balances were less than 30 kg/ha for plots receiving up to 160 kg/ha P fertiliser. At all three sites, marginal decreases in Olsen P were observed between 2009 and 2016 for plots receiving close to 100 kg/ha P fertiliser. Peldon again showed the largest increases in Olsen P for a given P balance, but differences between sites were less consistent than for the 2009 - 2013 period.

Figures 4.33 to 4.37 show the increase or decrease in Olsen P between 2009 and spring 2013 plotted against the P balance (input in autumn 2009 minus offtakes in harvest 2010-12) for Peldon, Great Carlton, Cholsey, Caythorpe and Cirencester. For all P treatment means 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 change in Olsen P for a P balance of zero was not negligible at some sites.

There was no apparent relationship between change in Olsen P and P balance at Weston when all P treatments were taken into account.

Similar relationships for Peldon, Great Carlton and Cholsey only, but between 2009 and spring 2016, are shown in Appendix 9 Figs. 9-11.

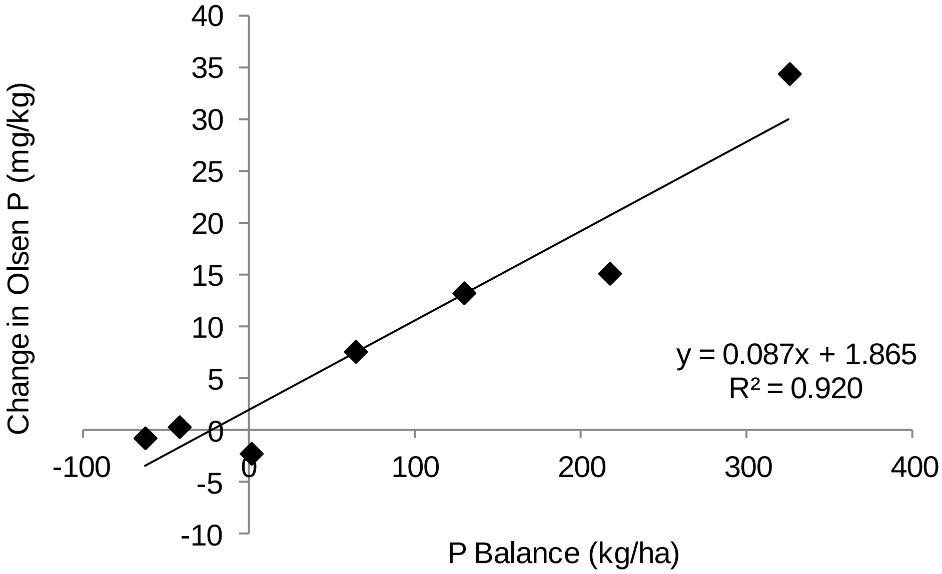


Fig. 4.33 Change in Olsen P (mg/kg) in relation to P balance (kg/ha) at Peldon (2009-13)

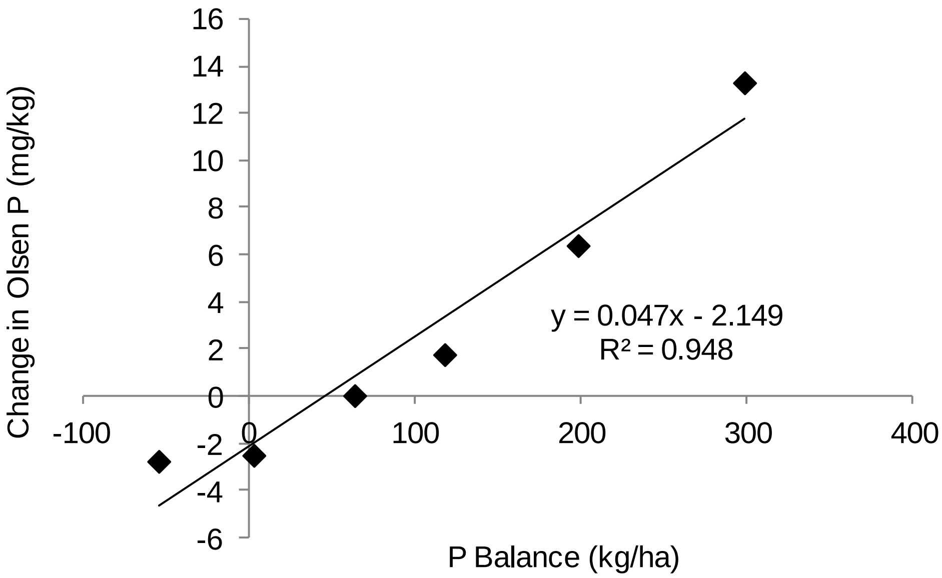


Fig. 4.34 Change in Olsen P (mg/kg) in relation to P balance (kg/ha) at Great Carlton (2009-13)

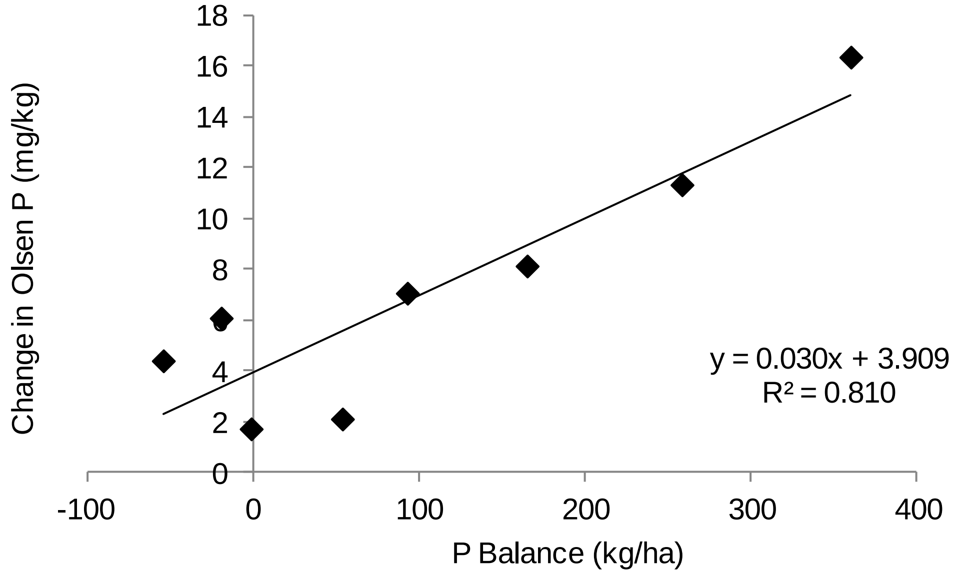


Fig. 4.35 Change in Olsen P (mg/kg) in relation to P balance (kg/ha) at Cholsey (2009-13)

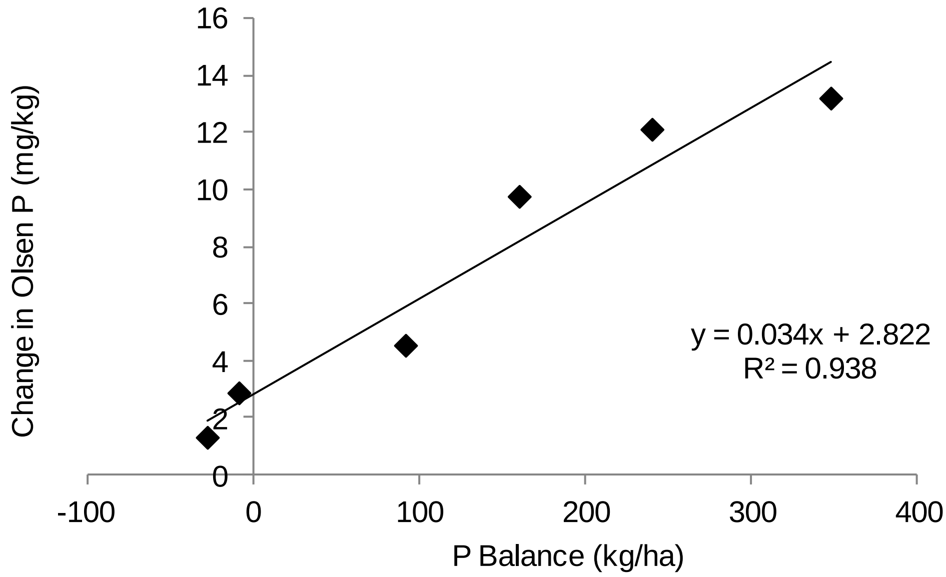


Fig. 4.36 Change in Olsen P (mg/kg) in relation to P balance (kg/ha) at Caythorpe (2009-13)

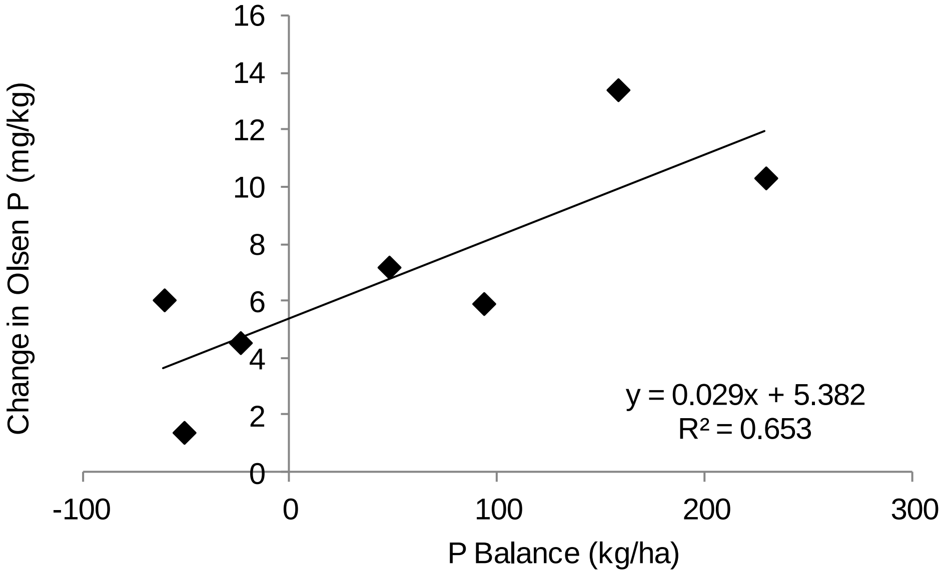


Fig. 4.37 Change in Olsen P (mg/kg) in relation to P balance (kg/ha) at Cirencester (2009-13)

The amounts of P (and P_2O_5) that needed to have been applied in autumn 2009, over and above cumulative offtake in harvests 2010 to 2012, to have resulted in an increase in Olsen P of 1 mg/kg in spring 2013 (compared to 2009) were determined for each site (Table 4.27). These were calculated from the slopes of the lines in Figs. 4.27-4.31, and the cultivation depths and soil bulk densities for each site (see Table 3.8, which also shows the initial estimates for the amount of P required to increase Olsen P by 1 mg/kg).

The actual amounts of P needed to have raised Olsen P by 1 mg/kg are similar to the estimate given in Table 3.8 for Great Carlton, and slightly higher for Caythorpe and Cholsey, while at Peldon the amount required was less than expected. At Cirencester, although there was an initial increase in Olsen P as expected, this was not maintained (see Appendix Fig. 3) and the amount of P that needed to have been applied to have raised Olsen P by 1 mg/kg was much higher than would have been expected. 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 92 kg P/ha (211 kg P_2O_5/ha) at Peldon but as much as 280 kg P/ha (642 kg P_2O_5/ha) at Cirencester.

Table 4.27. Amounts of P and P_2O_5 needed to have been applied in 2009 (over and above offtake in 2010-12) to have resulted in an increase in Olsen P of 1 mg/kg in spring 2013 compared to 2009

	Increase in Olsen P of 1 mg/kg		Increase in Olsen P of 1 Index (mid Index 0 to 1, or 1 to 2)	
Site	kg P/ha	kg P_2O_5/ha	kg P/ha	kg P_2O_5/ha
Peldon	12	26	92	211
Great Carlton	22	49	172	394
Cholsey	33	75	263	603
Caythorpe	30	69	239	548
Cirencester	35	80	280	642

The same calculation was done for the period from 2009 to 2016 for the sites that were continued for a further three years (Table 4.28), but in this case based on the slopes of the lines in Appendix Figs. 9-11. The amounts of P (and P_2O_5) needed to have been applied in autumn 2009, over and above cumulative offtake in harvests 2010 to 2015, to have resulted in an increase in Olsen P of 1 mg/kg in spring 2016 were more than double those indicated in Table 4.27. The difference was particularly large at Peldon, and reflects the apparent rapid decrease in the availability after 2013 of the fertiliser P applied in autumn 2009.

Table 4.28. Amounts of P and P_2O_5 needed to have been applied in 2009 (over and above offtake in 2010-2015) to have resulted in an increase in Olsen P of 1 mg/kg in spring 2016 compared to 2009

	Increase in Olsen P of 1 mg/kg		Increase in Olsen P of 1 Index (mid Index 0 to 1, or 1 to 2)	
Site	kg P/ha	kg P_2O_5/ha	kg P/ha	kg P_2O_5/ha
Peldon	40	91	318	730
Great Carlton	62	142	497	1138
Cholsey	67	154	537	1230

4.9. Economic Analysis

The number of years required for the value of additional wheat yield obtained at Olsen P Index 1 or 2 (compared to Index 0 or 1) to exceed the initial cost of raising the Olsen P level from (mid Index) 0 to 1, 0 to 2 or 1 to 2 (in a single year), and then maintaining it (by replacing annual offtake), was determined for the four sites (Peldon, Great Carlton, Cholsey and Caythorpe) where wheat was the only or predominant crop grown (to enable like-for-like comparison). The basis of the calculation is described in Section 3.11, with a further breakdown of the key values used provided in Appendix 10 Table 16. Results are summarised in Table 4.29 below.

Table 4.29. Net cost or benefit from raising Olsen P Index from 0 to 1, 0 to 2 or 1 to 2, and then maintaining it at that level, after 1, 2, 3, 4 or 5 years, based on successive winter wheat crops

Site and change in Olsen P Index	Net cost (-) or benefit (+) in £/ha from raising P Index and maintaining it, after:				
	1 year	2 years	3 years	4 years	5 years
Peldon					
Index 0 to 1	-37	+63	+163	+262	+362
Index 0 to 2	-98	+78	+254	+429	+605
Index 1 to 2	-61	+15	+91	+167	+243
Great Carlton					
Index 0 to 1	-191	-126	-61	+4	+69
Index 0 to 2	-369	-226	-83	+59	+201
Index 1 to 2	-178	-100	-22	+55	+133
Cholsey					
Index 0 to 1	-279	-166	-53	+59	+172
Index 0 to 2	-593	-403	-213	-23	+166
Index 1 to 2	-314	-237	-160	-83	-6
Caythorpe					
Index 0 to 1	-166	+24	+215	+405	+595
Index 0 to 2	-491	-270	-50	+171	+391
Index 1 to 2	-325	-295	-264	-234	-204

For Peldon, raising the soil Olsen P Index from 0 to 1 or 0 to 2 would have more than covered its cost after 2 years through increased wheat yield. Raising the Index to 2 rather than 1 would have been cost-effective after 2 years. For Great Carlton, it would have taken four years for the cumulative value of the increased wheat yields to exceed the cost of raising the Olsen P Index from 0 to 1 or 1 to 2, and again Index 2 was cost-effective compared to Index 1. At Cholsey, it also took four years to cover the cost of raising the Olsen P Index from 0 to 1, but five years for Index 2. It would have taken more than 5 years for Index 2 to have been cost-effective compared to Index 1. At Caythorpe, raising the soil Olsen P Index from 0 to 1 would have more than covered its cost after 2 years, but only after four years for Index 2, and even after 5 years Index 1 would have remained more cost-effective than Index 2.

5. Discussion

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 a maximum of seven cropping years. 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 Olsen P levels in soils 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. This may mean that the actual amounts of plant-available P that the soils were able to provide were over-estimated by the measurements of soil Olsen P each spring. However, the inclusion of a number of plots at each site that did not receive any P fertiliser even at the start provided a measure each year of the 'background' plant-available soil P.

It was accepted that some time would be required for levels of Olsen P to stabilise following the initial application of some large amounts of TSP required to give the desired range in Olsen P at each site. The results confirm this, although there was year to year variation at most sites. As expected, 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 long-term Rothamsted Research experiments on three soil types, a value of 15% was assumed. Across the five sites studied here, average P availability was around 10% in the 2-4 year period (2011 to 2013) after P application, slightly less than the 15% assumed. However, the 10% value is based on using the lower NRM equivalent Olsen P values, whereas 15% was based on Rothamsted Research Olsen P values. At the sites where measurements continued after 2013, P availability continued to decline below 10%. The higher percentage P availability at Peldon, especially in the first 2-4 years after P application, is interesting and suggests that there is an inherent soil factor affecting the retention of added P extractable by the Olsen reagent that may vary between soils.

The results highlight both the extent of the spatial variation in Olsen P that can occur in similarly treated soils within a small area, 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, levels of Olsen P increased between 2012 and 2013.The cause is uncertain but may relate to P release through wetting and drying.

At Cirencester and Cholsey it is evident that applying and incorporating a large amount of TSP fertiliser was ineffective at achieving a sustained increase in Olsen P above Index 1. These sites were 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 effectiveness. Peldon had the next highest level of extractable calcium at about 3000 mg/l, but an average pH nearer 7, and in contrast to Cirencester or Cholsey had the largest proportion of the added P remaining as Olsen P.

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 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 seven 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.

Favourable conditions during the autumn and spring led to generally high wheat yields in both 2014 and 2015, and this was reflected in the performance of crops grown at the three sites that continued. However, dull conditions in June 2016 meant that winter barley and oat yields were below average in the final year.

As Olsen P levels had not yet equilibrated, yield data from 2010 were excluded from the estimation of critical P levels. However, yields from all years were assessed 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 wheat yield penalties (relative to Index 2) were about 1.5 t/ha at Index 0 and 0.5 t/ha at Index 1.

According to the Professional Agricultural Analysis Group soil analysis data (PAAG, 2016), 5% of UK arable soil samples tested in 2015/16 were at P Index 0 and 16% were at P Index 1. If only 40% of these received fresh P fertiliser, based on the proportion of arable fields treated each year according to British Survey of Fertiliser Practice data (Anon, 2015), over the UK wheat area of about 1.9M ha, this could equate to a loss of as much as 85,000 tonnes of wheat grain each year in fields maintained at Index 0, and 90,000 tonnes on fields maintained at Index 1, worth up to £24M in total. Even if all wheat fields at Index 0 or 1 received fresh P fertiliser, this would still equate to a loss of 30,000 tonnes of wheat worth up to £4M.

Although a single large application of P fertiliser is not necessarily representative of how most farms would seek to correct Olsen P levels below Index 2, economic analysis of the data obtained in these experiments indicates that, based on successive winter wheat crops, the payback from raising the P Index from 0 to 1 in a single year, and then maintaining it, would have been cost-effective within 2-4 years. Current advice in RB209 is to raise soil P levels by applying higher than maintenance applications of P fertiliser over several years. This latter approach may be applicable 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 2013, 2014 and 2015 at 12 to 14 mg/kg (Index 1). The critical P level was much higher in 2011 at around 19 mg/kg (Index 2), even though maximum yield was not. However, the biggest contrast was between 2012 and 2016 where, despite equally high maximum yields, the critical P level was around 22 mg/kg in 2016 and less than 9 mg/kg (Index 0) in 2012. The reason for this large difference is unclear, but it is not dissimilar to that which was reported in Summary Figures 1 and 2 in Research Review No. 74 (Johnston and Poulton, 2011), and may be due to soil structure and seedbed conditions as well as weather. Great Carlton gave similar maximum yields and critical P levels in 2011 and 2012 (and at 13 mg/kg close to those obtained for Peldon in 2013 to 2015). This was under very different weather conditions, although seedbeds were good in both years. The three wheat crops with the highest critical P levels, at around 23 mg/kg, were at Caythorpe in 2012 and at Cholsey in 2013 and 2016, although the values obtained for Cholsey had high standard errors. Caythorpe was very low yielding due to poor soil conditions and waterlogging, which are also likely to have affected rooting and nutrient uptake, Caythorpe is notable for having large wheat yield penalties at P Indices below 2 in the first three cropping years. 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.

As noted in the Materials and Methods (section 3.5), Olsen P analysis for the years 2011 to 2013 was carried out by Rothamsted Research, rather than by NRM Laboratories (who undertook the analysis for the years 2014 to 2016). Following a standardisation exercise, the Olsen P data for each sample originally reported by Rothamsted Research was transformed to the equivalent for NRM Laboratories, in order to be able to present the changes in Olsen P over all seven years of the project in this report. It is important to acknowledge that the results from both laboratories are equally valid, neither is right or wrong. As there was a strong linear relationship between the Olsen P values from the two laboratories, the variance accounted for in the relationship between the grain or seed yield and Olsen P for each experiment was very similar, and where a large proportion of the variance was accounted for, Olsen P was good predictor of the plant-available P in the soil. However, there was a difference in the critical Olsen P determined from the yield / Olsen P relationship depending on which Olsen P values were used. Specifically, the calculated critical Olsen P values were higher for the Rothamsted Research Olsen P values than for the equivalent NRM Laboratories Olsen P values, because the Olsen P values themselves were higher.

Advice in the Nutrient Management Guide RB209 (AHDB, 2017) 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 observed in 2012 and 2013 indicate that a large amount of fresh P fertiliser (larger than that recommended in RB209) applied to wheat crops at Index 0 was, in general, effective at raising yields to the levels achieved at P Index 1, or when applied to wheat crops at Index 1 was effective at raising yields to the level achieved at Index 2. However, fresh P applied to wheat at Index 0 did not raise yields to the level achieved at Index 2.

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. However, the amount needed to achieve this may be larger than 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 were being maintained at P Index 1 or 2.

As reported in AHDB Cereals & Oilseeds Research Review 74, 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 within the middle of the range (92 – 280 kg P/ha) calculated over the period 2009 to 2013 for the five sites in this project. The difference between Peldon (92) and Cirencester (280) in the amount of P required reflects the apparent availability at each site of the P fertiliser applied in autumn 2009, suggesting there is still much to be researched about the link between soil type and P equilibria.

Although there was some variation between sites and seasons, grain P contents (as measured in plots that received no P fertiliser after autumn 2009) were consistently lower at soil Olsen P Index 0 than at Index 1, and in most cases lower at Index 1 than at Index 2, in the years 2014 – 2016 (so 5 to 7 years after the last P fertiliser was applied). In addition, even at Index 2, mean grain P contents were consistently lower than the value of 0.4% P assumed for cereal grains at 100% dry matter, as used in the Nutrient Management Guide*[1] (AHDB, 2017). At Index 0, mean grain P contents were only 50-60% of this value. For plots treated with fresh P fertiliser in autumn 2011 onwards, grain P contents tended to be marginally higher than for soil P only plots at the same P Index, but showed a similar relationship with Olsen P Index. Even for plots treated with fresh P fertiliser and at an Olsen P Index of 3 or higher, grain P contents were less than 0.4%.

Lower than expected P offtake could partly explain observed increases in soil Olsen P on farms where maintenance strategies are being applied. Previous studies by Withers (1999), Barraclough *et al*. (1997) and Barraclough *et al*. (2000) have extensively reported on the development of plant tissue testing to determine crop nutrient status and diagnosing nutrient deficiencies.

*[1] These values are a guide to what to use when the sample is not analysed. The values in RB209 were developed following a review of published literature. For P in winter wheat values around 0.35% P were typical, but this was rounded up to 0.4%.

Withers (1999) reported that plant analysis has a useful role in confirming P adequacy or over-supply to the cereal crop now that deficiency thresholds have been more precisely identified; recommended concentrations in young fully expanded leaves between growth stages 31 and 39 are P>0.38%DM for adequate supply. However, further work to develop P fertilisation strategies, taking account of soil, crop uptake during the season and crop offtake at harvest were suggested (Withers, 1999). The results from this project suggest that grain P content is not the same at all soil Olsen P levels and could lead to an opportunity to explore the use of grain P as a measure of the adequacy of soil P supply.

5.2. Conclusions

Results over 32 site years, from up to six sites on contrasting soils suggest that current advice, which is to maintain soils at P Index 2 for combinable crops will ensure that yields are not significantly limited by availability of P under a wide range of conditions and that other agronomic inputs, especially nitrogen fertiliser, are used effectively. However, across 10 site years for wheat, Critical P (to achieve 98% of maximum yield) ranged from 8.5 to 21.9 mg/kg with the critical P level falling within Index 1 for the majority of sites. This is consistent with the findings of AHDB Cereals & Oilseeds Research Review 74. There were differences between sites and crops or years in the responsiveness of yield to Olsen P, which may have been related, but not obviously, to soil conditions or other crop or site factors.
Maintaining all fields for combinable cropping at or below soil Olsen P Index 2 has been shown here to risk significant loss, but in the right circumstances, (in particular where soil structure and crop rooting are good) where the risk of any yield penalty could be minimised by ensuring annual applications of fresh P fertiliser, maintaining fields at Index 1 would be sufficient. This would have potential economic and environmental benefits.

There were differences between sites in the apparent availability of the applied P fertiliser once the increases in Olsen-P had equilibrated and accounting for offtake. Over five sites the proportion of P remaining available 2-4 years after its application ranged from 1-20%, with availability highest on a heavy clay soil and lowest on a shallow limestone soil. There were differences between the two soils in measured pH (although less so at the time that the P fertiliser was applied), and in the amount of extractable calcium present. When calculated over a longer time period (up to 7 years after P fertiliser application), apparent P availability on the clay soil had decreased further, suggesting that differences in the rate at which P availability decreases may be important, but P availability was still higher for the clay soil than a shallow soil over chalk. In view of the large area of calcareous / chalk soils growing combinable crops in the UK, the reason for these differences warrants further investigation and potentially an alternative approach to ensuring an adequate supply of plant-available P.

In most cases, P balances for the period 2009-13 or 2009-16 (P added in autumn 2009 minus P removed in subsequent harvests) indicated small increases in soil Olsen P where P balance was zero.

Measured P contents (%) in cereal grain were less than those quoted in the Nutrient Management Guide RB209, and they declined with decreasing soil Olsen P level. Therefore, actual P_2O_5 offtakes per tonne of grain yield would have been less, 4.4-6.1 kg/t for wheat, than that, 7.8 kg/t of fresh grain at 85% DM given in RB209. On farms, where maintenance dressings are being applied, lower than expected P offtake could partly explain observed increases in soil Olsen P and it would be of considerable interest to investigate further, to help understand the dynamics between P offtake, P fertiliser additions and soil Olsen P.

The relationships between grain P content and soil Olsen P, and grain P content and yield, which were observed in this project, highlight the potential for grain P content to be a useful indicator of the adequacy of soil P supply. It is important to emphasise again that the potential for systematic differences with a test such as Olsen P underlines the advantage of, where possible, sample at the same soil depth and time of the year and stick to the same laboratory when monitoring changes in soil Olsen P over years.

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7. Acknowledgments

The authors gratefully acknowledge the assistance of colleagues at NIAB TAG and Rothamsted Research in carrying out the field experiments and data analysis; NRM Laboratories for conducting grain and soil analyses, the cooperation of our site host farmers, and the guidance received from AHDB Cereals & Oilseeds staff and committees.

8. Appendices

8.1. Appendix 1 P Analysis

8.1.1. 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 Nutrient Management Guide RB209 (AHDB, 2017) 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	

8.1.2. 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, a known mass of soil and volume of extractant were used, 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 RB209, recommendations for phosphate applications are given as P_2O_5 to facilitate calculation of the amount of fertiliser needed. 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.

8.2. 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	-	-	-	-	-
Great Carlton	barley	osr	wheat	barley	wheat	-	-	-	-	-
Cholsey	-	wheat	wheat	osr	wheat	-	-	-	-	-
Caythorpe	grass	grass	grass	grass	wheat	-	-	-	-	-
Weston	barley	w beans	wheat	barley	s beans	-	-	-	-	yes
Cirencester	barley	osr	wheat	barley	osr	-	-	-	-	-

Appendix Table 3. Soil K and Mg levels for each site in spring 2009, 2012 and 2016

		Spring 2009		Spring 2012		Spring 2016	
Site	Field Name	Soil K (mg/l)	Soil Mg (mg/l)	Soil K (mg/l)	Soil Mg (mg/l)	Soil K (mg/l)	Soil Mg (mg/l)
Peldon	Tanners	137	186	184	167	146	175
Great Carlton	-	95*	94	96	123	104	103
Cholsey	8D	264	66	171	43	201	51
Caythorpe	New Field	152*	110	170	107		
Weston	Hungry Hill	158	77	169	97		
Cirencester	Paddimore	209	70	289	99		

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

8.3. Appendix 3 Full Soil Structure Quality Assessment Results

Appendix Table 4a. Seedbed quality scores assessed early spring

Site	Date	Area	Overall block Depth (cm)	First (top) layer Depth of (cm)	First (top) layer Sq score	Second layer Depth (cm)	Second layer Sq score	Third (bottom) layer Depth (cm)	Third (bottom) layer Sq score	Overall block 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 Table 4b. Seedbed quality scores assessed early spring.

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*
Peldon	27/03/14	1	25	15	4.0	10	3.0	-	-	3.6
		2	24	10	5.0	7	4.0	7	3.0	4.1
		3	25	15	4.0	10	3.0	-	-	3.6
		4	25	17	4.0	8	3.5	-	-	3.8
Peldon	01/04/15	1	30	20	2.5	10	3	-	-	2.7
		2	27	20	2.3	7	3	-	-	2.5
		3	20	17	2.3	3	2.7	-	-	2.4
		4	28	20	2.5	8	2.7	-	-	2.6
Peldon	15/03/16	1	20	3	1.0	10	3.0	7	2.3	2.5
		2	19	5	1.3	7	3.3	7	2.5	2.5
		3	21	4	1.3	11	2.7	6	2.5	2.4
		4	23	6	1.3	11	2.5	6	2.3	2.3
Great Carlton	19/03/14	1	34	13	2	21	3	-	-	2.6
		2	32	20	2	12	4	-	-	2.8
		3	33	17	1	16	4	-	-	2.5
		4	31	9	1	22	4	-	-	3.1
Great Carlton	24/03/15	1	25	4	2	21	4	-	-	3.68
		2	25	6	2	19	4	-	-	3.52
		3	20	3	2	17	4	-	-	3.7
		4	25	4	2	21	4	-	-	3.68
Great Carlton	29/02/16	1	25	10	2	15	4	-	-	3.2
		2	25	5	1	10	2	10	4	2.6
		3	25	10	2	15	4	-	-	3.2
		4	25	10	2	15	4	-	-	3.2

*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

8.4. Appendix 4 Full Olsen P data

Appendix Table 5a. 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					26.9		35.8	
b	8.9	26.9	51.2	34.2	38.1		50.9	
c						31.6		30.1
2 a						13.1		13.3
b	8.2	8.2	10.7	8.9	7.2		7.7	
c					5.9		7.2	
3 a					6.6		7.9	
b	7.7	7.7	11.4	10.1	6.9		9.3	
c						20.2		13.0
4 a					12.1		14.4	
b	7.4	13.4	28.4	12.4	14.9		25.7	
c						17.9		16.6
5 a						25.3		26.5
b	7.1	16.1	33.5	24.9	17.9		18.4	
c					18.0		22.4	
6 a					8.5		7.5	
b	6.8	6.8	9.5	8.6	8.8		8.9	
c						12.4		13.1
7 a					27.8		26.5	
b	9.5	22.5	29.2	26.1	30.1		35.9	
c						27.5		36.6
8 a						15.9		18.3
b	5.6	5.6	8.3	9.0	9.9		8.0	
c					7.6		7.3	
9 a					6.2		9.2	
b	9.6	10.6	13.8	11.1	10.2		11.3	
c						16.8		18.7
10 a					21.8		27.0	
b	13.9	26.9	44.7	29.0	27.2		22.9	
c						28.1		31.2
11 a						8.1		22.2
b	8.2	8.2	6.5	6.7	5.9		6.1	
c					6.8		7.1	
12 a					26.0		21.7	
b	11.1	24.1	73.0	25.8	41.5		26.1	
c						35.5		28.7
13 a					9.0		7.9	
b	9.8	10.8	10.1	8.7	7.3		11.9	
c						13.3		11.3
14 a						18.6		18.0
b	10.8	16.8	16.6	14.1	16.2		12.8	
c					11.9		14.0	
15 a					6.8		6.9	
b	6.7	6.7	5.2	7.1	7.3		6.0	
c						14.4		14.7
16 a					4.8		5.3	
b	9.5	9.5	5.5	7.4	4.8		5.6	
c						7.0		12.4
17 a						10.6		19.3
b	10.5	13.5	7.6	9.5	7.0		9.3	
c					5.7		7.3	
18 a					4.5		5.7	
b	9.0	9.0	6.5	5.5	4.1		5.3	
c						17.1		17.3

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

Large plot (and sub plot)		2014 Actual		2015 Actual		2016 Actual	
		No fresh P	Fresh P	No fresh P	Fresh P	No fresh P	Fresh P
1	a	33.6		24.4		14.5	
	b	30.0		27.8		17.6	
	c		43.0		38.2		31.4
2	a		19.2		25.4		20.4
	b	12.4		8.3		8.3	
	c	9.6		7.2		7.3	
3	a	9.0		6.9		6.8	
	b	9.0		7.4		10.2	
	c		27.0		18.1		15.4
4	a	20.6		9.3		9.5	
	b	27.2		10.9		4.5	
	c		29.4		19.8		29.6
5	a		20.6		17.9		23.6
	b	12.8		15.0		14.2	
	c	10.9		11.6		11.4	
6	a	8.0		9.5		7.1	
	b	9.8		10.4		13.3	
	c		12.2		16.9		12.3
7	a	27.8		21.8		15.8	
	b	24.4		19.6		20.2	
	c		40.4		25.4		38.4
8	a		23.2		15.9		17.0
	b	10.1		10.9		8.2	
	c	8.6		7.3		7.0	
9	a	9.8		8.7		7.7	
	b	11.3		9.6		11.0	
	c		20.6		15.7		45.8
10	a	21.4		14.2		16.2	
	b	17.4		13.9		16.1	
	c		25.2		27.0		23.8
11	a		15.5		11.5		12.5
	b	8.7		5.5		6.9	
	c	8.3		5.4		5.8	
12	a	12.7		14.7		10.9	
	b	22.0		21.4		13.0	
	c		25.2		21.4		25.0
13	a	10.0		6.1		7.6	
	b	8.6		6.9		8.5	
	c		14.5		14.7		23.8
14	a		25.2		17.9		37.6
	b	16.5		9.5		10.1	
	c	11.8		8.8		8.7	
15	a	6.8		4.8		6.6	
	b	7.9		5.7		5.4	
	c		23.4		11.8		28.2
16	a	5.7		5.1		7.2	
	b	6.6		5.2		5.8	
	c		11.8		8.5		14.2
17	a		19.8		13.7		15.6
	b	9.6		7.2		8.3	
	c	6.7		4.8		5.3	
18	a	5.3		3.1		4.3	
	b	4.7		4.3		5.0	
	c		15.6		13.4		25.0

Appendix Table 6a. Great Carlton, 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					7.0		7.5	
b	9.6	9.6	9.3	8.3	7.5		7.9	
c						9.7		15.6
2 a						12.8		20.5
b	11.4	20.4	19.3	11.1	11.5		12.4	
c					12.1		13.9	
3 a						11.5		19.3
b	11.0	14.0	11.7	8.6	9.1		9.2	
c					9.1		9.6	
4 a					18.1		19.0	
b	11.4	24.4	27.7	15.9	17.0		18.7	
c						18.6		35.3
5 a						7.0		18.1
b	11.0	11.0	6.4	6.8	5.9		6.9	
c					6.6		7.0	
6 a						7.8		23.4
b	10.4	10.4	6.4	6.1	6.3		7.4	
c					6.5		6.5	
7 a					20.7		33.8	
b	12.4	30.4	32.4	19.1	21.7		21.6	
c						26.6		19.2
8 a						9.1		14.8
b	10.4	10.4	7.6	6.8	7.5		6.8	
c					7.9		6.9	
9 a						14.3		19.6
b	11.1	17.1	16.1	10.4	10.7		9.7	
c					10.5		10.7	
10 a					6.8		7.0	
b	9.9	9.9	6.1	6.1	6.9		8.7	
c						7.3		15.3
11 a						7.5		19.1
b	9.2	9.2	7.3	6.2	6.6		6.8	
c					6.6		6.5	
12 a						7.2		20.1
b	10.2	10.2	5.9	5.8	6.6		6.4	
c					6.0		7.1	
13 a					17.4		15.4	
b	11.1	24.1	26.4	20.0	20.8		17.5	
c						23.2		32.3
14 a						11.5		20.1
b	7.9	7.9	6.4	6.4	7.0		7.3	
c					6.5		6.5	
15 a						10.5		20.9
b	9.5	15.5	14.1	8.3	11.0		10.2	
c					10.0		10.7	
16 a					26.7		30.1	
b	13.6	31.6	49.2	20.7	22.0		20.0	
c						23.8		36.7
17 a						10.6		25.3
b	10.5	13.5	11.4	6.7	7.8		7.6	
c					7.0		6.7	
18 a						14.4		20.1
b	9.3	18.3	21.6	9.5	12.1		11.3	
c					11.0		11.0	

Appendix Table 6b. Great Carlton, Olsen P, mg/kg, in 0–22cm depth of soil

Large plot (and sub plot)		2014 Actual		2015 Actual		2016 Actual	
		No fresh P	Fresh P	No fresh P	Fresh P	No fresh P	Fresh P
1	a	7.7		9.6		7.9	
	b	8.6		9.0		7.9	
	c		16.0		16.2		29.8
2	a		14.6		18.0		20.0
	b	10.2		12.8		10.9	
	c	11.3		11.4		12.5	
3	a		13.8		12.7		22.8
	b	7.1		10.1		13.0	
	c	8.5		10.3		10.2	
4	a	15.4		17.7		15.3	
	b	15.0		20.6		13.7	
	c		22.6		26.0		27.6
5	a		12.0		16.9		17.1
	b	6.9		7.1		9.2	
	c	6.7		9.3		7.2	
6	a		11.0		13.7		13.7
	b	19.5		9.0		9.2	
	c	20.6		8.2		6.5	
7	a	19.5		18.1		15.1	
	b	20.6		18.4		14.9	
	c		26.4		25.4		29.0
8	a		11.4		15.5		13.0
	b	7.7		9.0		8.8	
	c	7.2		9.2		8.3	
9	a		14.6		17.5		15.0
	b	9.4		12.8		10.0	
	c	9.0		11.0		9.4	
10	a	6.3		7.9		5.9	
	b	6.5		7.7		6.4	
	c		10.9		14.3		15.9
11	a		12.0		13.5		16.1
	b	6.7		8.1		6.9	
	c	6.6		8.0		7.0	
12	a		9.5		13.5		18.1
	b	7.0		8.2		9.5	
	c	6.9		7.8		8.2	
13	a	15.1		16.8		12.7	
	b	14.9		15.4		17.0	
	c		20.6		22.0		15.8
14	a		12.2		10.0		13.6
	b	6.9		5.7		7.1	
	c	5.5		4.6		6.7	
15	a		13.7		12.6		12.9
	b	9.5		7.9		11.4	
	c	9.2		7.2		9.7	
16	a	22.2		16.4		16.8	
	b	20.6		18.6		16.5	
	c		32.8		24.8		35.6
17	a		15.2		12.7		23.4
	b	8.0		7.5		9.3	
	c	6.8		5.8		7.5	
18	a		14.2		12.7		14.8
	b	9.6		8.3		9.9	
	c	9.6		8.0		10.5	

Appendix Table 7a. 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						9.6		17.8
b	6.4	12.4	20.3	9.5	8.1		8.4	
c					8.4		8.6	
2 a						7.9		15.1
b	4.9	4.9	5.5	5.2	5.7		8.0	
c					5.3		6.9	
3 a						7.6		18.3
b	6.4	9.4	18.4	5.2	6.6		8.7	
c					6.6		7.9	
4 a						22.4		21.1
b	5.8	23.8	39.5	21.0	15.0		13.7	
c					14.3		12.9	
5 a						7.9		20.2
b	6.2	6.2	7.4	5.2	3.9		8.5	
c					3.9		7.3	
6 a						5.0		22.3
b	5.9	5.9	6.7	5.2	4.7		7.5	
c					4.1		7.5	
7 a						19.3		30.5
b	5.6	29.6	56.0	25.3	15.5		19.5	
c					14.4		17.6	
8 a						4.8		20.8
b	4.6	4.6	7.7	11.4	4.2		7.9	
c					4.7		8.5	
9 a						22.0		27.2
b	5.0	18.0	42.2	18.2	14.0		17.9	
c					13.9		14.1	
10 a						12.8		27.8
b	5.3	23.3	22.1	15.3	12.4		21.7	
c					15.9		19.3	
11 a						43.3		29.6
b	5.3	29.3	78.2	30.5	17.3		28.0	
c					22.7		22.4	
12 a						8.4		16.7
b	3.9	3.9	5.3	21.6	5.7		13.3	
c					5.1		15.5	
13 a						4.7		23.0
b	4.6	4.6	4.9	6.8	4.5		12.2	
c					4.7		10.1	
14 a						23.0		22.1
b	4.6	13.6	20.1	19.4	8.4		12.6	
c					14.3		10.7	
15 a						5.1		21.6
b	5.0	7.0	6.8	16.3	9.7		12.6	
c					6.2		12.1	
16 a						9.0		22.7
b	5.6	8.6	14.1	6.7	5.4		7.5	
c					4.5		6.8	
17 a						6.6		15.1
b	4.9	6.9	8.9	7.1	5.1		11.2	
c					5.1		8.4	
18 a						11.6		23.3
b	5.5	18.5	45.5	14.4	9.6		9.6	
c					12.2		12.1	

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

Large plot (and sub plot)		2014 Actual		2015 Actual		2016 Actual	
		No fresh P	Fresh P	No fresh P	Fresh P	No fresh P	Fresh P
1	a		11.8		23.2		13.7
	b	6.7		6.2		6.1	
	c	7.0		5.9		5.1	
2	a		9.9		18.6		10.5
	b	7.6		6.0		5.7	
	c	5.4		3.6		5.1	
3	a		5.6		28.4		15.5
	b	6.1		7.3		5.3	
	c	5.6		5.9		4.8	
4	a		14.9		40.0		14.3
	b	11.5		22.4		9.9	
	c	10.2		12.7		6.5	
5	a		9.3		8.4		33.2
	b	5.3		5.1		7.4	
	c	5.5		5.6		4.7	
6	a		10.9		18.5		12.9
	b	6.2		7.0		5.3	
	c	5.7		5.1		4.9	
7	a		14.9		57.4		21.4
	b	12.9		12.9		10.0	
	c	13.0		11.9		8.9	
8	a		10.3		23.4		14.5
	b	6.3		6.2		5.9	
	c	9.3		6.6		5.2	
9	a		13.7		17.3		15.6
	b	10.7		10.0		10.5	
	c	11.7		8.4		8.4	
10	a		13.2		23.4		35.8
	b	10.9		10.2		11.8	
	c	12.8		9.4		7.5	
11	a		22.2		12.7		22.6
	b	18.4		12.5		13.9	
	c	16.8		13.9		12.6	
12	a		13.8		7.6		29.6
	b	8.2		5.6		6.2	
	c	6.8		5.3		5.6	
13	a		10.4		20.2		19.2
	b	7.6		5.8		6.1	
	c	6.1		4.8		4.9	
14	a		14.7		20.6		15.9
	b	11.0		7.0		6.7	
	c	7.8		6.1		6.7	
15	a		11.8		15.9		10.7
	b	8.6		6.0		5.6	
	c	6.9		5.2		4.9	
16	a		8.3		24.2		36.4
	b	5.9		6.4		7.7	
	c	4.7		5.4		5.3	
17	a		8.6		14.1		17.1
	b	5.1		5.1		5.6	
	c	4.6		6.7		4.5	
18	a		9.0		16.4		16.9
	b	7.7		7.5		9.1	
	c	6.5		7.5		6.4	

Appendix Table 8. Caythorpe, 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						40.5		47.1
	b	19.3	25.3	23.5	25.6	23.0		24.9	
	c					16.4		20.5	
2	a					19.0		22.8	
	b	8.7	17.7	21.9	18.4	16.2		19.2	
	c						23.2		25.2
3	a					7.8		9.6	
	b	5.6	5.6	7.6	7.3	8.2		8.9	
	c						11.8		12.7
4	a						21.4		21.7
	b	8.9	9.9	14.8	13.9	13.3		15.0	
	c					9.7		12.1	
5	a					15.2		19.8	
	b	8.2	21.2	24.7	17.3	16.4		21.8	
	c						22.7		19.8
6	a					8.5		9.2	
	b	7.6	7.6	7.4	8.2	7.3		9.8	
	c						10.2		18.1
7	a						18.6		30.5
	b	11.6	11.6	11.4	9.0	10.0		11.4	
	c					7.9		8.7	
8	a					8.8		7.5	
	b	6.4	6.4	9.2	7.7	7.8		7.7	
	c						13.6		16.9
9	a					7.2		7.7	
	b	6.8	6.8	8.0	6.2	7.2		6.9	
	c						11.5		12.8
10	a						33.7		39.1
	b	8.5	26.5	35.5	23.0	20.4		22.1	
	c					20.1		21.3	
11	a					8.8		9.2	
	b	9.2	9.2	7.3	6.7	7.3		8.7	
	c						12.7		13.9
12	a					11.0		13.1	
	b	6.5	12.5	12.4	10.2	10.3		11.3	
	c						13.1		15.9
13	a						22.1		29.0
	b	8.0	17.0	14.2	12.7	12.8		13.0	
	c					13.7		17.6	
14	a					7.2		9.4	
	b	5.2	5.2	6.4	5.0	5.7		7.4	
	c						9.4		16.4
15	a					5.1		6.7	
	b	4.9	4.9	4.8	5.0	4.4		6.8	
	c						9.6		12.2
16	a						23.0		28.7
	b	8.2	21.2	22.7	19.8	14.9		16.4	
	c					19.0		23.1	
17	a					6.9		9.3	
	b	6.5	7.5	7.7	6.7	6.3		7.9	
	c						12.7		10.4
18	a					6.6		8.9	
	b	6.7	7.7	9.3	6.1	5.7		8.3	
	c						14.9		7.2

Appendix Table 9. 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		2013 Actual	
					No fresh P	Fresh P	No fresh P	Fresh P
1 a						9.3		9.9
b	3.9	21.9	41.2	10.4	12.3		30.1	
c					9.3		10.1	
2 a						6.5		7.9
b	3.9	12.9	38.5	3.9	6.7		13.4	
c					4.5		9.9	
3 a					4.0		12.4	
b	3.9	3.9	4.5	5.6	3.6		7.6	
c						3.0		11.4
4 a						11.6		10.3
b	3.9	6.9	14.5	13.0	13.6		13.0	
c					8.6		19.8	
5 a						9.6		26.3
b	3.9	6.9	7.6	5.6	7.9		12.6	
c					10.8		13.3	
6 a					11.3		14.9	
b	3.9	27.9	43.5	6.4	5.9		19.1	
c						10.5		8.5
7 a						9.6		6.8
b	3.9	9.9	17.6	8.9	22.8		18.1	
c					14.2		13.6	
8 a						14.8		14.5
b	3.9	16.9	20.3	18.5	10.8		19.8	
c					16.1		10.1	
9 a					21.5		13.6	
b	3.9	3.9	5.0	18.4	16.7		18.7	
c						11.4		37.5
10 a						7.6		12.3
b	3.9	6.9	7.6	9.6	9.5		18.6	
c					9.5		17.6	
11 a						15.9		18.4
b	3.9	9.9	20.6	10.1	17.5		41.1	
c					26.8		22.8	
12 a					9.3		9.8	
b	3.9	21.9	32.9	13.3	7.9		7.3	
c						5.3		8.3
13 a						8.3		12.9
b	3.9	12.9	13.9	7.6	16.7		13.0	
c					11.4		15.0	
14 a						19.3		14.1
b	3.9	27.9	54.5	22.2	17.8		13.8	
c					17.2		19.8	
15 a					19.6		13.6	
b	3.9	16.9	20.6	17.0	15.7		12.8	
c						21.5		23.2
16 a						15.1		34.6
b	3.9	3.9	4.8	16.1	17.0		11.6	
c					8.0		11.3	
17 a						14.2		22.6
b	3.9	6.9	10.1	19.6	28.9		16.8	
c					24.1		20.2	
18 a					17.3		11.9	
b	3.9	3.9	4.9	23.3	21.0		16.0	
c						13.3		20.6

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

Appendix Table 10. 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						18.3		22.6
b	6.1	15.1	15.0	9.9	10.9		16.1	
c					8.4		14.4	
2 a						14.3		16.2
b	6.1	19.1	21.2	8.7	7.6		10.8	
c					9.0		13.2	
3 a						14.7		15.5
b	7.3	7.3	7.7	7.7	8.4		11.9	
c					6.8		10.2	
4 a						8.5		23.4
b	8.0	32.0	20.0	10.7	11.3		17.8	
c					10.9		18.9	
5 a						18.0		22.0
b	6.8	7.8	11.6	9.6	12.7		5.1	
c					12.1		11.3	
6 a						13.9		16.0
b	5.3	5.3	9.0	7.7	8.1		16.0	
c					8.4		13.6	
7 a						9.9		13.0
b	7.9	10.9	6.8	7.1	7.9		13.6	
c					7.3		9.0	
8 a						33.1		19.0
b	6.5	24.5	32.0	15.3	10.9		27.4	
c					11.2		19.3	
9 a						19.6		15.9
b	5.3	5.3	14.5	9.2	9.9		15.6	
c					11.6		10.5	
10 a						13.0		24.9
b	8.6	8.6	12.3	8.9	9.0		12.0	
c					9.1		12.1	
11 a						12.2		22.6
b	13.0	16.0	18.2	9.0	11.3		19.7	
c					8.2		16.7	
12 a						13.9		27.8
b	11.7	20.7	16.3	9.6	9.0		17.6	
c					9.9		16.2	
13 a						14.3		26.2
b	8.3	8.3	11.4	11.7	10.6		13.4	
c					10.0		16.4	
14 a						19.3		25.6
b	9.9	9.9	10.2	9.9	9.0		18.5	
c					8.1		14.7	
15 a						18.7		25.4
b	9.2	27.2	21.2	11.7	10.5		20.4	
c					8.8		18.0	
16 a						14.7		20.5
b	8.3	8.3	12.7	10.8	11.9		13.9	
c					11.3		14.4	
17 a						16.1		25.5
b	9.0	12.0	15.1	10.8	12.7		13.2	
c					12.4		14.9	
18 a						15.8		14.2
b	6.5	6.5	12.7	8.9	9.6		11.2	
c					8.4		11.8	

Appendix Table 11. Cirencester, Olsen P, mg/kg, in 15–30cm depth of soil

Large plot (and sub plot)		2012 Actual		2013 Actual	
		No fresh P	Fresh P	No fresh P	Fresh P
1	a		9.0		10.5
	b	5.5		9.5	
	c	8.2		5.4	
2	a		6.7		6.8
	b	4.9		4.3	
	c	4.8		5.2	
3	a		4.6		4.8
	b	4.6		3.9	
	c	4.2		2.8	
4	a		6.5		8.7
	b	6.7		6.4	
	c	6.5		6.4	
5	a		7.4		4.8
	b	7.1		4.9	
	c	5.6		6.0	
6	a		6.4		7.9
	b	5.5		6.2	
	c	4.6		6.0	
7	a		5.9		5.4
	b	5.5		4.3	
	c	5.3		3.4	
8	a		9.9		6.1
	b	6.1		6.2	
	c	6.7		6.6	
9	a		7.0		5.7
	b	8.5		5.6	
	c	5.2		5.9	
10	a		6.5		6.0
	b	5.8		6.7	
	c	6.1		7.5	
11	a		7.6		7.3
	b	7.0		8.5	
	c	6.2		5.9	
12	a		6.5		8.3
	b	8.9		9.9	
	c	7.4		7.7	
13	a		8.5		8.7
	b	8.2		7.0	
	c	6.8		6.8	
14	a		7.4		8.2
	b	6.1		7.0	
	c	6.1		6.6	
15	a		8.9		11.1
	b	7.3		11.9	
	c	6.1		9.6	
16	a		6.5		5.6
	b	6.1		6.0	
	c	6.5		5.7	
17	a		6.1		8.2
	b	5.3		4.9	
	c	5.2		5.9	
18	a		5.0		7.8
	b	6.1		3.9	
	c	4.6		5.6	

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

Site	P	Olsen P	2009	2010	2011	2012 No fresh P		2013 No fresh P	
	Index	mg/kg	Large	Large	Large	Individ.	Mean	Individ.	Mean
Peldon	0	0-9	12	7	9	20	11	20	9
	1	10-15	6	4	4	5	2	5	3
	2	16-25	0	1	1	4	2	4	4
	3	26-45	0	4	4	7	3	6	2
	4+	46+	0	2	0	0	0	1	0
Great Carlton	0	0-9	4	8	12	20	10	19	10
	1	10-15	14	3	2	8	4	10	4
	2	16-25	0	3	4	7	4	5	3
	3	26-45	0	3	0	1	0	2	1
	4+	46+	0	1	0	0	0	0	0
Cholsey	0	0-9	18	8	8	22	11	15	7
	1	10-15	0	1	3	11	6	14	7
	2	16-25	0	4	6	3	1	6	4
	3	26-45	0	3	1	0	0	1	0
	4+	46+	0	2	0	0	0	0	0
Caythorpe	0	0-9	16	9	10	19	10	17	9
	1	10-15	1	4	3	9	3	8	4
	2	16-25	1	4	4	8	5	11	5
	3	26-45	0	1	1	0	0	0	0
	4+	46+	0	0	0	0	0	0	0
Weston (plots 16-18 excluded after 2010)	0	0-9	18	6	6	12	6	2	1
	1	10-15	0	3	5	7	4	17	6
	2	16-25	0	4	4	10	5	9	7
	3	26-45	0	4	0	1	0	2	1
	4+	46+	0	1	0	0	0	0	0
Cirencester	0	0-9	15	3	8	17	8	2	1
	1	10-15	3	9	10	19	10	19	11
	2	16-25	0	5	0	0	0	14	6
	3	26-45	0	1	0	0	0	1	0
	4+	46+	0	0	0	0	0	0	0

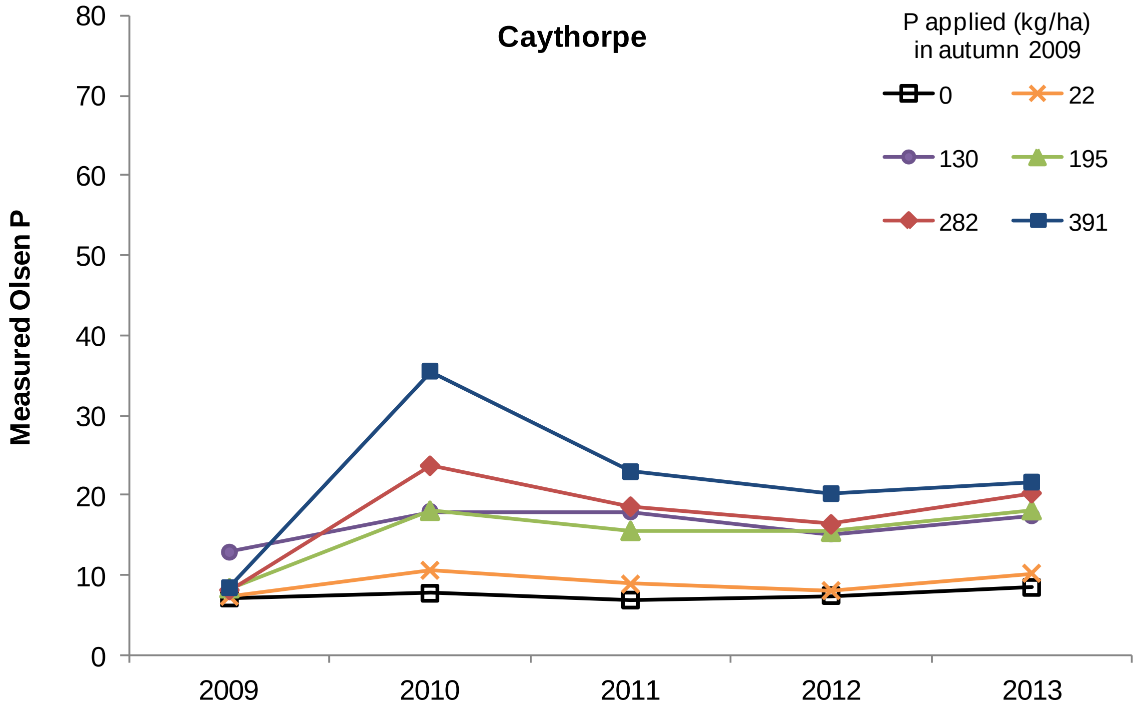
Appendix Table 12b. Number of plots in each P Index in 2014, 2015 and 2016

Site	P	Olsen P	2014 No fresh P		2015 No fresh P		2016 No fresh P	
	Index	mg/kg	Individ.	Mean	Individ.	Mean	Individ.	Mean
Peldon	0	0-9	14	9	20	11	21	12
	1	10-15	12	4	11	4	10	3
	2	16-25	6	3	4	2	5	3
	3	26-45	4	2	1	1	0	0
	4+	46+	0	0	0	0	0	0
Great Carlton	0	0-9	23	12	21	11	18	9
	1	10-15	9	4	8	3	15	8
	2	16-25	4	2	7	4	3	1
	3	26-45	0	0	0	0	0	0
	4+	46+	0	0	0	0	0	0
Cholsey	0	0-9	25	13	28	14	30	16
	1	10-15	9	4	7	3	6	2
	2	16-25	2	1	1	1	0	0
	3	26-45	0	0	0	0	0	0
	4+	46+	0	0	0	0	0	0

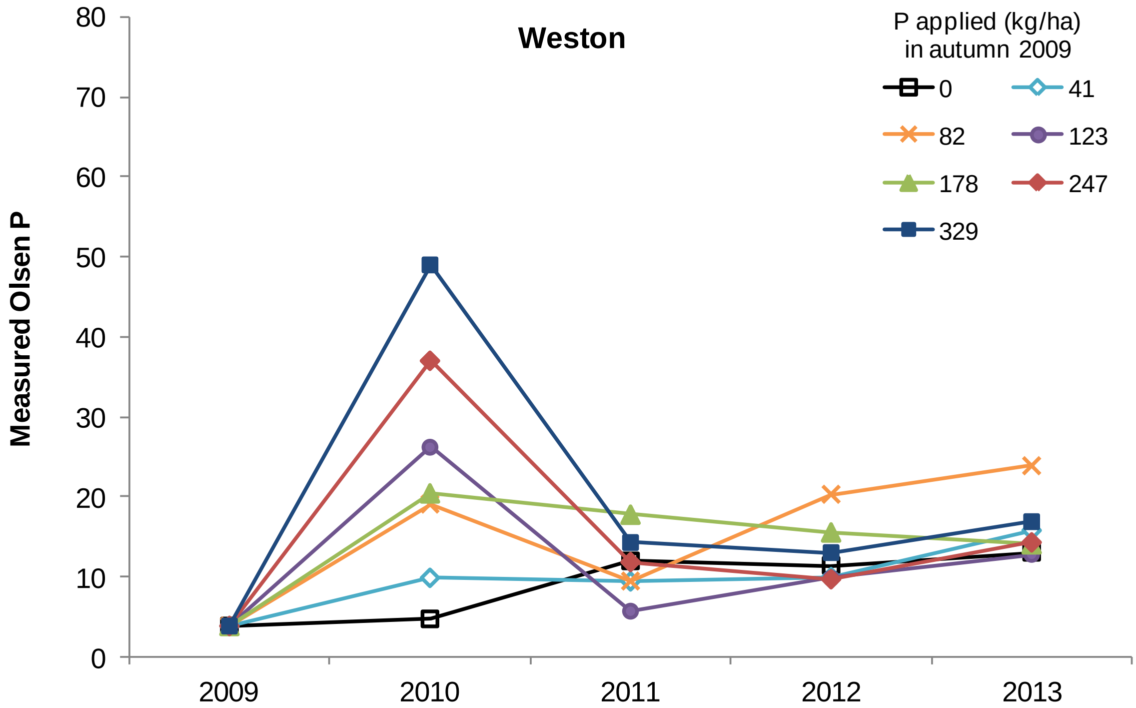
8.5. Appendix 5 Additional Soil Olsen P Charts

8.5.1. Measured Olsen P Levels (excluding fresh P plots)

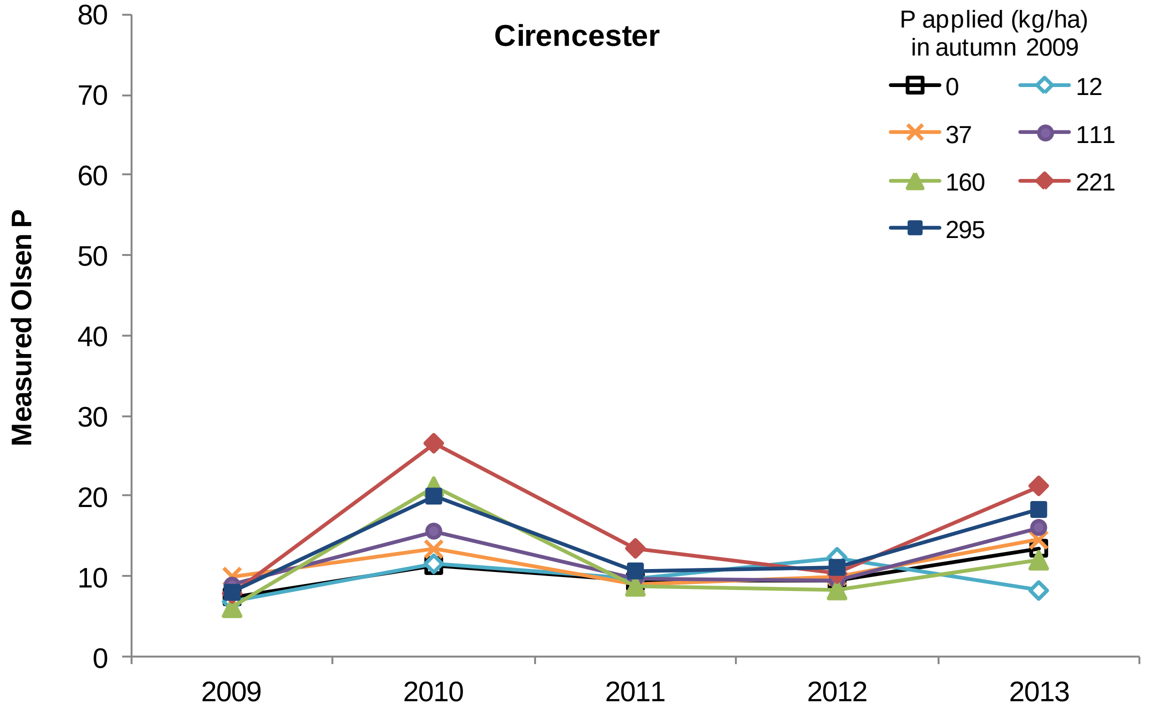
Year-to-year change in Soil Olsen P levels for three sites used in 2009-2013 only



Appendix Fig. 1. 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

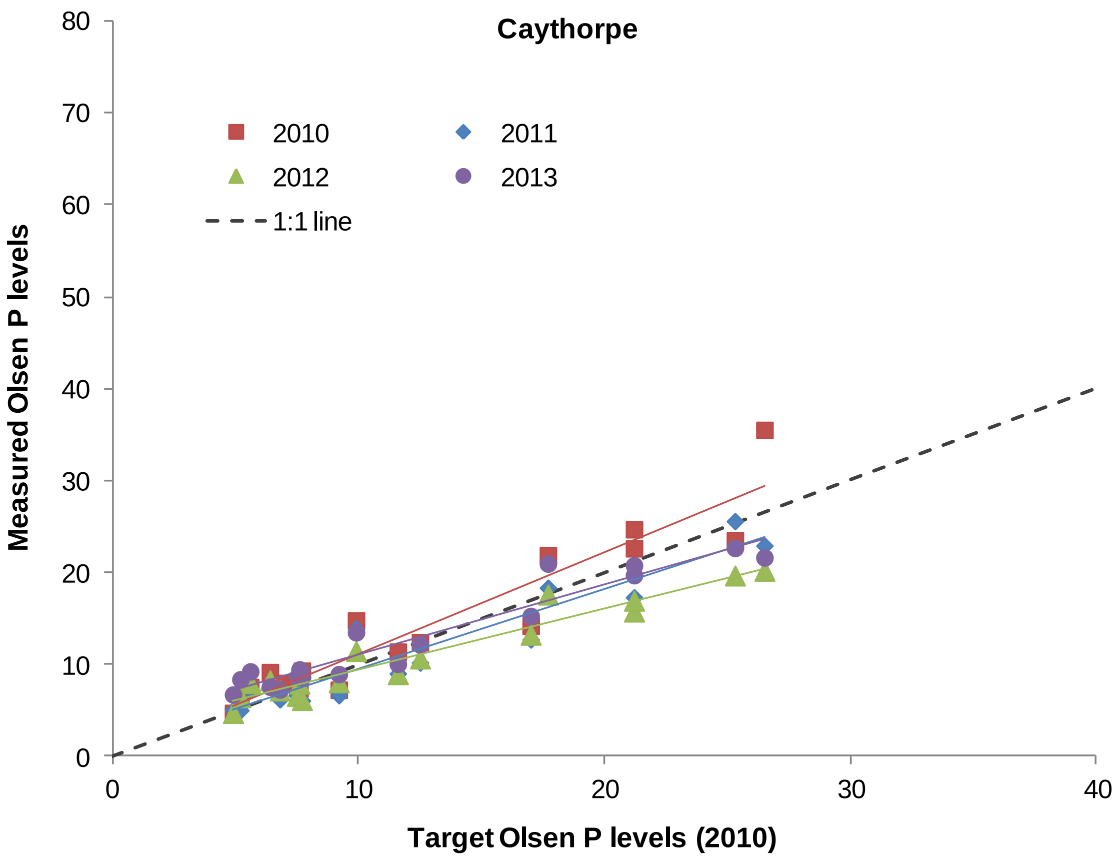


Appendix Fig. 2. Average measured Olsen P, mg/kg, at the Weston site from 2009 to 2013, for plots receiving different amounts of P fertiliser in autumn 2009

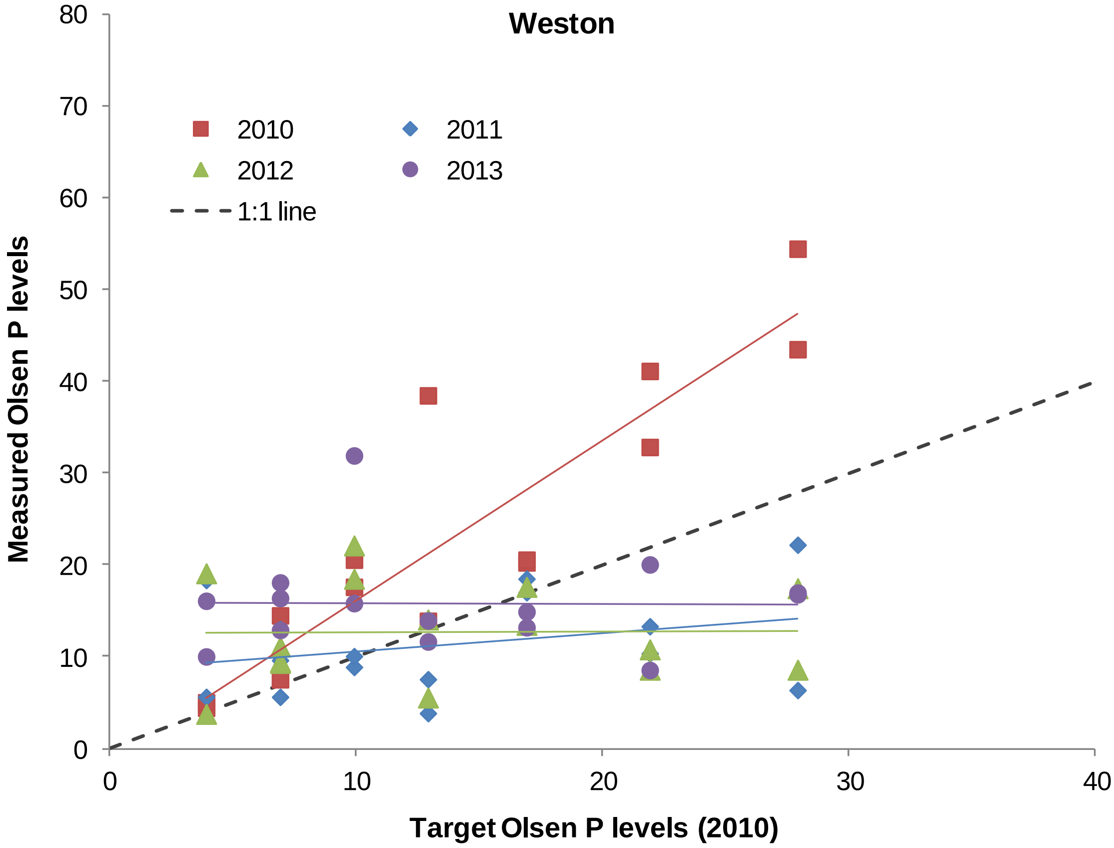


Appendix Fig. 3. Average measured Olsen P, mg/kg, at the Cirencester site from 2009 to 2013, for plots receiving different amounts of P fertiliser in autumn 2009

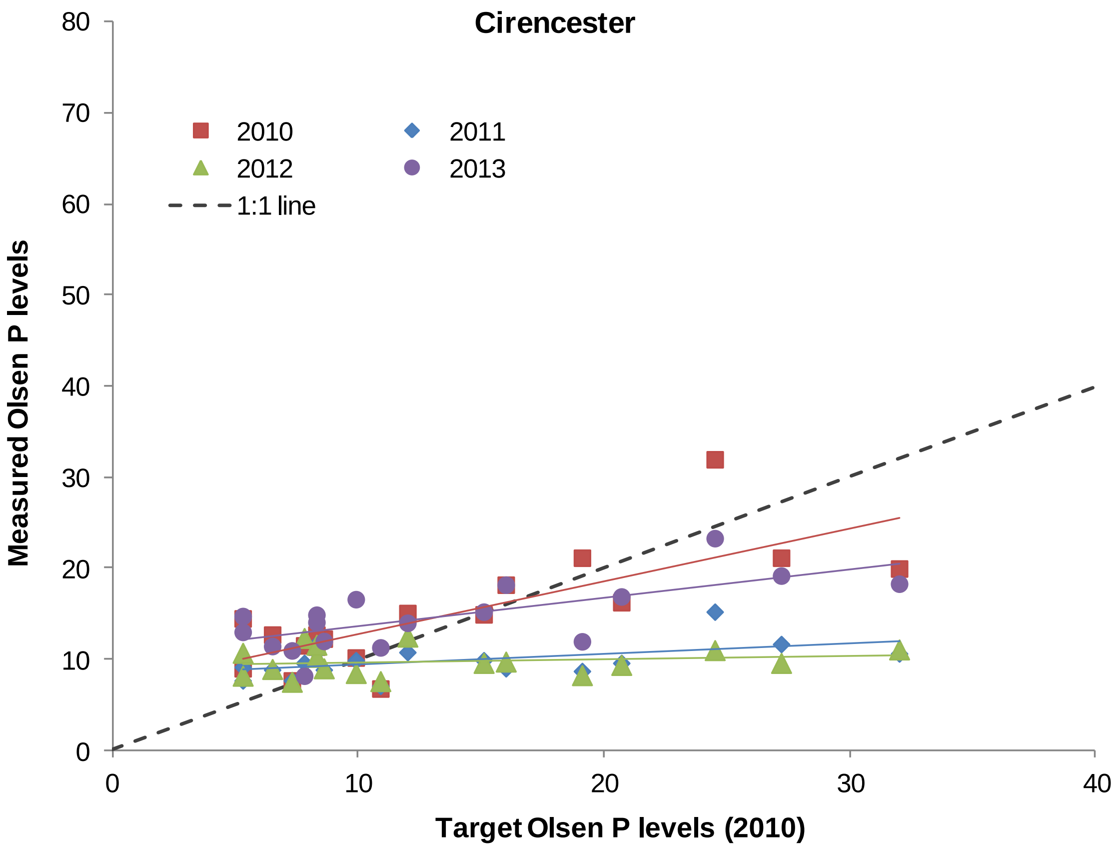
8.5.2. Relationship between Target and Measured Olsen P Levels



Appendix Fig. 4. Measured Olsen P, mg/kg, compared to 2010 target levels at Caythorpe

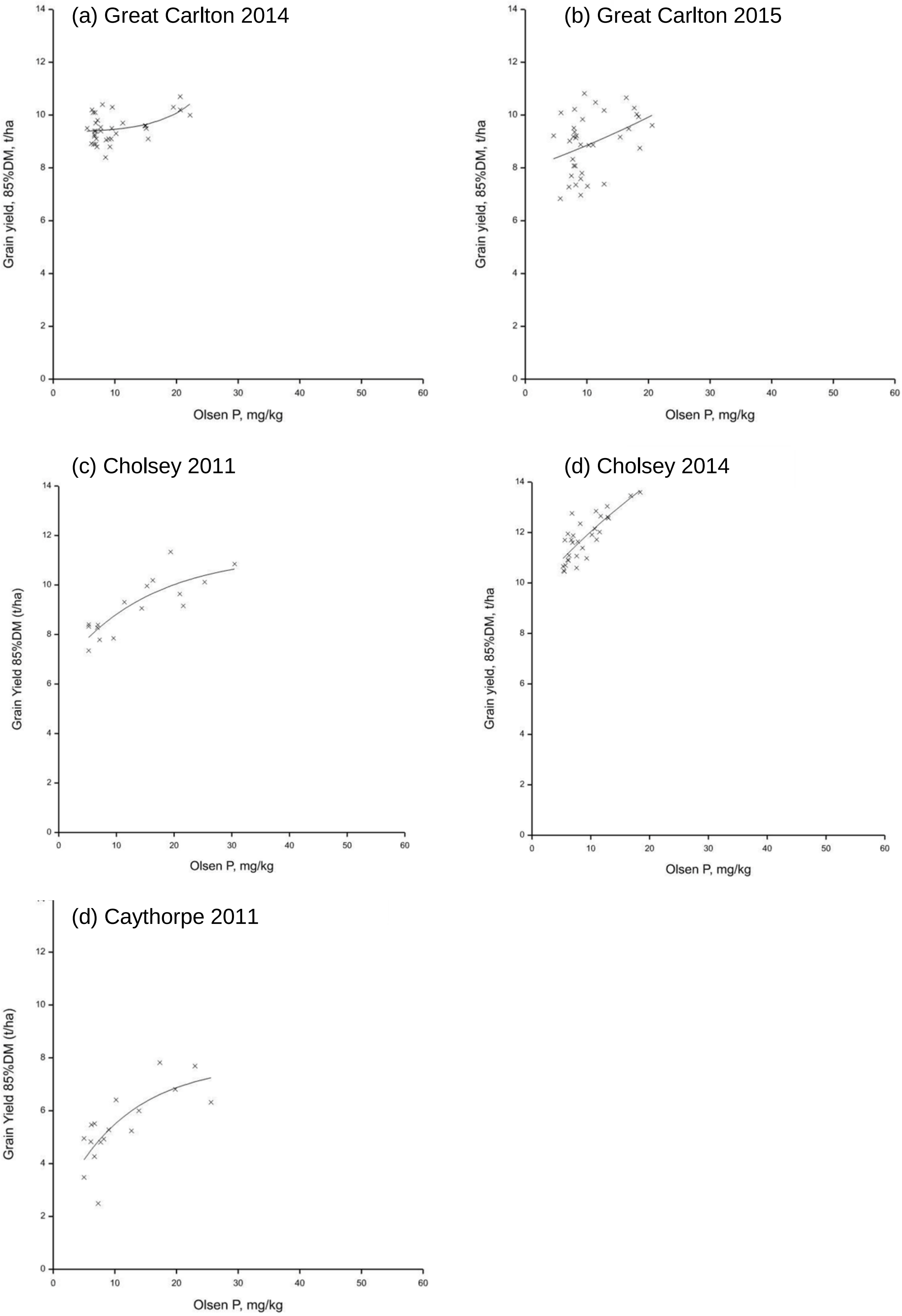


Appendix Fig. 5. Measured Olsen P, mg/kg, compared to 2010 target levels at Weston (excl. plots 16-18)



Appendix Fig. 6. Measured Olsen P, mg/kg, compared to 2010 target levels at Cirencester

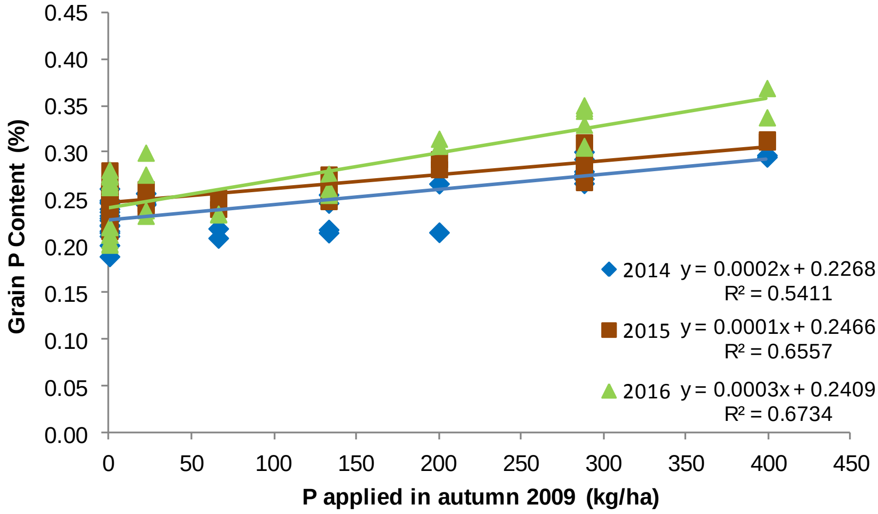
8.6. Appendix 6 Additional Wheat Yield Response Curves to Soil Olsen P



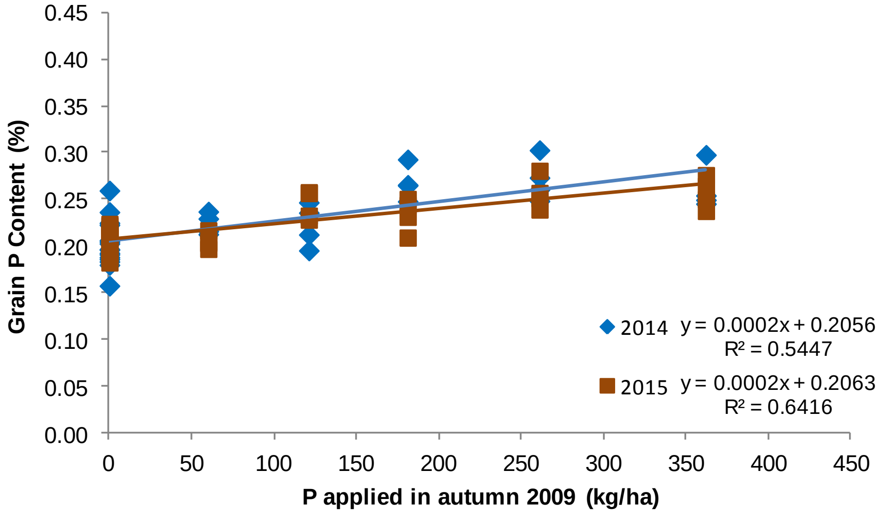
Appendix Fig. 7a-e. Fitted yield response curves to soil Olsen P for wheat crops where it was not possible to obtain meaningful estimates of critical P levels

8.7. Appendix 7 Additional Grain P Content Charts

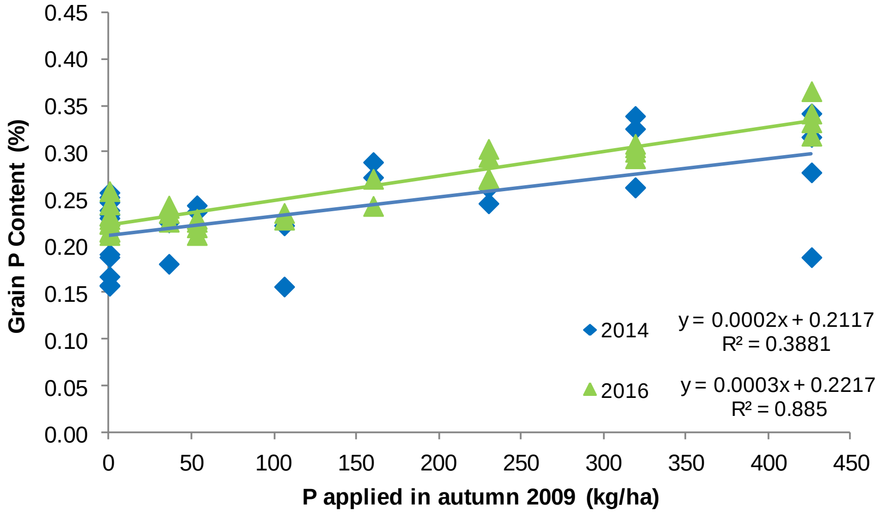
(a) Peldon



(b) Great Carlton



(c) Cholsey



Appendix Fig. 8a-c. Relationship between amount of P fertiliser applied in autumn 2009 and P content of wheat grain harvested in 2014, 2015 and/or 2016 at Peldon (a), Great Carlton (b) and Cholsey (c)

8.8. Appendix 8 Annual P and P_2O_5 Offtake Data

Appendix Table 13. Average offtake of P and P_2O_5 in wheat grain at each P Index (2010-2013 based on estimated wheat grain P content values; 2014-2016 based on measured grain P content values)

Site		Offtake of P (kg/ha)					Offtake of P_2O_5 (kg/ha)				
	Index	0	1	2	3+	Mean	0	1	2	3+	Mean
Peldon	2010	22	22	25	25	23	51	52	57	57	53
	2011	16	18	19	20	18	38	41	43	45	41
	2012	24	26	26	27	25	55	59	60	62	57
	2013	16	16	20	21	17	36	36	45	48	39
	Mean	20	21	22	23	21	45	47	51	53	48
	2014	17	20	22	23	20	38	46	50	53	45
	2015	19	24	27	26	22	44	55	63	60	50
	2016	18	26	32	-	22	42	59	74	-	51
	Mean	19	22	24	24	21	43	50	56	54	48
Great Carlton	2011	16	18	19	-	17	38	40	44	-	39
	2012	15	17	18	-	16	34	39	42	-	37
	Mean	16	17	19	-	17	36	40	43	-	38
	2014	17	22	23	-	19	38	50	52	-	43
	2015	15	18	22	-	17	35	41	50	-	39
	Mean	16	19	20	-	17	36	42	47	-	40
Cholsey	2010	17	18	19	20	18	38	42	43	46	42
	2011	18	21	23	24	21	42	48	53	55	47
	2013	21	23	24	-	22	48	52	55	-	51
	Mean	19	21	22	-	20	43	47	50	-	47
	2014	22	28	38	-	24	50	65	87	-	56
	2016	17	26	-	-	19	40	60	-	-	43
	Mean	19	23	26	-	21	44	53	59	-	48
Caythorpe	2010	13	16	15	18	14	29	38	35	42	33
	2011	10	13	14	14	12	23	30	33	32	27
	2012	4	7	10	-	6	10	17	23	-	15
	Mean	9	12	13	-	11	21	28	30	-	25
Ciren’ster	2012	16	16	-	-	16	37	38	-	-	37
Weston	2010	17	20	20	21	19	39	45	46	47	44
	2012	21	22	23	-	22	48	51	52	-	50
	Mean	19	21	22	-	21	44	48	49	-	47

Appendix Table 14. Average offtake of P and P_2O_5 in oilseed rape at each P Index (2010-2013 based on standard seed P content values)

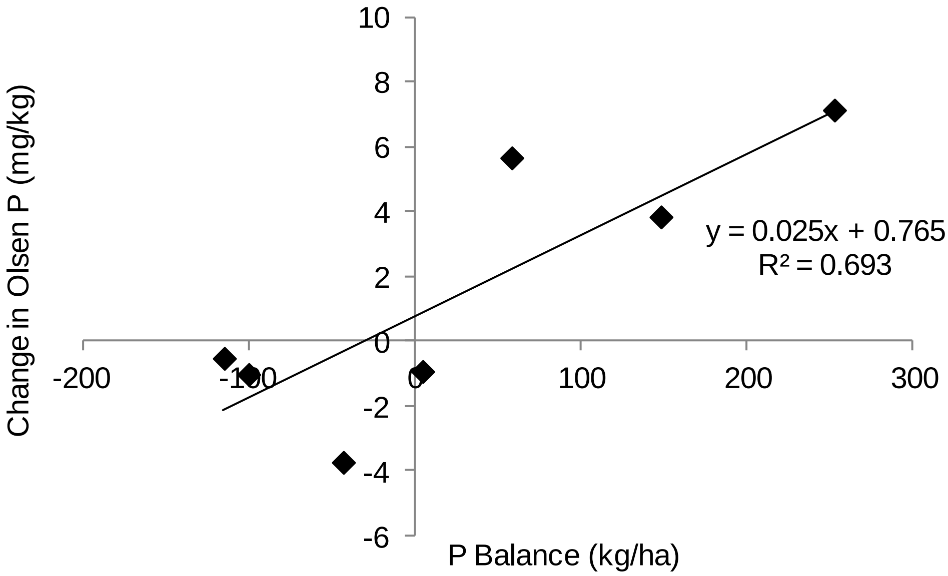
Site		Offtake of P (kg/ha)					Offtake of P_2O_5 (kg/ha)				
	Year	0	1	2	3+	Mean	0	1	2	3+	Mean
Weston	2013	28	26	26	26	26	63	60	60	60	61
Great Carlton	2010	24	24	25	26	25	54	56	58	59	56
Cholsey	2012	18	21	21	-	19	41	49	49	-	44
Cirencester	2011	25	26	-	-	25	57	59	-	-	58

Appendix Table 15. Average offtake of P and P_2O_5 in barley at each P Index (2010-2013 based on estimated barley grain P content values; 2016 based on measured grain P content values)

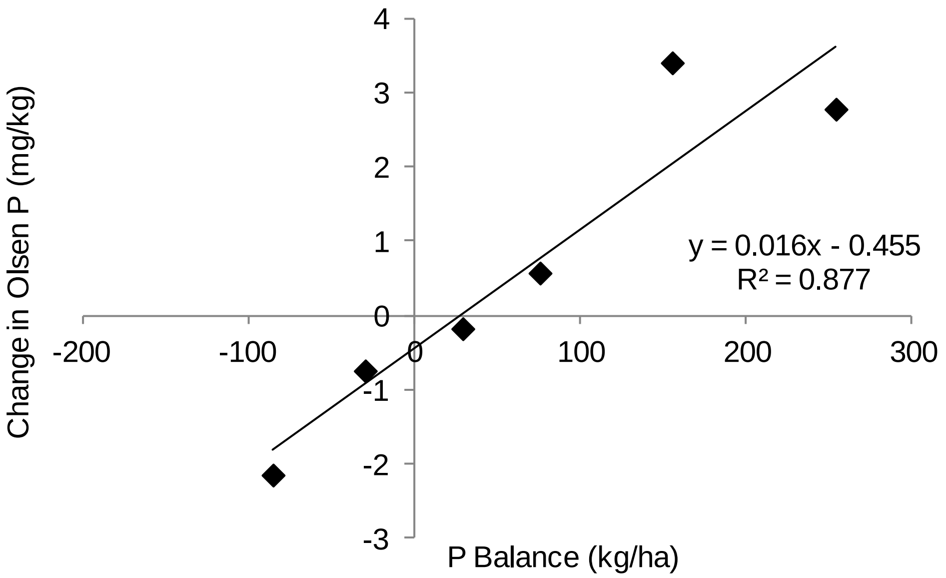
Site		Offtake of P (kg/ha)					Offtake of P_2O_5 (kg/ha)				
	Year	0	1	2	3+	Mean	0	1	2	3+	Mean
Cirencester	2010	21	21	20	20	20	48	47	46	47	47
	2013	16	16	15	-	16	37	37	35	-	36
Caythorpe	2013	23	23	24	-	23	52	53	54	-	53
Great Carlton	2016	19	22	23	-	20	43	50	53	-	47

8.9. Appendix 9 P Balance and Change in Soil Olsen P from 2009 to 2016

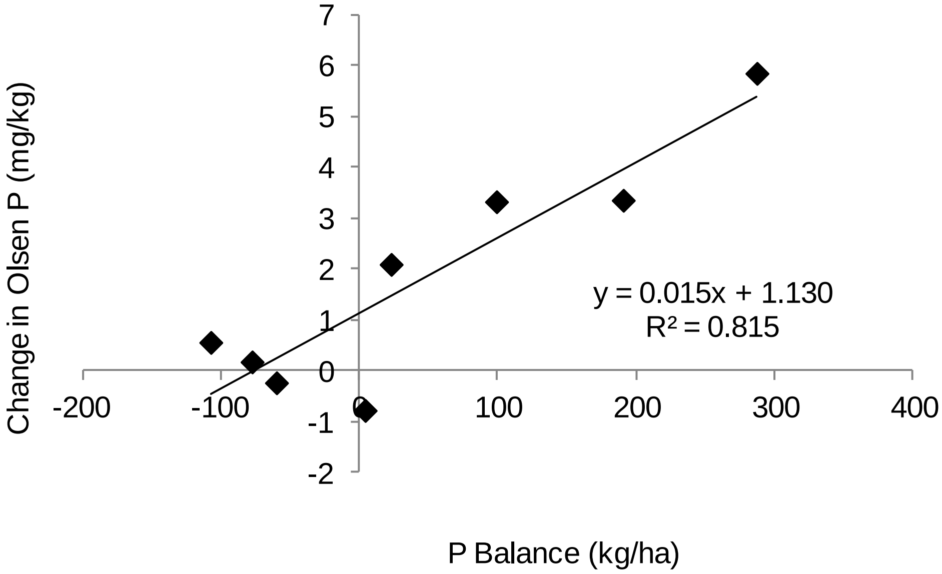
P balances based on grain P contents estimated from 2014-16 values for wheat and barley, but standard values for oilseed rape.



Appendix Fig. 9. Change in Olsen P (mg/kg) in relation to P balance (kg/ha) at Peldon (2009-16)



Appendix Fig. 10. Change in Olsen P (mg/kg) in relation to P balance (kg/ha) at Great Carlton (2009-16)



Appendix Fig. 11. Change in Olsen P (mg/kg) in relation to P balance (kg/ha) at Cholsey (2009-16)

8.10. Appendix 10 Breakdown of Economic Analysis

Appendix Table 16. Initial and replacement quantities of P_2O_5 and their costs, annual wheat yields and values, and net values after 1, 2, 3, 4 or 5 years (assuming successive wheat crops) at four sites

Site and Olsen P Index	Initial P_2O_5		Annual offtake		Annual wheat		Net value (£/ha) after				
	Dose kg/ha	Cost £/ha	Quant kg/ha	Cost £/ha	Yield t/ha	Value £/ha	1 Yr	2 Yrs	3 Yrs	4 Yrs	5 Yrs
Peldon											
Index 0	0	0	39	25	8.85	1195	1169	2339	3508	4678	5847
Index 1	211	137	51	33	9.67	1305	1132	2402	3671	4940	6209
Index 2	422	274	59	38	10.29	1389	1071	2417	3762	5107	6452
Gt Carlton											
Index 0	0	0	35	23	8.04	1085	1062	2125	3187	4250	5312
Index 1	394	256	46	30	8.61	1162	871	1999	3126	4254	5381
Index 2	788	512	53	34	9.26	1250	693	1899	3104	4309	5513
Cholsey											
Index 0	0	0	40	26	9.16	1237	1210	2421	3631	4842	6052
Index 1	603	392	54	35	10.12	1366	932	2255	3578	4901	6224
Index 2	1206	784	62	40	10.79	1457	617	2018	3418	4818	6218
Caythorpe											
Index 0	0	0	18	12	4.11	555	543	1086	1629	2172	2715
Index 1	548	356	30	19	5.63	760	377	1111	1844	2577	3310
Index 2	1096	712	34	22	5.93	801	52	816	1580	2343	3106