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Final Project Report

Cost-effective Phosphorus Management on UK Arable Farms

Includes the report on Work-Package 3:

Improving the efficiency of fresh P applications

Roger Sylvester-Bradley[1], Alison Rollett[2], Edward Downing[3], Steve Dudman[3], Mike Slater[3], Nathan Morris[4], Stuart Knight[5] and Paul Withers[6]

[1] ADAS Boxworth, Battlegate Road, Boxworth, Cambridgeshire, CB23 4NN

[2] ADAS Gleadthorpe, Netherfield Lane, Meden Vale, Nottinghamshire, NG20 9PD

[3] Frontier Agriculture Ltd., Brecklands Estate, Downham Road, Swaffham, PE37 7QE

[4] NIAB TAG, Morley Business Centre, Morley, Wymondham, Norfolk, NR18 9DF

[5] NIAB TAG, Huntingdon Road, Cambridge, CB3 0LE

[6] Lancaster Environment Centre, Lancaster University, Lancaster LA1 4YQ.

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Abbreviations

AHDB	Agricultural and Horticultural Development Board
ASPR	Apparent Soil Phosphate Requirement: the quantity (kg ha^{-1}) of phosphate determined by subtracting offtake from inputs, associated with a change in soil test P (mg L^{-1}).
CV	Coefficient of variation
DAP	Di-ammonium phosphate
Defra	The UK Government's Department for the Environment, Food and Rural Affairs
DM	Dry Matter
EU	European Union
Grain P	P concentration in grain DM, expressed here as a percentage, but expressed in various other ways in the literature e.g. 0.32% is the same as 3,200 mg/kg, 3,200 ppm or 3.2 g/kg.
GS	Growth stage
Available P	The P that is immediately able to contribute to plant uptake.
MAFF	The UK Government's Ministry of Agriculture, Fisheries and Food; superseded by Defra in 2002.
MAP	Mono-ammonium phosphate
N	Nitrogen
P	Phosphorus: To minimise confusion P is usually expressed on an elemental basis throughout this report. P can be converted to P_2O_5 by multiplying by 2.29.
PEN	Phosphorus Efficiency Network
P_2O_5	Phosphate; the form of phosphorus used to define the nutrient content of fertilisers; 2.29 kg P_2O_5 = 1 kg P.
PR	Phosphate rock
P offtake	'Crop P removal' is calculated using the weight and P composition of harvested biomass (as DM).
P uptake	'Total P uptake' exceeds 'P offtake' due to P in haulm or straw and chaff.
RB209	Reference number of the AHDB Nutrient Management Guide, and preceding editions of the Fertiliser Recommendations published by Defra and MAFF.
SD, SE & SED	Standard Deviation, Standard Error and Standard Error of a Difference
Soil P	Extractable soil P concentrations are typically quoted as mg kg^{-1} (research) or mg L^{-1} (advisory). They should not be treated as interchangeable due to variation in bulk density (see Drewry *et al*., 2013). Soil extractable P concentrations are sometimes converted to an area or volume equivalent basis, such as kg / ha / sample depth. This is particularly helpful when calculating long-term trends in P balances and when comparing with fertiliser applications or crop removal.
STP	Soil Test Phosphorus refers to the various soil extraction and analysis procedures used for advisory purposes.
TSP	Triple super phosphate
WFD	Water Framework Directive
WP	Work Package

Abstract 1:
of the 3rd & final report on Project RD-2160004

AHDB Project RD-2160004 aimed to improve the cost-effectiveness of phosphorus (P) management on UK arable farms. After publishing two 'final' reports on the first two work-packages (WP) of the project, this third section of the final report addressed three issues by both reanalysing data from Work-Package (WP) 2 and reporting results from WP3 on (i) critical grain P values, (ii) dependence of soil P run-down rates on previous P management, and (iii) responses to fertiliser P placement at field scale, as follows:

(i) Data from twelve site-seasons were statistically analysed to show that grain P analysis could usefully augment and improve on the capacity of soil P analysis to predict sufficiency (or otherwise) of crop P supplies. Grain P of less than 0.32% DM indicated that P supplies had been deficient[1].

(ii) Soil data over seven years from sites with different soil P statuses at the start were also analysed to show that soil P run-down was markedly faster where levels had recently been built-up to Index 2 than where they had been maintained at Index 2.

(iii) Twelve tramline trials were conducted on fields with low and variable soil P to assess the frequencies and sizes of yield responses to fresh applications of P (applied as triple superphosphate or di-ammonium phosphate), whether broadcast or placed. Adding fresh P (either in 'maintenance' or smaller quantities) almost always gave better grain yields than without any P applied; the benefits (range -0.2 to +0.8 t/ha) were significantly positive overall but only just cost-effective, averaging only 0.33 t/ha, equivalent to the cost of 70 kg/ha P_2O_5; there was no significant advantage of placing rather than broadcasting the fertiliser. With generally low soil P levels, intra-field spatial variation in grain yields of half of the twelve fields related to soil P levels, implying that crop yields were significantly affected by inherent soil P supplies.

This third section of the final report also drew together and discussed the above findings in relation to all major findings from two precursor AHDB-funded research projects. Recommendations were made for changes to the AHDB Nutrient Management Guide (RB209) and for a further knowledge generation programme to further improve cost-effectiveness of P management on arable farms. The headline conclusion is that:

P management in arable farming should become 'crop focussed',
particularly by introducing routine crop analysis. Arguments supporting this conclusion are outlined in the abstract on the next page.

[1] 'Exhibiting a positive effect on crop yield or value from increasing crop uptake of P, by whatever means.'

Abstract 2:
for AHDB Arable Phosphorus Research from 2009-2019

From three AHDB-funded research projects conducted between 2009 and 2019[2] on 'Targeted', 'Critical' and 'Cost-Effective' Phosphorus (P) the headline finding was that:

P management in arable farming should become 'crop focussed'.

This is because:

- Diagnosis of crop responsiveness to P applications was found to be possible and more precise through P analysis of grain, the critical value being 0.32% in DM[3],
- Analysis of P in harvested materials (i.e. grain here) was more reliable and indicative than soil analysis for P so, although more expensive than soil P analysis, can be used for routine monitoring of crop P sufficiency, as well as crop P offtake,
- About one quarter of cereal crops, and probably many other arable crops also, were deemed to be P deficient[4] according to the new critical crop P value,
- Results of routine soil P analysis varied such that they were best interpreted after (i) double-checking against other results determined concurrently in adjacent locations as well as previously at the same location, (ii) recognising the likely soil P sorption (or P fixation) capacity, and whether recent land P balances suggest build-up, maintenance or run-down of soil P, and (iii) noting recent crop P concentrations. For example, annual soil P fluctuations were significant and haphazard, and run-down rates were markedly faster on three sites where levels had recently been built-up to Index 2, compared to four sites which had recently been maintained at Index 2.
- Although critical soil P levels varied significantly between Index 0 and Index 3, it was cost-effective to maintain soils at P Index 1 rather than P Index 2 if the rotation included only autumn-sown crops and if fresh P was applied annually.
- Initial recoveries of fertiliser P applications averaged only 4%, so showed massive scope for improvement through both
    - Innovations in products and practices that increase P recovery by crops,
    - Use of materials containing recycled P.
- Many fertiliser and crop nutrition companies are working to improve P efficiency, and this project developed testing sites where such new products and practices

[2] AHDB Projects RD-2007-3454, RD-2008-3554 & RD-2160004 respectively.
[3] 3,200 mg/kg, 3,200 ppm or 3.2 g/kg
[4] 'Having a crop P content at which further P uptake, by whatever means, is likely to enhance crop yield or value.'

could be independently validated in future. Fair and independent testing is the key requirement for improving the efficiency and cost-effectiveness of P use.

The whole farming industry needs to recognise the need for improved sustainability of, as well as returns from, its P use, and to become engaged in making improvements. Key routes to preserving global P resources and reducing P pollution are maximising P recycling and reducing soil P content.

The widespread P deficiencies, the significant uncertainties about soil P interpretation and the very poor crop recoveries of P from fertilisers all suggest that AHDB's Nutrient Management strategy for arable agriculture needs to be comprehensively revised such that its emphasis becomes focussed much more firmly on ensuring crop P sufficiency, rather than on soil P fertility, with crop P status being assessed routinely, especially if circumstances indicate P deficiencies to be possible.

At the same time, a new industry-wide 'P Efficiency Network' is proposed, designed to facilitate on-farm P monitoring, and to support the development and testing of new products and practices with potential to enhance direct recovery of P by arable crops; the network's aim would be to improve both the cost-effectiveness and the sustainability of P use in UK agriculture.

1 Introduction

The overall aim of this project was to maximise the cost-effectiveness of phosphate management on UK arable farms, by:

- improving our understanding of the factors affecting rates of change in soil P status with P additions from both fertiliser and organic P sources,
- providing robust evidence on critical levels of soil P for modern combinable crops,
- maximising and determining the value of fresh fertiliser P applications in terms of crop yield and quality under varying levels of soil P fertility.

The project integrated and developed previous research themes on managing soil P and forged partnerships with arable farming stakeholders so as to enable effective transfer of the results into practice. The project had three work-packages (targeting the three bullet points above), the first two of which have already been reported (Rollett *et al*., 2017; Morris *et al*., 2017), so this final report focusses on Work-Package 3 (WP3), and then provides an over-view of conclusions from all three work-packages. Before introducing WP3, the abstracts of the first two work-packages are repeated below.

1.1 WP1 abstract: Apparent Soil Phosphate Requirements

Two datasets, one experimental and one commercial, were analysed to explore how changes in soil phosphorus (P) related to phosphate (P_2O_5) balances (inputs minus crop offtakes) maintained on arable land. At each location an ‘apparent soil P_2O_5 requirement’ (ASPR) was determined, being the average P_2O_5 balance (positive or negative) relating to a soil P change of 1 mg/l.

First, results from seven long-term experiments (funded by MAFF/Defra and managed by ADAS since the early 1990s) were used to assess effects of manufactured fertilisers and organic materials (i.e. farmyard manure, slurry, poultry manure and biosolids). These provided regular measurements of Olsen P status plus annual measurements of P_2O_5 inputs and offtakes from replicated treatments. Data from the site testing triple superphosphate fertiliser (TSP) suggested an ASPR of approximately 68 kg/ha/mg/l, whereas experiments testing livestock manures suggested an ASPR of approximately 105 kg/ha/mg/l. This difference may be due to the lower availability of P in livestock manures (50-60%) compared to manufactured fertilisers (TSP >90% available). No ASPR could be determined for sites testing biosolids, probably because of their high soil P (P Index 3 or 4).

Secondly, a large dataset of about 6,500 spatially-defined points was collated from the precision farming support company SOYL, relating to 36 farms with sampling positions where combinable crops had been grown, that had not received organic manures, where two successive soil analyses had been undertaken, and for which crop types and fertiliser recommendations were known. Initial soil levels ranged from P Index 0 to Index 7, with a median of 18 mg/l, i.e. Index 2. Positive P_2O_5 balances had been maintained at points below soil P Index 2 and negative at or above Index 2, thus the majority of P_2O_5 balances were negative (mean -6 kg/ha/year). However, the majority of repeat soil analyses after 4 or 5 years showed positive changes in soil P (mean +0.4 mg/l/year). There were no significant differences in ASPR between soil types but many farms showed significant differences in ASPR, most ranging between 10 and 30 kg/ha/mg/l. It is concluded that soil P comparisons through time cannot be taken as reliable, but that spatial comparisons of soil P, within farms, may be useful in improving future P fertiliser management strategies farm by farm.

Overall conclusions from this Work-Package are that:

- Farms should strive to maintain as consistent an approach to soil sampling and analysis as possible. Nevertheless, the precision of soil P testing should never be over-estimated.
- There is a case for an agency to provide quality assurance of soil P testing (including sampling and interpretation, as well as lab analysis) on behalf of the industry nationally, for instance so as to alert the industry of any drift in national soil P results.
- On many farms, it appears that soils have been more responsive to phosphate additions or removals than the value suggested in RB209 (40 kg P_2O_5 per hectare per mg soil P per litre).

Hence, where farms have enough data, they should calculate their own ASPRs, so that they can deduce more accurate P_2O_5 management strategies.

1.2 WP2 abstract: Critical levels of soil P Abstract

The WP2 report updates the findings from a previously reported project (Knight *et al*., 2014) by adding a further three years of new data obtained for three of the six original field experiments. Outputs from this project contributed to the revision of phosphate management advice for cereals and oilseed rape within the AHDB Nutrient Management Guide ‘RB209’ (AHDB, 2017).

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 i.e. 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, three of these experiments were continued for a further three years and are reported here. 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 had been established with varying amounts of TSP being applied to create a range of Olsen P levels within each experiment. 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.

Results over the 32 site years, from up to six sites suggested that current advice to maintain soils at P Index 2 for combinable crops will ensure that yields are not significantly limited by P availability, and that other agronomic inputs, especially nitrogen fertiliser, will be 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 critical P levels 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, but not obviously, to soil conditions or other crop or site factors. Maintaining all fields for combinable cropping at below soil Olsen P Index 2 has been shown here to risk significant loss, but in the right circumstances (only autumn-sown combinable crops are planned, soil conditions are generally good, fresh P is applied annually, or the soil is calcareous) 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 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 when 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 AHDB 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 4.4-6.1 kg/t for wheat, compared to 7.8 kg/t stated in RB209. On farms, where maintenance dressings are 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 is 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.

1.3 Introduction to WP3: Improving the efficiency of fresh P applications

Based on a wide-ranging review of the literature, Edwards *et al*. (2013) concluded that reliance on soil P storage rather than on fresh P arises due to poor capture of freshly-applied P by plant root systems and rapid immobilisation of plant-available P into less available forms in the soil matrix. Soil structure, moisture, temperature, pH and redox conditions all constrain P supply from soil to root. Edwards *et al*. point out that growers have some justification for low confidence in current soil P tests because several decades have elapsed and several significant technical changes have occurred since the methods were developed; thus at least some on-farm P use may be inappropriate and unprofitable.

These authors also raise concerns about reliance on the balance method to assess efficiency of fertiliser P use, and suggest, that after further R&D, there might be scope to improve efficiency by aiming to feed the crop rather than the soil. They propose three key strategies to improve sustainable P use: (i) minimising crop P requirements, (ii) maximising root recovery of soil P, and (iii) developing targeted fertiliser technologies with as complete P recovery as possible. To facilitate this, they advocate that a network of long-term experimental sites should be developed and sustained to facilitate development and validation of more efficient P fertilisers and P-efficient varieties.

Organic materials are becoming increasingly important, but are a somewhat neglected component of P-balances; it should be noted that c.60% of total P inputs to arable land are derived from organic materials (c.35% from livestock manures, 20% from biosolids and 5% from compost and various digestates). RB209 recommendations are that fresh P additions cannot fully make up for residual soil P i.e. crop yields on soils at P Index <2 are inevitably reduced, irrespective of fresh fertiliser P applications. However, results so far from the Critical P project (Knight *et al*., 2014) have not necessarily supported this.

Edwards *et al*. (2013) suggest that integrated P management strategies might include use of P fertiliser placement, seed P coatings, foliar P applications, re-cycled products, and products that modify soil P availability; these might provide many potential opportunities to improve fertiliser P recovery, so these should be developed further, and particularly targeted to meet crop P demand at the most susceptible stages (i.e. establishment to stem extension), so as to reduce reliance on soil P fertility. However, Edwards *et al*. (2013) point out that new high-precision field experiments are required to provide confidence in the efficiencies of any P targeting technologies.

The Targeted P Project (Sylvester-Bradley *et al*., 2016) made an initial attempt to explore whether more efficient fresh P applications could overcome the need to maintain soil P Index at 2. Two field trials with barley at P Index 1, and some pot experiments, showed advantages of placing rather than broadcast-incorporation of fresh P. Results with Avail-treated TSP were mixed, but more promising results were achieved with the recycled-P product Struvite, especially if placed. Thus the research in WP3 reported here was originally funded and undertaken to enable growers to know the best way(s) to apply fresh P, and its cost effectiveness.

Three multifactor experiments were originally proposed, to augment the experiments on fertiliser products and application methods completed in the Targeted P project (Sylvester-Bradley *et al*., 2016). However, the 'run-down' treatments in the four trial sites inherited from the Targeted-P Project (on which these multi-factor experiments were due to be conducted) proved to take considerably longer than anticipated to run-down from soil P index 2 to P Index 1. Funding for WP3 was therefore re-allocated during the project so that these four sites could be run-down for longer, and no multifactor experiments were undertaken. With this change, the time-course of P run-down from Index 2 could be studied over a six or seven year period and run-down rates could be compared with the notion of Johnston *et al*. (2016) that, under annual cropping without P applications, soil P has a 'half-life' of about nine years, deduced from several sites managed by Rothamsted Research through the past century.

Additionally, the series of simple tramline trials originally proposed in WP3 went ahead, to extend to a wider range of soils and growing conditions earlier findings on fertiliser placement (Sylvester-Bradley *et al*., 2016). These were multi-collaborative field-scale trials conducted using precision-farming techniques; the repeated measures possible with yield-mapping combine harvesters were expected to enable up to 20 low-cost tests of yield effects of P fertiliser placement. SOYL undertook to identify sites with a range of soil types and/or soil P levels. Then Frontier undertook to manage farmer liaison, treatment verification and yield verification, with ADAS analysing the data.

Concurrent with this project, ADAS and partners developed new techniques, including new statistical methods, to analyse data, particularly grain yields, from farmers' tramline comparisons such as those set up by Frontier here. Availability of these new methods was not assumed at the outset of the project but since they have recently been published (Marchant *et al*., 2019), they were applied to most of the datasets (those with GPS information) from the Frontier-managed trials.

In summary, having shown (in WP1) that there is significant farm-based variation in rates at which soil P may change and then (in WP2) that 'critical' soil P levels (needed for crops to be unconstrained by P supply) also vary significantly, WP3 was undertaken to (a) explore the time-course of soil P run-down from P Index 2, whilst setting up land where P-efficiency testing could be undertaken in future, and (b) to test whether fertiliser placement improved the effectiveness of water-soluble P fertilisers.

Two additional issues arose as a result of the WP3 research which could be explored from data created within this project, so the initial aims of WP3 were augmented by posing two additional questions: (i) whether rates of soil P run-down of soils only recently raised to P Index 2 differed from those where soils had been maintained at P Index 2 (in WP3), and (ii) whether the grain P level at which grain yields maximised (in WP2) showed any consistency across sites and seasons, thus whether a critical grain P level could be identified, for retrospective diagnosis of crop P deficiencies. The idea emerged during the project of using P levels in harvested biomass to retrospectively gauge whether crops had been deficient in P supplies during their grown. It was suggested that this approach might complement the use of soil P analysis to gauge crop P sufficiency. Before this project, data relevant to this idea had only been found in the literature for crops that were low yielding and in contrasting conditions to those of the UK (see Sylvester-Bradley *et al.*, 2016, section 6.4.1, pages 115-120).

Finally, as this project integrated the main research strands that had been undertaken on arable P management in the UK over the past decade, and since the principal independent research groups (ADAS, NIAB, Rothamsted Research, and Bangor University) all collaborated within this project, the members of the steering group for this project set out some integrated suggestions on how current fertiliser recommendations might be revised in the light of all their recent research and, more pertinently, they outlined a strategy whereby the UK's arable industry might develop its P management most expeditiously and cost-effectively into the future, so that progress toward greater sustainability and profitability can be made as quickly as possible.

2 Materials and Methods

2.1 WP2: Soil P run-down

In order to compare and contrast P rundown of soils that had only recently been built up with that of soils that had recently been maintained at P index 2, data from the three sites (Peldon in Essex, Great Carlton in Lincolnshire and Cholsey in Oxfordshire) that were funded during this project were collated from the Appendix of the WP2 report (Morris *et al.*, 2017), graphed and analysed by regression to determine rates of change in soil P.

2.2 WP2: Grain P analysis

All grain yield and grain P data from WP2 were collated and used to estimate standard values for grain P offtake under Project 91110003 (Rollett *et al.*, 2018). These grain P data were then reanalysed in relation to the respective grain yields and grain yield responses to fresh P in order to explore the extent to which grain P might be used to indicate deficiencies of P supply and perhaps suggest a critical value for grain P (analogous to a critical value for soil P, as was the original aim of WP2). Whilst all details are provided by Morris *et al.* (2016), it should be noted that:

- Grain samples for harvest years 2014, 2015 and 2016 were tested straight after harvest, with no storage, but samples from 2013 were tested in 2016, having been stored for three years.

- Also, the analytical laboratory (NRM laboratories) changed their grain P analysis procedures between 2014 and 2015, and measured consistently more P in grain as a result. Thus values for 2014 can be compared internally, but will be less than from harvests 2015 and 2016.
- The rate of fresh P applied to the 'fresh P' sub-plots was intentionally large (200 kg/ha P_2O_5) and was repeated to these same sub-plots in each autumn of 2011, 2012, 2014 and 2015.

2.3 WP3 Run-Down experiments

2.3.1 Site selection

Soil P run-down experiments were established at four sites in 2010 or 2011 (Table 1) as part of the LINK 'Targeted P' project (Sylvester-Bradley *et al*., 2016). Sites were chosen to have a starting Olsen P level of c.20 mg L-1 (mid P Index 2) and to represent a range of soil types and climatic conditions. Soil P levels were monitored for five years (2010-2015) during the Targeted P project and then during the current project (2016-2019).

Table 1. Run-down site locations, soil types and initial soil P levels (all Index 2)

Site	**Soil type**	**Initial soil sample date**	**Initial Soil P, mg L^{-1}**
Boxworth, South Cambridgeshire	Clay loam	26 Nov 2010	24.0
Stetchworth, East Cambridgeshire	Sandy loam	16 Feb 2012	19.4
King's Pyon, Herefordshire	Silty clay loam	3 Mar 2011	16.4
Modbury, Devon	Silty clay loam[1]	24 Sept 2010	20.7

[1]The soil series at Modbury is Denbeigh, described as a silty clay loam over Devonian shale and slates, and is considered to be a P-fixing soil.

2.3.2 Experimental treatments & assessments

At each site, eight large plots (c. 0.5 ha) were established in 2010 or 2011. Four of the plots were fertilised annually in order to maintain soil P at Index 2, whilst the other four plots received no P fertiliser inputs. All sites were cropped according to the on-farm rotation (Table 2).

Annual fertiliser P input requirements were estimated, based on RB209 recommendations, and broadcast as TSP, typically before autumn cultivations. Plot-specific crop yields and P concentrations were not measured from 2011 to 2016 so, to estimate the crop P offtakes (and hence fertiliser P requirements), average crop yields for each farm were multiplied by standard P concentrations from RB209 (Defra, 2010).

For harvests in 2017 & 2018, harvest yield was estimated using five randomly placed 0.25 m^2 quadrats per plot. The crop was sampled from ground level, separated into grain and straw fractions, weighed (fresh weight) and then dried (80°C for 24 hours) before being reweighed (dry weight). Samples were sent to the laboratory to measure P concentration in the straw and grain fractions.

Table 2. Crops grown in harvest years 2011 to 2019, and mean rates of P applied as TSP to the 'maintenance' plots at the four Run-Down Experiments. (NB: W, winter; Sp, spring; OSR, oilseed rape; Bn, Beans; cer, cereal; by, barley; G, grass; wt, wheat; Lin, linseed; SBt, sugar beet; Trit, Triticale).

Site	2011	2012	2013	2014	2015	2016	2017	2018	2019
S. Cambs.	WCer	WWt	WOSR	WWt	WBy	WBn	W Wt	SpBy	WOSR
E. Cambs.	-	SpWt	SpBy	WBy	SBt	SpWt	Peas	WWt	SBt
Herefords.	SpLin	Lin	WWt	WWt	WOSR	WWt	Trit	GLey	GLey
Devon	WOSR	W Wt	WOat	WWt	WOSR	WWt	WOat	WWt	WOSR
					P applied, kg ha^{-1}				
S. Cambs.	26	26	33	26	26	17	26	22	22
E. Cambs.	-	33	33	35	22	22	17	28	22
Herefords.	39	13	48	39	22	28	20	33	TBC
Devon	22	28	33	39	22	28	24	28	22

To assess the progress towards the target soil P indices [i.e. with 'maintenance' plots all at P Index 2 and 'run-down' plots all at P Index 1], soil samples were taken from each plot after harvest at the end of each growing season, and were subjected to Olsen's analysis (at the NRM labs.) for soil P.

2.4 WP3 Tramline trials on phosphate placement

2.4.1 Site selection

Over the four seasons of harvest years 2015-2018, eight farms were selected which had a combine drill (able to place fertiliser close to the seed), had suitable fields with soil nutrient maps showing low or variable soil P, and had yield mapping capability. Twelve fields were selected over the four seasons where a cereal was due to be grown and where organic manures had not been applied recently. Sites (coded by their harvest year and post-code) were as follows and are mapped in Fig. 1.

2015 NN7: Lodge Field, Courteenhall, Collingtree, Northants (SP 75072 54312)
2016 CB21: Heath field, Bartlow Estate, West Wickham, Cambridgeshire (TL 57140 44222)
2016 NN7: Sharman's Barn field, Courteenhall, Collingtree, Northants (SP 76476 52474)
2016 CM5: Further Field, Schwier Farm, Fyfield, Essex (TL 55728 07685)
2017 CB21: Oaks Field, Bartlow Estates, Bartlow, Cambridgeshire (TL 57140 44222)
2017 NR21: Long 13 field, Manor Farm, Barsham, Walsingham, Norfolk (TF 91883 36848)
2017 CT15: Coleman Field, Ashely, Ripple Farms, Kent (TR 30274 48786)
2017 PE8: Airfield, Hemington Lodge Farm, Hemington, East Northants (TL 10260 86013)
2017 NN7: Great Holt field, Quinton, South Northants (SP 77708 53746)
2018 SO24: Slipsgate field, Newhouse Farm, Northington, Alresford, Hants. (SU 55609 37822)
2018 CM5: Gypsy Field, Nether Hall Farm, Fyfield, Essex (TL 56153 06965)
2018 LE10: Field BW-D, Burton Fields Farm, Burton Hastings, Leics. (SP 41801 90308)

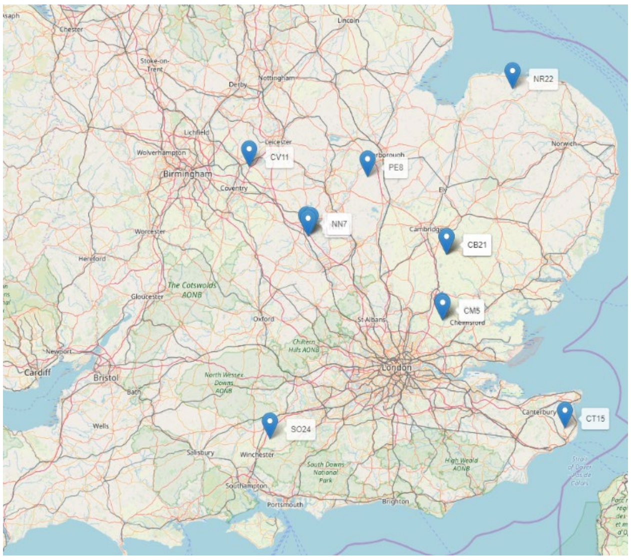

Figure 1. Locations of 12 tramline trials on P placement, 2015-2018; CB21 & CM5 had two trials and NN7 had three trials.

2.4.2 Treatments

Trials were set up at drilling with two or more of the following treatments:

1. Nil P applied
2. ~20 kg/ha P_2O_5 placed
3. 70 kg/ha P_2O_5 placed
4. 70 kg/ha P_2O_5 broadcast

The standard farm practice of P application was considered as a separate treatment where this differed from all the above treatments. A few farms used only two or three of these treatments and farm CB21 used liquid fertiliser and compared treatments as follows:

1. Nil P
2. 20 kg/ha P_2O_5 placed (with 7 kg/ha N)
3. 40 kg/ha P_2O_5 placed (with 14 kg/ha N)

Widths of drills, sprayers and harvesters differed between farms so arrangements of drilling, tramline separation, treatment allocations and harvesting protocols differed between farms but were arranged to allow some replication and fair comparisons between treatments. However, treatment allocations to tramlines were regular rather than random, it being assumed that inherent variability in measurements could be detected and accommodated using spatial analysis techniques (see below; Marchant *et al.*, 2019). In most cases, quantitative tramline comparisons were being made by protagonists for the first time, availability of suitable sites was limited, and many lessons were learned about the various aspects of successful research using this large-scale ‘Agronomics’ approach: farm choice, farmer-experimenter communications, field choice, optimum allocation and orientation of treatments for comparisons being made at tramline scale, data transfer and reporting.

2.4.3 Measurements and data analysis

Maps of soil P (and soil K, Mg and pH) were provided by SOYL, having been sampled according to their standard protocol (samples being taken on a 100m x 100m grid, with each sample composed of 20 cores taken to 15cm depth), and analysed using Olsen's method of analysis by NRM.

Grain yields were determined by farms' own combine harvesters, records being derived from the integral yield monitors and GPS sensors fitted on those harvesters. Data were then transferred from the farms (or their data stores) to ADAS where they were uploaded into their Agronomics database. Except for the first trial in 2015, grain yields were analysed using the ADAS Agronomics portal and Graphical User Interface (GUI) for which processes are described in full by Marchant *et al*. (2019).

In brief, the yield data were first corrected to 15% moisture, cleaned to remove headlands, anomalous combine runs (header not full or spanning two treatment areas) and locally extreme data points, and to correct inaccurate GPS data and any offset created by changes in combine direction. Each data-point was then allocated to a treatment; note that harvester bouts containing wheelings were generally included in the remaining data. On occasion (e.g. with John Deere harvesters), the resulting number of data exceeded the capacity of the Agronomics software, in which case neighbouring data-points were averaged to halve (or more) the number of data. The resulting thousands of yield data-points per field were deemed as 'processed' and were summarised with averages and standard deviations.

Then a model of underlying variation was applied to the data to account for spatial variation across and along rows, and to test for any additional effects of the treatments. Treatment comparisons involved two approaches considering:

(i) All data-points within all replicates of each treatment area, here called 'Spatially Corrected Differences' (SCD). This returned treatment effects and estimates of 95% confidence limits (as least significant differences; 'LSD's). Note that, because of spatial correction, estimated effects of treatments delivered by this approach differ from the direct arithmetic differences between mean yields of treatments, estimated directly from the processed data, as above.

(ii) Differences along treatment boundaries using 'Spatial Discontinuity Analysis' (SDA). This approach was only used where approach (i) proved inconclusive, or where an interaction with inherent spatial variation was suspected e.g. due to soil P fertility; this approach returned graphs of differences by distance along the treatment boundary with 95% confidence limits. The confidence limits depend on the distance over which comparisons are made; i.e. the longer the length of boundary being compared, the smaller the confidence limits and the more confidence applies to the comparison. Uncertainty in comparisons made over small distances of 2 to 10m were always large, and such small distances were not thought relevant to commercial practice so comparisons were made over 50m, the longest length estimated in the software.

3 Results

3.1 WP2: Soil P (mg/l) run-down rates after recent build-up with fresh P

Annual soil P data were available for each 'large plot' (18m wide x 10m long) at each of the three sites. Data were taken from all 18 large plots per site, 10 of which received fresh fertiliser P in autumn 2009, and none of which received fertiliser P thereafter. As stated by Morris *et al*. (2017), treatment allocation to these plots was not randomised but was selected to achieve specific target soil P levels after equilibration. However, no relationship between initial soil P and intended increase in soil P was evident at any site (Fig. 2), and the range of initial soil P was small at each site (Peldon, 7-14 mg/l; Great Carlton, 9-14 mg/l; Cholsey, 4-6 mg/l) relative to the increases in soil P intended (3-24 mg/l) so any confounding of P rundown rates with initial P was deemed small enough to ignore.

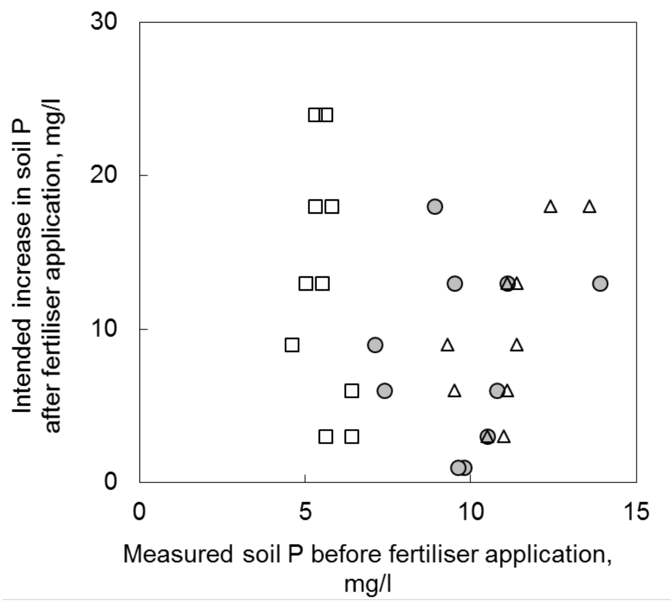

Figure 2. Allocation of fertiliser treatments in 2009 (indicated by intended soil P levels after fertiliser application) at Peldon (circles), Great Carlton (triangles) and Cholsey (squares) according to soil P levels measured before fertiliser application.

Soil P data from all large plots receiving fertiliser P in the autumn on 2009 are shown in Fig. 3. Data from 2011 to 2016 were analysed by regression for each plot separately (omitting 2010 because soil P levels were deemed to be still equilibrating within a year of fertiliser application) to give a fitted soil P value for 2010, and a rate of soil P run down.

There were clear, statistically significant relationships between initial soil P levels and run down rates at all three sites, with slopes between -0.08 and -0.14 year^{-1}. Thus, for the range of initial soil P values, recently created using fresh fertiliser P at these three sites, the half-lives ranged between 3.5 and 6 years (Fig. 4). These can now be considered with the results from WP3 where, over the same seasons, but at four different sites where farming strategies had been to maintain soils at P

Index 2, crops have been grown without any additional P, and soil P levels have been measured annually.

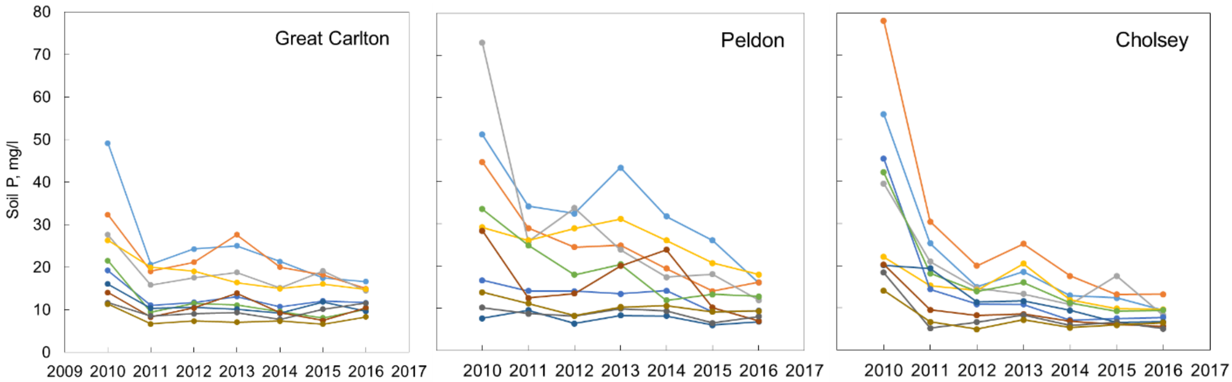

Figure 3. Soil P levels through time at the three sites described in WP2 (Morris *et al.*, 2017).

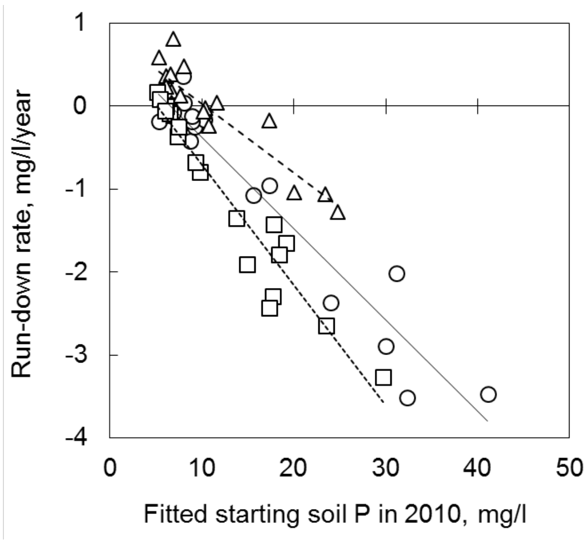

Figure 4. Linear trends of fitted run-down rates in soil P at Peldon (circles, full line), Great Carlton (triangles, dashed line) and Cholsey (squares, dotted line) with fitted values of soil P in 2010. Slopes indicate average half-lives of 4.5, 6.0 and 3.5 years respectively.

3.2 WP2: Interpretation of grain P

3.2.1 Grain yield and grain P as affected by soil P supply

The Critical P dataset contributing to the review of P & K offtakes by Alison *et al*. (2018) contained 426 values for grain P without fresh fertiliser P being applied and 195 values after use of fresh fertiliser P. These arose from four harvest years at Peldon (2013-2016), three harvest years at Great Carlton (2014-2016) and six harvest years at Cholsey (2010, 2011, & 2013-2016). Almost all grain P values could be associated with a grain yield. Crops were all of winter wheat except at Cholsey in 2015 (oats) and Great Carlton in 2016 (barley).

Overall, grain P values ranged between 0.14% and 0.39% (Fig. 5). These were low compared with 0.40% P assumed as the average content of cereal grain in RB209 (equivalent to 7.8 kg P_2O_5 per tonne grain at 85%DM). Responses in grain P to the large dressings of fertiliser P applied in autumn of 2009 are represented by the x-axes in Fig. 5; they were observed in all crops and were generally large averaging +0.18% at Peldon, and +0.23% at both Great Carlton and Cholsey i.e. almost doubling the minimum untreated values on most occasions.

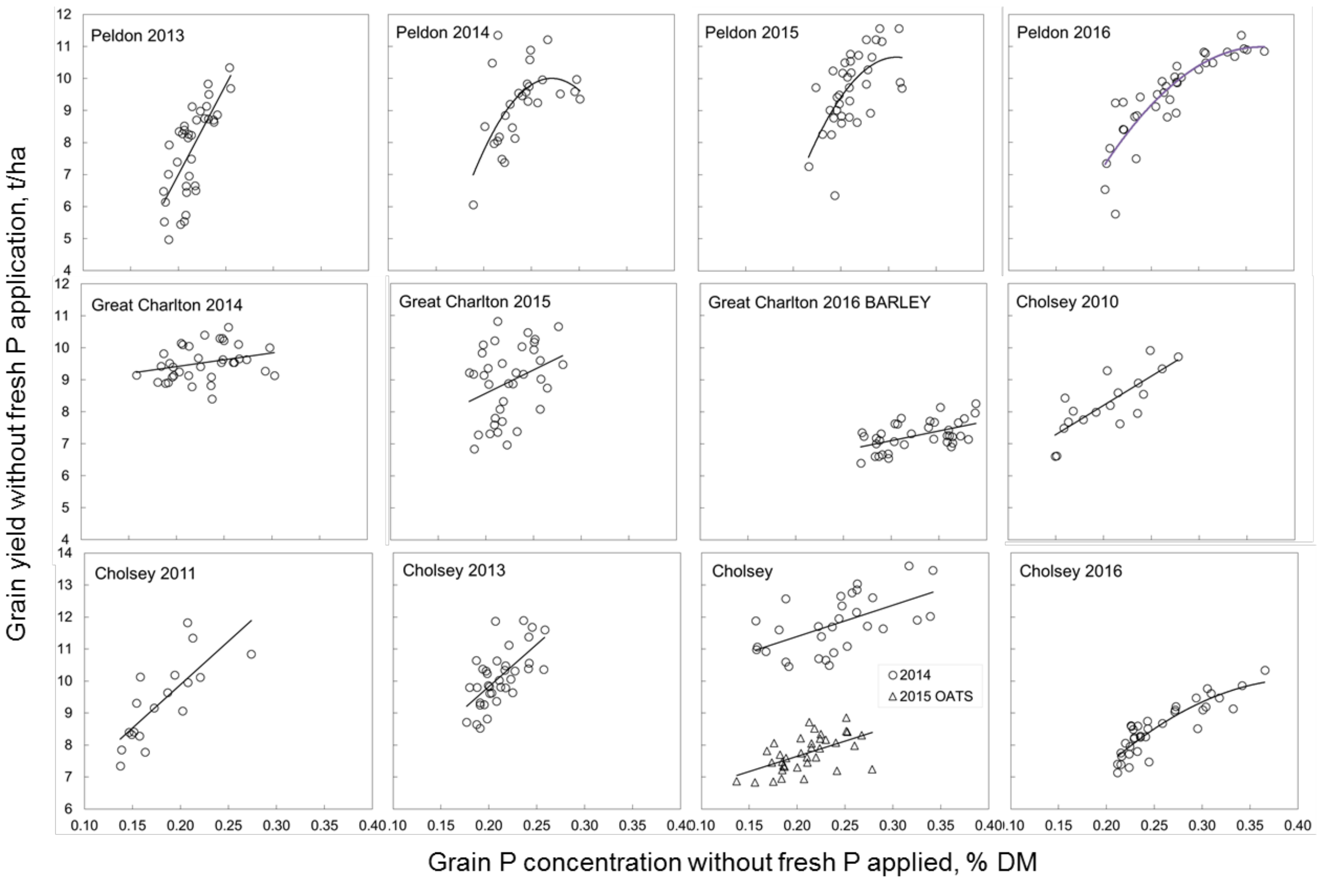

Figure 5. Trends with grain P in grain yields without fresh applications of P for all 13 site-seasons in which grain P was measured, showing significant trends at P<0.1 (R^2 >0.14).

Grain yield responses were similarly positive and large; based on the fitted relationships in Fig. 5, grain P increases of +0.1% (from 0.2 to 0.3%) were associated with grain yield increases of 3.7 t/ha at Peldon, 0.8 t/ha at Great Carlton, and 1.8 t/ha at Cholsey. Yield responses of the two crops of barley and oats were somewhat smaller than those of winter wheat, but this may have occurred by chance.

3.2.2 Grain yield and grain P as affected by fresh fertiliser P

Compared to the effects of 'soil P', effects of annual applications of fresh P were relatively modest (Fig. 6).

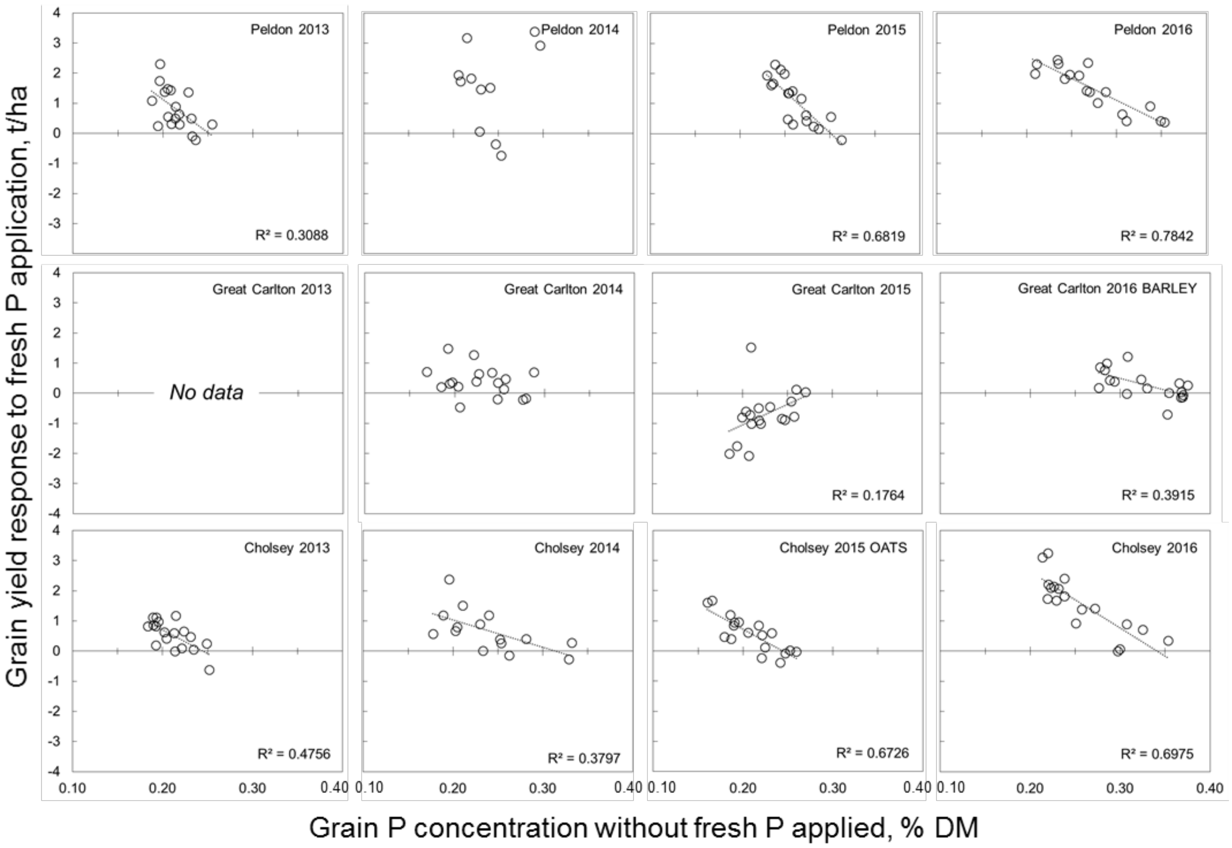

Figure 6. Grain yield responses to fresh applications of P for all 11 site-seasons in which grain P was measured, as they related to grain P without fresh fertiliser P applied, showing significant trends at P<0.1 (R^2 >0.14).

Effects on grain P were +0.04% at Peldon and Great Carlton and +0.06% at Cholsey. The effects on grain yield were generally positive and significant; however, at Great Carlton there was no significant pattern with grain P effects in 2014, there was a puzzling negative relationship with grain P in 2015 and the expected negative relationship between yield increases and untreated grain P effect was only small for the barley crop grown in 2016. There were also some puzzlingly large positive effects of fresh P on grain yield at a few plots at Peldon in 2014. Nevertheless, overall Fig. 6

shows that yield responses to fresh fertiliser P did generally relate in the expected negative way to grain P contents of the untreated crops, such that crops with larger grain P were less responsive to applications of fresh fertiliser P.

3.2.3 Critical values of grain P?

It is now possible to summarise all grain P data available from the three ‘Critical P’ experiments and to discuss and decide whether and how to use grain P analysis to detect whether crops are deficient in P (as an additional tool to soil P analysis). The total of over 600 values from three widely dispersed sites over six recent seasons represents a significant body of evidence. All the pertinent data are summarised in Table 3.

It is clear that crops experienced marked P deficiencies at each of the three sites in almost all seasons for which data are available – crop yield responses to soil P were large and to fresh P were also economically as well as statistically significant. [The only exception was Great Carlton in 2015 where the yield response to soil P was barely significant (Fig. 5) and the yield response to fresh P was significantly negative (-0.71 t/ha), despite the grain P response to fresh P being ‘normal’ (+0.04%); possibly this crop experienced deficiency of an additional nutrient which was exacerbated by the application of fresh P?]

Examining the ‘soil P’ treatments, both grain yield and grain P showed strong positive effects in all crops, with only four crops demonstrating any diminishing relationship between grain yield and grain P (Fig. 5; Table 3); so most crops continued to respond right up to the maximum level of soil P supply. Note that, due to the analytical and sample storage issues explained in Section 2.2, absolute values of grain P should be expected to be less for 2014, and possibly also for 2013, than for 2015 and 2016.

Grain yield responses only began to diminish with grain P at four sites, so grain P optima for grain yield could only be determined in these cases; they ranged between 0.27% (Peldon 2014) and 0.41% P in grain DM (Cholsey, 2016; although the latter value was determined by extrapolation from a maximum value of 0.37%). Grain yield responses with increasing grain P (say from 0.20% to 0.30%) were large at almost all sites, ranging from +0.4 t/ha at Great Carlton in 2014 to +5.6 t/ha at Peldon in 2013, and averaging +2.2 t/ha overall; the mean yield response associated with increasing grain P from 0.25% to 0.30% was smaller but nevertheless still sizable at +0.90 t/ha (Table 3). If the optimum grain P values here are taken as ‘critical’ grain P values for grain yield (or maximum grain P values are considered to be conservative estimates, where optima were not determined), then the ‘mean critical grain P value’ from the 13 site-seasons here was 0.31% (±0.051%; Table 3).

Turning to the analysis of yield responses to fresh fertiliser P, it was remarkable, given the variability in these field data, that almost all datasets showed the negative relationship between grain P without fresh fertiliser P applied, and yield responses to fresh P (Fig. 6), as would be required if grain P were to be considered a useful tool in predicting whether fresh P applications would be worthwhile. Indeed it was encouraging that it proved possible to estimate intercepts on the x-axes of the most graphs illustrated in Fig. 6; since these can be taken as another estimate of 'critical grain P'. Eleven such estimates were made of which one (at Peldon in 2014) was particularly uncertain (Table 3); these ranged from 0.24% at Cholsey in 2013 to 0.38% at Peldon in 2016.

Table 3. Summary of grain P (% DM) and yield responses associated with grain P values at three sites where large fertiliser P applications were used in autumn 2009 to create a range of 'soil P' levels from Index 0 to 2 or more, and where large 'fresh P' applications were made on a subset of plots. Values are shown both without and with 'fresh' fertiliser P.

Site	WITHOUT fresh P					WITH fresh P			
Harvest year	No. values	Min. grain P, % DM	[1] Yield model form & R^2 with grain P	Max (or Opt) grain P, % DM	[2] Yield (t/ha) with +0.05% grain P	No. values	Yield model[1] with grain P, R^2	Yield (t/ha) with +0.05% grain P	[3] Grain P (% DM) for nil yield response
Peldon, Essex									
2013	36	0.184	L 0.53	0.255	2.82	18	0.309	1.10	0.251
2014	36	0.189	Q 0.37	(0.271)	-0.17	18	0.034[4]		0.248[4]
2015	36	0.216	Q 0.41	(0.308)	1.22	18	0.682	1.38	0.301
2016	36	0.201	Q 0.78	(0.366)	1.23	18	0.784	0.73	0.375
Great Carlton, Lincolnshire									
2014	36	0.158	L 0.08	0.303	0.21	18	0.076	0.20	0.326
2015	36	0.183	L 0.11	0.281	0.73	18	-0.176[4]		
2016[5]	36	0.268	L 0.28	0.389	0.31	18	0.392	0.39	0.364
Cholsey, Oxfordshire									
2010	18	0.149	L 0.63	0.278	0.91	0			
2011	18	0.137	L 0.60	0.274	1.36	0			
2012	0					0			
2013	36	0.177	L 0.42	0.258	1.32	18	0.476	0.79	0.245
2014	30	0.157	L 0.33	0.342	0.49	15	0.380	0.45	0.314
2015[6]	36	0.137	L 0.31	0.278	0.47	18	0.673	0.82	0.244
2016	36	0.212	Q 0.79	(0.407)	0.84	18	0.698	0.93	0.341
Overall site & season totals and means									
	426			0.308	0.90	195		0.75	0.301

[1] *Polynomial models were fitted to relate grain yields (Fig. 5), or in the case of fresh P to grain yield responses (Fig. 6), to grain P concentrations (untreated with fresh P) within each dataset. A linear model (L) was selected where Pearson's r was significant at P<0.05; a quadratic model (Q) was selected where this explained significantly more of the variation than the linear model.*

[2] *Yield responses to soil P (without fresh P) were determined as the difference between the fitted yields at 0.25% and 0.30% grain P from the selected model.*

[3] *These are calculated from the fitted lines in Fig. 6 as being the intercepts on the x-axes. i.e. the grain P value at which fresh P gives no positive yield response.*

[4] *All models showed significant negative relationships between untreated grain P and grain yield response to fresh P except at Peldon in 2014 and Great Carlton in 2015. Two outliers with large yield responses were removed in order to estimate the grain P for nil yield response, albeit with increased uncertainty (Fig. 6).*

[5] *Barley;* [6] *Oats.*

These ‘critical grain P’ values estimated from fresh P treatments and their mean of 0.30%, were remarkably similar to the ‘critical grain P’ values estimated from soil P treatments above, with their mean being 0.31% (Fig. 7). It would therefore appear that, using two relatively independent estimation approaches in these experiments, critical grain P values (omitting data for 2013 & 2014 because of analytical uncertainty) ranged between 0.24% and 0.38% and that, if these site-seasons can be taken as generally representative for cereal crops across the UK, there should some value in analysing grain for its P concentration, not only to support estimation of P offtakes (Alison *et al*., 2018) but also to support strategic diagnosis of crop P deficiencies-sufficiencies.

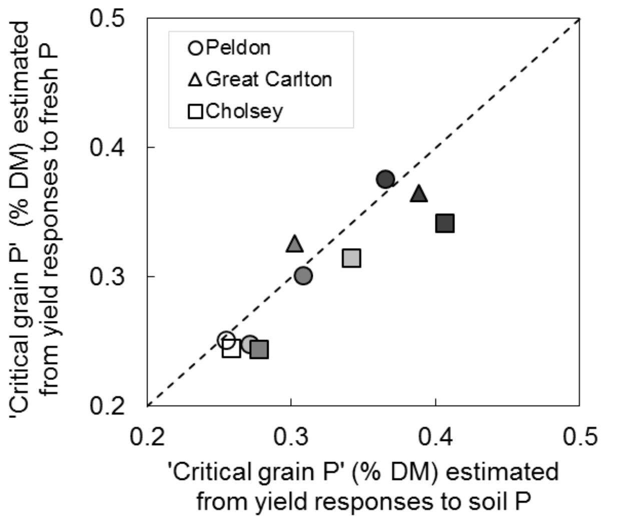

Figure 7. Congruence between ‘critical grain P values’ estimated from yield responses to soil P treatment and those estimated from grain yield responses to fresh applications of P at three sites over four seasons: (2013-2016; clear, light grey, grey & dark grey symbols respectively).

3.3 WP3: P run-down experiments

3.3.1 Soil P

Annual soil P levels for ‘maintenance’ and ‘run-down’ (nil P applied) treatments are shown for each of the four ‘Run-down’ sites in Fig. 8. With four replicate measurements in each year at each site, the precision of soil P assessments was generally good (mean SE 1.78 mg/L) so that, beyond the first year or two, clear treatment effects could be detected with confidence.

Nil ‘run-down’ treatments at the three sites that started in Index 2 (16-25 mg/L) all ran down significantly over the eight years of the experiments, if not consistently from year to year. However, the overall rates of run-down were somewhat slower than the 9 year half-life found by Johnston *et al*. (2016) at sites managed through the last century by Rothamsted Research. Soil P with the nil treatment at the Herefordshire site (which started closer to P Index 1) surprisingly tended to increase; nothing known about this site provides an obvious explanation of the increases, so further investigation appears merited. The largely similar year to year changes for both treatments at each site were generally larger than the confidence limits of the measurements, so it would appear that, although assessments were made by the same staff, with the same sampling technique, and using the same analytical laboratory at all sites over all years, there were other factors that caused annual perturbations in soil P levels, and sometimes these were major.

The maintenance treatments largely achieved their purpose at all sites, albeit that the pattern of annual changes was somewhat erratic, particularly at King's Pyon and in the last year (Fig. 8a). This last result may arise from the fertiliser P applied in spring 2018 remaining available through to autumn due to the very dry summer of 2018 and the lack of topsoil disturbance due to establishment of a herbage seed crop here. A repeat measurement will be taken in spring 2019 to confirm the soil P status prior to fertiliser additions.

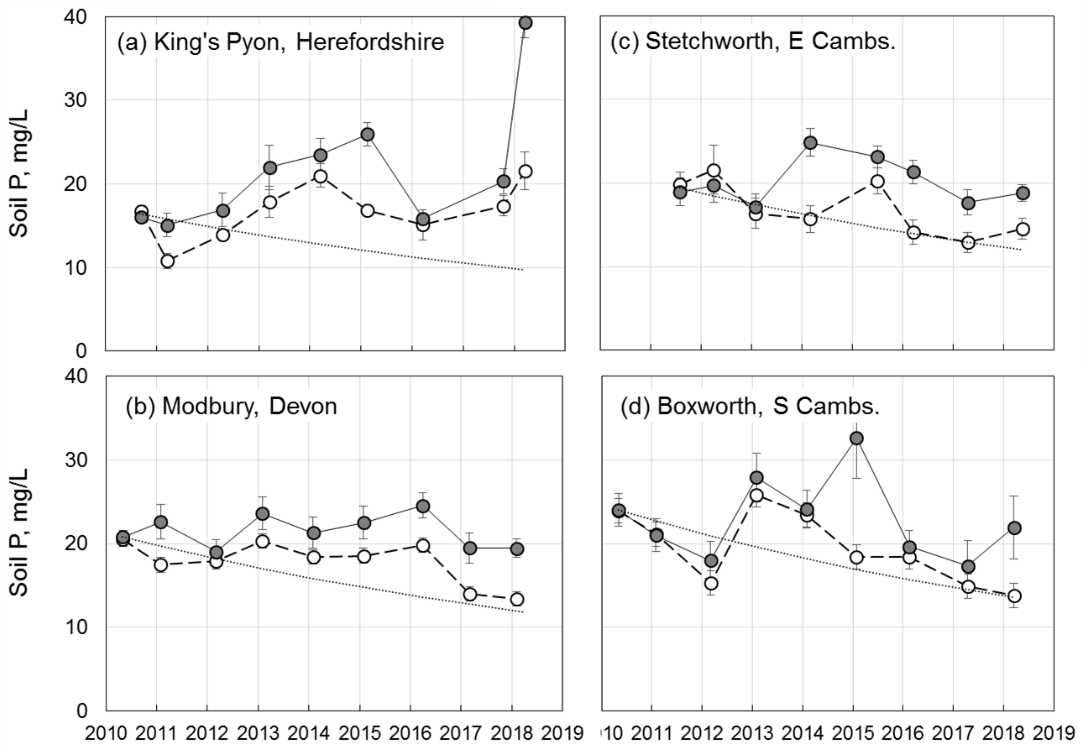

Figure 8. Levels of soil P assessed annually at four sites in the UK starting each at P Index 2 (16-25 mg/L) with annual applications of nil P (open circles) or fertiliser P to replace crop offtake (closed circles). The dotted line shows the expected soil P for the nil treatment if the soil P half-life was 9 years (Johnston *et al.*, 2016).

As regards the differences between the treatments, these arose within the first year at the two western sites, but developed more gradually at the eastern sites. Differences have not increased markedly over the past five years (Fig. 8), averaging 5.3 mg/l at Boxworth, 5.7 mg/l at Stetchworth, 6.6 mg/l (or 3.8 mg/l if the September 2018 result is omitted) at King's Pyon and 4.6 mg/l at Modbury over this period. During that time the Run-down treatments were within P Index 1 for two years at

Boxworth, for three years at Stetchworth, one year at King's Pyon and two years at Modbury; these were usually the most recent years. However, the inter-annual variation has been such that no site can be assumed to remain exactly within the narrow range of P Index 1 (10-15 mg/l) in future seasons. The minimum value recorded was 12.9 mg/l at Stetchworth in October 2017. Ignoring the King's Pyon site where soil P appears to be increasing, linear trend lines for other sites predict that run-down plots will reach the middle of P Index 1 by 2020 (Stetchworth) or 2021 (Boxworth & Modbury), and the top of P Index 0 by 2023 at Stetchworth, 2024 at Boxworth and 2026 at Modbury.

3.3.2 Crop effects

Crop measurements at these sites only commenced in 2017, when the decision was made to delay the start of multi-factor experimentation on efficient P management systems. Crop yields were reduced in the run-down treatments at Boxworth in 2017 and at Modbury and Stetchworth in 2018 (Table 4); the yield decreases ranged from 0.34 to 0.88 t/ha. In comparison, there was no difference in crop yields between maintenance and rundown treatments at Modbury in 2017 and Boxworth in 2018.

Table 4. Crop yields (t/ha @ 85% dry matter) in 2017 and 2018 at the four run-down sites. (Mt, maintenance[1]; Rd, Run-Down).

Year	King's Pyon, Herefords		Modbury, Devon		Stetchworth, E Cambs		Boxworth, S Cambs	
	Mt[1]	*Rd[2]*	*Mt[1]*	*Rd[2]*	*Mt[1]*	*Rd[2]*	*Mt[1]*	*Rd[2]*
2017	***Triticale***		***Winter oats***		***Peas***		***Winter wheat***	
Yield, t/ha	No yield data		No yield data		7.31	7.32	2.98	2.64
[SD]					[0.95]	[0.77]	[0.55]	[0.28]
Mt-Rd						+0.01		-0.34
2018	***Grass ley***		***Winter barley***		***Winter wheat***		***Spring barley***	
Yield, t/ha	No yield data		7.73	6.85	9.31	8.76	5.25	5.25
[SD]			[1.29]	[0.85]	[0.51]	[0.59]	[0.86]	[0.62]
Mt-Rd				-0.88		-0.55		0.00

[1] Mt: maintenance plots (i.e. P applied to maintain soil at P Index 2) [2] Rd: nil P applied but cropping continued as Mt.

In 2017, grain P concentrations were closely similar in the maintenance and run-down treatments at both Modbury and Boxworth (Table 5). In 2018, grain P concentrations were relatively low compared to the critical values identified in the previous section, and the run-down treatment caused reduced concentrations at both Modbury and Stetchworth. At Boxworth, grain P was greater from the run-down than the maintenance treatment, but this and other differences were generally within the confidence limits of these measurements (Table 5) so should be interpreted with caution.

These experiments are due to be maintained until after harvest in 2019, so one further year of crop data will be available. They may then offer a useful testbed in 2020 and beyond for practices and products that might enhance efficient P use; however, further funding will be required to keep these sites running beyond 2019.

Table 5. Grain P concentration (% dry matter) in 2017 and 2018 at the four run-down sites.

Year	King's Pyon, Herefords		Modbury, Devon		Stetchworth, E Cambs		Boxworth, S Cambs	
	Mt[1]	*Rd*[2]	*Mt*[1]	*Rd*[2]	*Mt*[1]	*Rd*[2]	*Mt*[1]	*Rd*[2]
2017	***Triticale***		***Winter oats***		***Peas***		***Winter wheat***	
Grain P (%), [SD]	No yield data		No yield data		0.362 [0.008]	0.361 [0.028]	0.341 [0.009]	0.340 [0.015]
Mt-Rd						-0.001		-0.001
2018	***Grass ley***		***Winter barley***		***Winter wheat***		***Spring barley***	
Grain P (%), [SD]	No yield data		0.323 [0.031]	0.305 [0.024]	0.321 [0.028]	0.273 [0.035]	0.370 [0.036]	0.413 [0.046]
Mt-Rd				-0.018		-0.048		+0.043

[1] Mt: maintenance plots (i.e. P applied to maintain soil at P Index 2) [2] Rd: nil P applied but cropping continued as Mt.

3.4 WP3 Tramline trials on phosphate placement

Each of the twelve tramline trials is described individually through the following subsections, and then data from all twelve trials are collated , analysed and discussed together.

3.4.1 2015 NN7: Courteenhall

Lodge Field on the Courteenhall Estate near Collingtree is immediately west of Junction 15 on the M1; the soil is a clay loam with P levels ranging from 17 to 30 mg/L (Fig. 9a). On 2nd October 2014 winter wheat was sown after peas with a 12m Horsch Sprinter drill, placing the seed 5cm deep, with fertiliser placed in front of the seed and 5cm below. Coulters were at 300mm centres, spreading seed across a 120-150mm band. The broadcast treatment was achieved by disconnecting the fertiliser feed to the coulters.

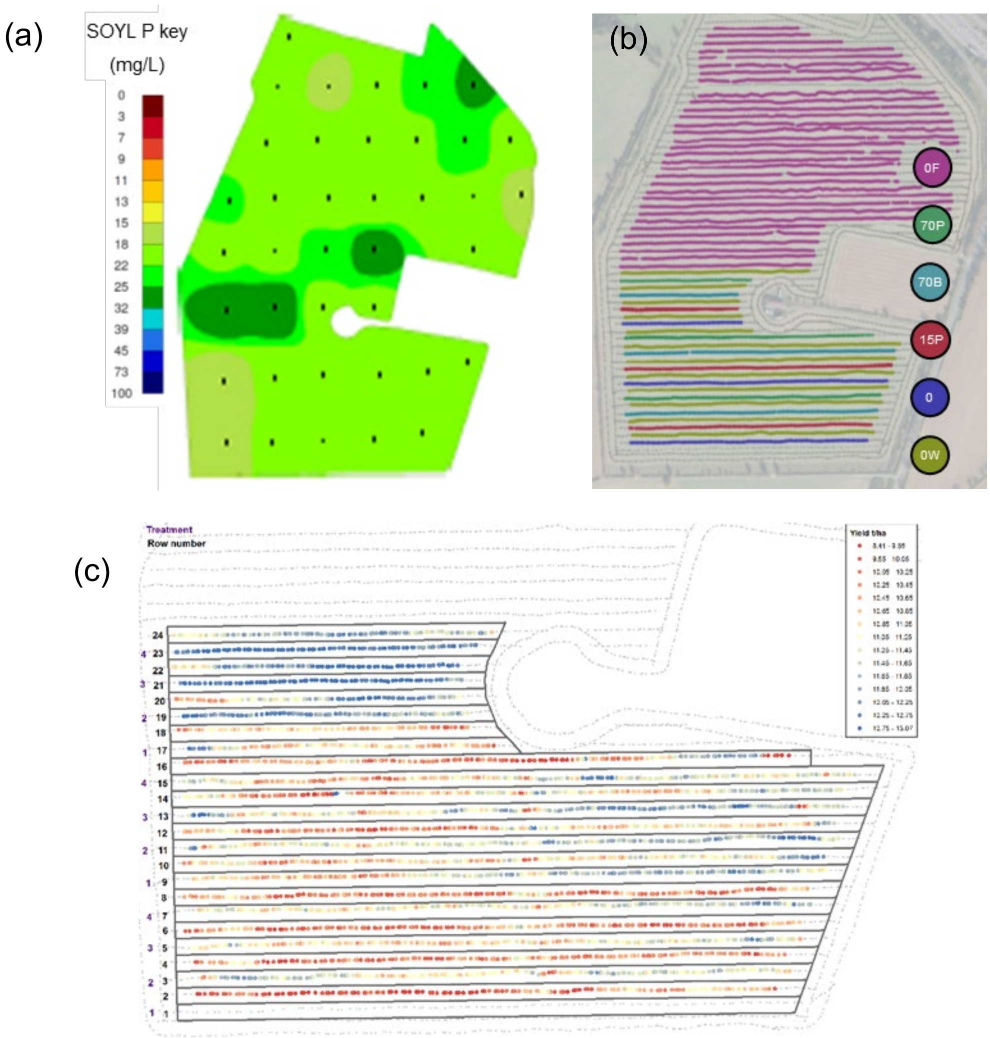

Figure 9. Maps of Lodge Field, Courteenhall showing (a) soil P levels, (b) fertiliser P treatments: 0F = farm standard treatment (nil), 0W = nil with wheeling, 0 = nil without wheeling, 15P = 15 kg/ha P_2O_5 placed, 70P = 70 kg/ha P_2O_5 placed, 70B = 70 kg/ha P_2O_5 broadcast; and (c) grain yields ranging from 9.5 (red) to 12.5 (blue) t/ha.

There were three replicates of the treatments listed in Fig. 9 but treatments were not randomised. High P fertility zones in Lodge Field lay close to the Lodge buildings in the centre of the field, and there was a smaller positive P fertility gradient from west to east within the trial area (Fig. 9a). Unfortunately treatments were laid out such that their comparison was somewhat confounded with the positive trend in soil P fertility running from south to north (Fig. 9b). However, untreated drill bouts containing the sprayer wheelings ran between each tramline treatment (Fig. 9c) so yields of these were used as a standard reference to adjust the yields of adjacent treatments for any fertility trend across the treatments. Yields were high, harvest bouts with or without wheelings usually exceeding 10 t/ha. Spatial yield patterns did relate to soil P patterns in the field. Agronomics analysis did not identify any significant treatment effects (Table 6) although the nil treatment with wheelings did yield least and placement of 15 kg/ha P_2O_5 yielded almost as much as either placement or broadcasting of 70 kg/ha P_2O_5 (Fig. 10). Mean grain P was 0.29% with no significant treatment effects.

Table 6. Effects of phosphate fertiliser treatments on yield of winter wheat at Lodge Field, Courteenhall in 2015 with spatially corrected differences (SCDs) and LSDs.

Treatment		Yield, t/ha	SD, t/ha	Comparison	SCD t/ha	LSD (95%), t/ha
T1	Nil (with wheelings)	10.77	0.838			
T5	Nil	11.23	0.552	T1 v T5	0.41	0.891
T2	Placed P_2O_5, 15 kg/ha	11.56	0.550	T1 v T2	0.81	0.712
T3	Placed P_2O_5, 70 kg/ha	11.54	0.865	T1 v T3	0.77	0.725
T4	Broadcast P_2O_5, 70 kg/ha	11.64	0.899	T1 v T4	0.75	0.716

3.4.2 2016 CB21: Bartlow

Heath Field near Bartlow, East Cambridgeshire is of sandy clay loam over chalk with soil P levels varying widely between 8 and 22 mg/L (Fig. 11a). Winter wheat was sown after peas on 1st October 2015 using a 8m wide Vaderstad Rapid drill which placed the seed at 5cm depth and provided liquid fertiliser (7%N : 20%P_2O_5: 0%K_2O) at the same depth. A nil treatment was compared with two rates of liquid fertiliser, 100 and 200 L/ha, each treatment being applied to a 40m wide block and replicated twice but treatments were not randomised (Fig. 11b). The pattern of soil P variation ran from South East to North West in the field. The tramline treatments ran across this variation in soil P, but avoided the patch of very low soil P to the east of the field (Fig. 11). Yield variation was large, from 8 to 13 t/ha, but the spatial pattern of yield variation ran counter to the spatial pattern of soil P fertility (Fig. 11c).

Analysis of yield data with the ADAS Agronomics SCD approach (Marchant *et al*., 2019) excluded data from the distal ends of the treated tramlines (Fig. 11c). Treatment effects were small but the level of precision achieved was modest so the response to fertiliser use (either 100 or 200 L/ha) of about 0.2 t/ha was not statistically significant (Table 7).

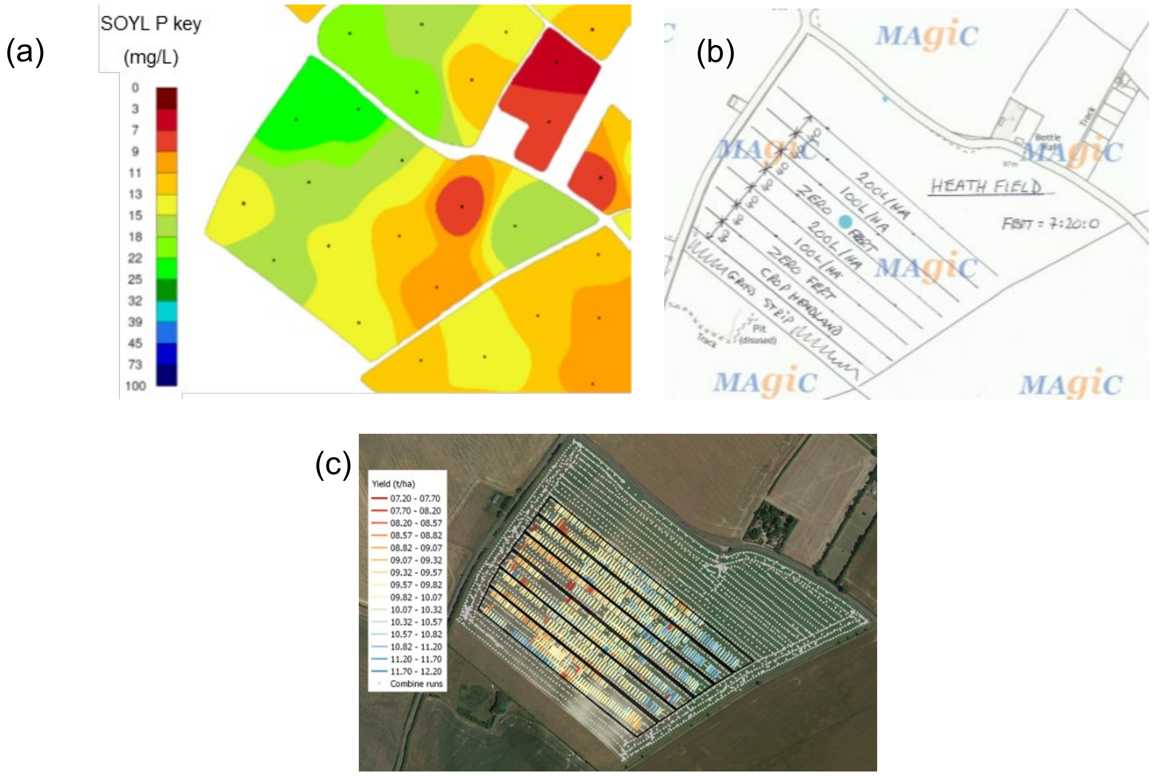

Figure 11. Maps of Heath Field, CB21, showing (a) soil P levels, (b) fertiliser P treatments: nil, 100 L/ha & 200 L/ha liquid fertiliser (containing 7%N : 20%P_2O_5: 0%K_2O), and (c) wheat yields in 2016 ranging from 8 (red) to 13 (blue) t/ha. Treatment boundaries are shown in pink.

Table 7. Effect of liquid fertiliser treatments (containing 7%N, 20%P_2O_5 & 0%K_2O and placed with the seed) on grain yield of winter wheat at Heath Field, CB21; and spatially corrected differences (SCDs) with LSDs.

Treatments	Fertiliser	Grain yield t/ha	Treatment effects	SCD, t/ha	LSD, t/ha
T1	Zero	9.72	T1 v T2	0.17	0.364
T2	100 L/ha	9.93	T1 v T3	0.20	0.344
T3	200 L/ha	9.82			

3.4.3 2016 NN7: Courteenhall

Sharman's Barn Field on the Courteenhall Estate near Collingtree, Northants. has clay loam soil with P levels ranging from 12 to 23 mg/L (Fig. 12a). It was sown on 16th October 2015 with winter wheat following oilseed rape using a 12m Horsch Sprinter drill, placing the seed 5cm deep, with fertiliser placed in front of the seed and 5cm below. Coulters were at 300mm centres, spreading seed across a 120-150mm band. The broadcast treatment was achieved by disconnecting the fertiliser feed to the coulters. The field contains five lone trees which interrupt the straight running of tramline passes and harvesting bouts (Fig. 12b). There were four treatments (nil, 15 kg/ha P_2O_5 placed, 70 kg/ha P_2O_5 broadcast and 70 kg/ha P_2O_5 placed in tramlines 24m wide, replicated twice in that order (starting in the north). Unfortunately these tramlines ran east-west whereas the main trend in soil P increased from south to north. The field was harvested on 25th August 2016. Two approaches were taken to analysing the yield data: (i) using the whole field, or (ii) using only the eastern half of the field, where there were no trees (Figs. 12c & d).

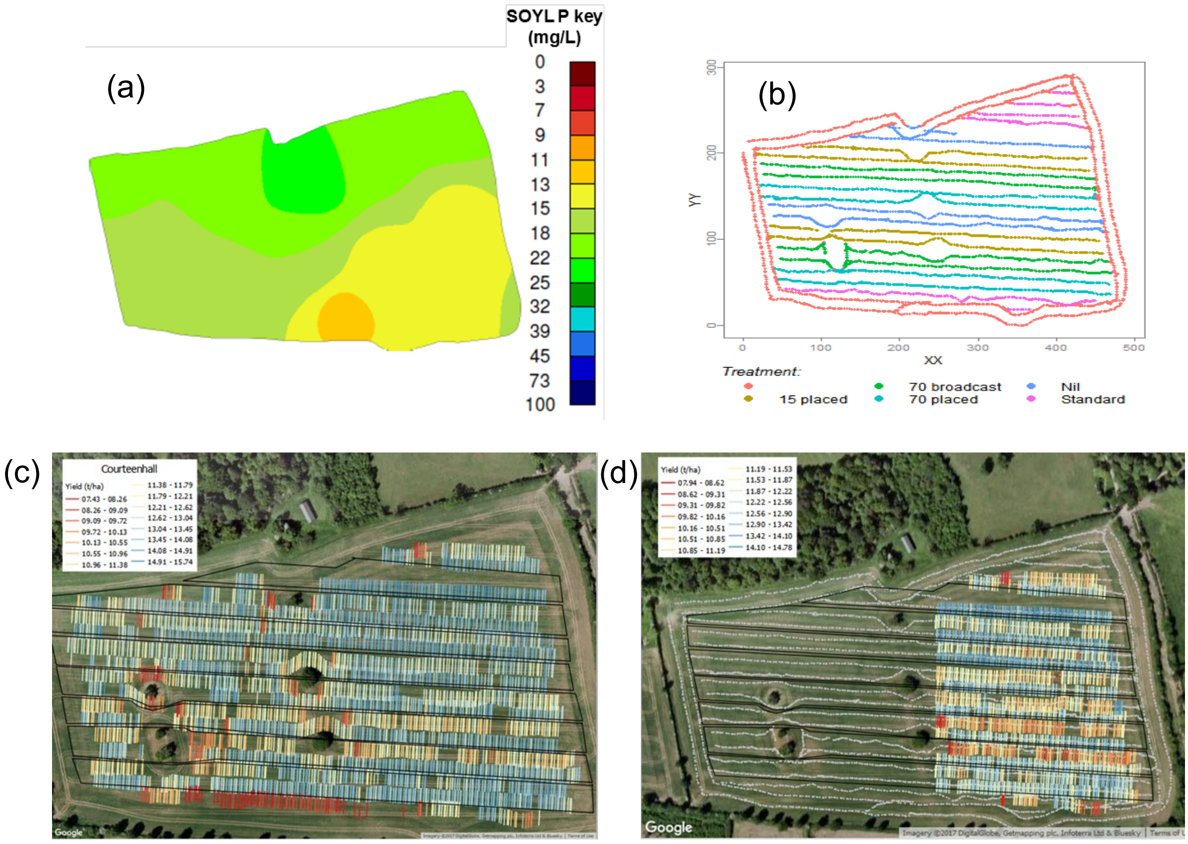

Figure 12. Maps of Sharman's Barn Field showing (a) soil P levels, (b) fertiliser P treatments (with axes showing distances in metres) and (c & d) wheat yields in 2016 ranging from 8 to 14 t/ha (red to blue). Treatment boundaries are shown by black lines.

The area over which yields were summarised affected their means and medians (Table 8). Yields averaged around 13 t/ha, even without applying fertiliser P. Whether yields were summarised across the whole field or just in the eastern half, yield treatment effects were generally very small and not statistically significant. Yield analysis in the eastern half of the field gave greater precision of the treatment comparisons (Table 8) so more emphasis should probably be placed on these results. However, when boundary line analysis was undertaken on the eight treatment boundaries within these data it was concluded that the trend in yield from south to north (probably related to the trend in soil P from south to north) was confounded with the treatments, such that no significant treatment effects could be inferred.

Table 8. Effects of fertiliser treatments on grain yield of winter wheat at Sharman's Barn Field, Courteenhall, 2016 with spatially corrected differences (SCDs) and LSDs. Analyses are reported for the whole field (with trees) and just the eastern part (without trees).

Treatment		Mean yield, t/ha	Median yield, t/ha	Comp-arison	SCD in yield, t/ha	LSD t/ha
Whole field						
T1	Nil	13.01	13.11	T4-T1	0.064	0.642
T2	15 kg/ha P_2O_5 placed	12.70	13.00	T4-T2	0.045	0.556
T3	70 kg/ha P_2O_5 placed	13.05	13.19	T4-T3	0.628	0.574
T4	70 kg/ha P_2O_5 broadcast	12.75	12.97			
Eastern half of field						
T1	Nil	12.93	13.05	T4-T1	0.643	0.312
T2	15 kg/ha P2O5 placed	12.62	12.96	T4-T2	0.093	0.310
T3	70 kg/ha P2O5 placed	13.06	13.20	T4-T3	0.374	0.292
T4	70 kg/ha P2O5 broadcast	12.77	13.01			

3.4.4 2016 CM5: Fyfield

Further Field near Fyfield in Essex is a 700m long field with clay loam and soil P levels ranging from 9 to 24 mg/L, the low P levels being across the centre of the field. It was sown with winter wheat (following winter wheat) on 2nd October 2015 with a 8m Horsch Sprinter drill placing the seed 5cm deep and the fertiliser in front of the seed and 5cm below; coulters were at 300mm centres, with seed spread across 120-150mm. Three treatments of nil, 70 kg/ha P_2O_5 placed, 70 kg/ha P_2O_5 broadcast were applied to 36m tramlines, and replicated twice but not randomised.

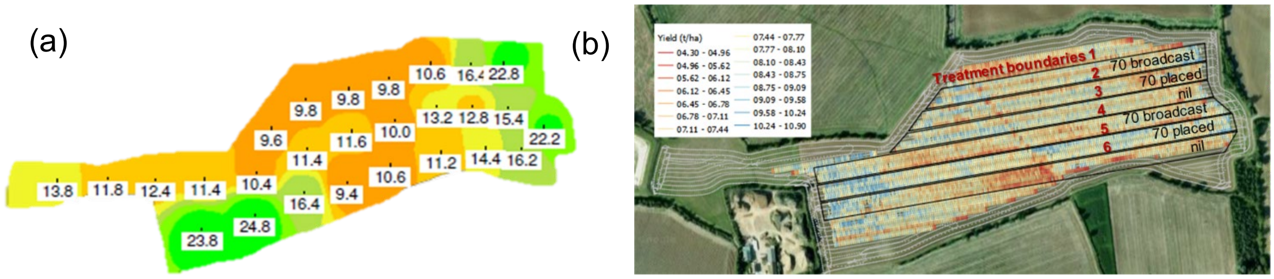

Figure 13. Maps of Further Field, CM5, showing (a) soil P levels (mg/L), (b) fertiliser P treatments (kg/ha P_2O_5; treatment boundaries are shown by black lines) and wheat yields in 2016 ranging from 5 to 10 t/ha (red to blue).

Yields varied between 5 and 10 t/ha, averaging at around 7.5 t/ha; there was an apparent increase in yield of ~0.2 t/ha (depending on method of estimation) due to P application. However, the 0.2 t/ha yield increase was not statistically significant when SCDs were compared (Table 9). When boundary line analysis was used (Marchant *et al.*, 2019) this was due to inconsistent comparisons between effects along the shorter Boundary 2 which showed an advantage from broadcasting (significant towards the eastern end; Fig. 14a) and the longer Boundary 5 (Fig. 14b) which showed significant advantages from placement along most of its length, and particularly in the central portion of the field where soil P levels were lowest (Fig. 14b). These differences have been used to show the potential of SDA for revealing relationships between the size of yield responses and the spatial variation in soil P levels (Fig. 14c).

Table 9. Effects of phosphate fertiliser treatments on yield of winter wheat at Further Field, Fyfield, Essex 2016 with spatially corrected differences (SCDs) and LSDs.

Treatment		Yield, t/ha	Diff'ce, t/ha	Comparison	SCD t/ha	LSD (95%), t/ha
T1	Nil	7.19				
T2	Broadcast P_2O_5, 70 kg/ha	7.41	0.22	T1 v T2	0.29	0.314
T3	Placed P_2O_5, 70 kg/ha	7.55	0.14	T2 v T3	0.15	0.321

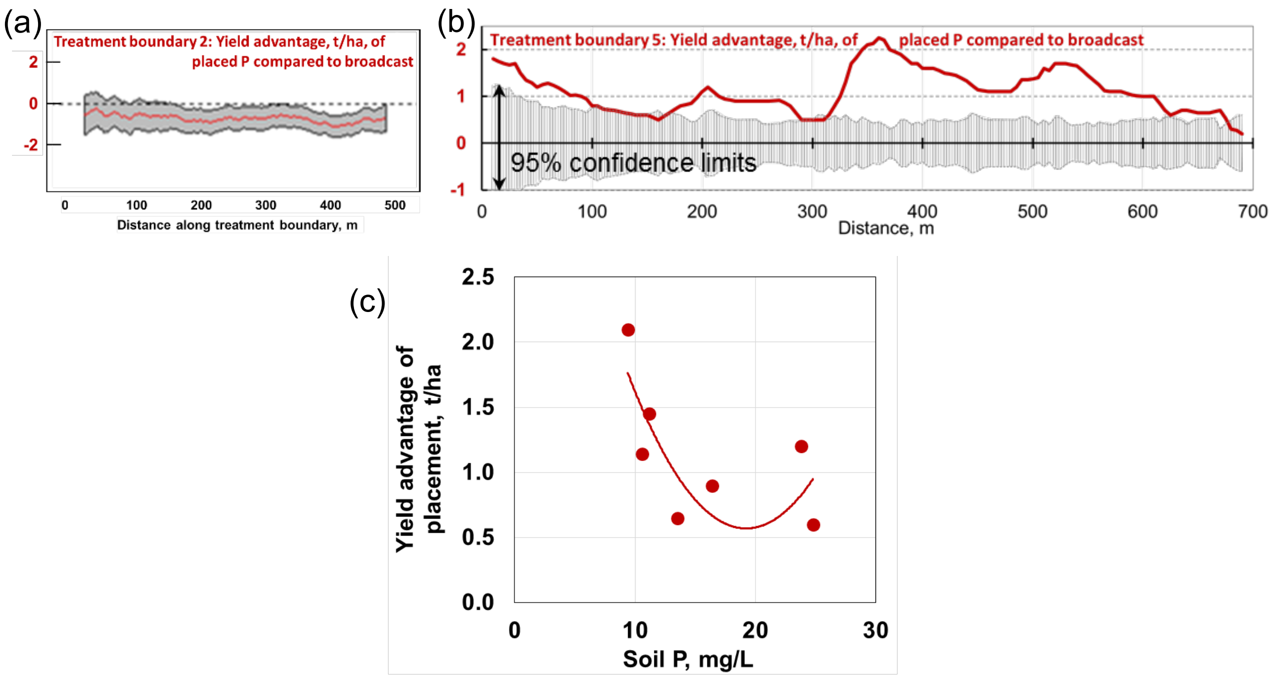

Figure 14. Result of spatial discontinuity analysis (SDA) along the 5th boundary line in Further Field (Fig. 13b) showing changes in response to placement along (a) Boundary 2 and (b) Boundary 5 with 95% confidence limits for yields averaged over 50m lengths, and (c) how the Boundary 5 responses diminished with increasing soil P levels (mg/L).

3.4.5 2017 CB21: Bartlow

Oaks Field near Bartlow in East Cambridgeshire is 32 ha of clay loam over clay with chalk, the topsoil having P levels ranging from 11 to 18 mg/L; most of the field was had fairly uniform soil P fertility but there was a low spot in the east and a high spot in the south west (Fig. 15a). Winter wheat was sown after wheat on 26th September 2016 using a 8m wide Vaderstad Rapid drill which placed the seed at 5cm depth and provided liquid fertiliser (7%N : 20%P_2O_5: 0%K_2O) at the same depth. At drilling the soil was dry with a loose top 2”, and firm below. A nil treatment was compared with two rates of liquid fertiliser, 100 and 200 L/ha, each treatment being applied to a 40m block and replicated three times (Fig. 15b). The field was harvested on 4th August 2017 with by a harvester with 12m cut width.

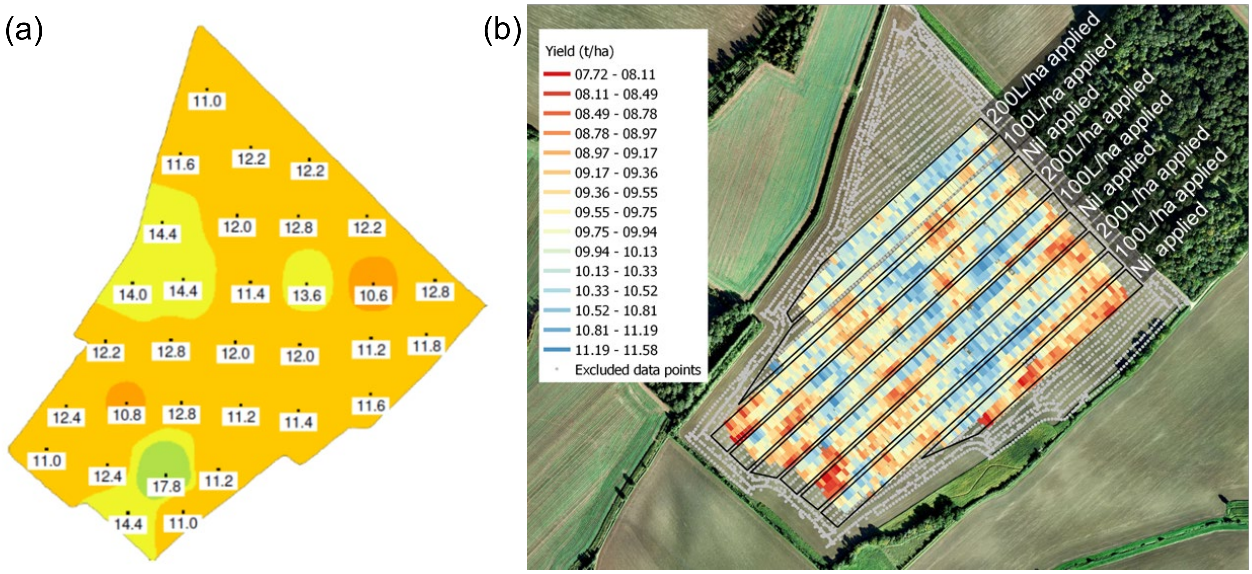

Figure 15. Maps of Oaks Field, Bartlow in 2017 showing (a) soil P levels (mg/L), (b) fertiliser P treatments: nil, 100 L/ha & 200 L/ha liquid fertiliser (containing 7%N : 20%P_2O_5: 0%K_2O), and also wheat yields in 2017 ranging from 8 (red) to 11 (blue) t/ha. Treatment boundaries are shown by black lines.

Grain yields varied between 8 and 11 t/ha; spatial patterns in yield did not relate well to the patterns in soil P fertility. Treatment 2 (100 L/ha) out-yielded the zero fertiliser treatment by only 0.043 t/ha (±0.365) and Treatment 3 (200 L/ha) out-yielded Treatment 2 by 0.188 t/ha (±0.368). These effects were in direction expected, but were small and not statistically significant. Boundary line analysis also showed no significant effects

3.4.6 2017 NR21: Barsham

Wheat was sown in autumn 2017 on Long 13 field near Barsham which has a medium sandy clay loam soil over chalky subsoil at 40-50cm, with topsoil P levels varying from 9 to 12 mg/L (Fig. 16a). P was placed or broadcast with a Vaderstad Spirit 400 drill 4m wide which placed fertiliser behind front working discs, which were between the seed coulter discs i.e. fertiliser was not mixed with the seed. Tramline bouts were 24m wide and, since this was a small field, treatments were laid out to be harvested in a single combine bout, with a 9m cut. There were four treatments (nil, 24 kg/ha P_2O_5 placed, 70 kg/ha P_2O_5 placed, and 70 kg/ha P_2O_5 broadcast) each 12m wide (in tramlines 24m wide), replicated three times in that order (starting in the south; Fig. 16b). These tramlines ran east-west and whilst the whole field was low in soil P, main trend in soil P also ran east-west (Fig. 16a).

Average grain yield recorded by the harvester was about 11 t/ha with little evidence of significant spatial variation across the field (Fig. 16c). However, the Agronomics process identified that about a quarter of the data had to excluded before spatial modelling (Fig. 16c).

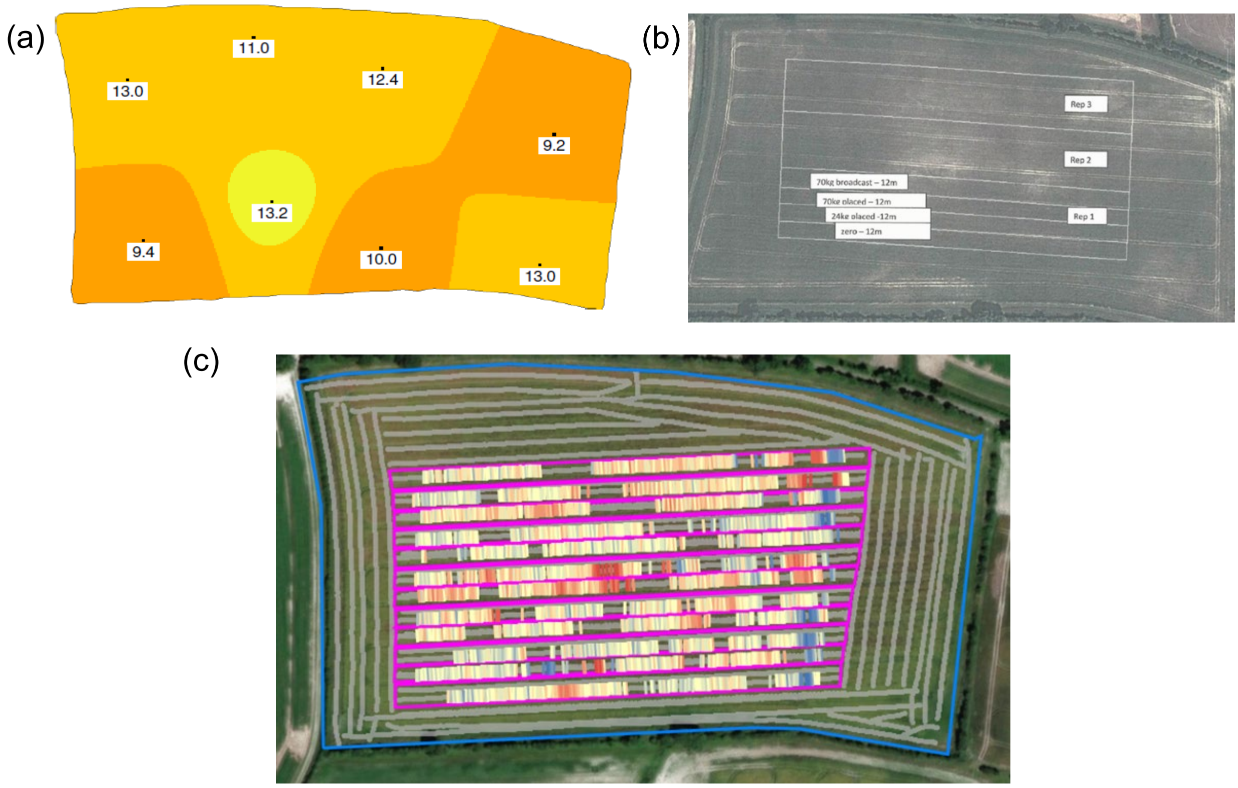

Figure 16. Maps of Long 13 Field, Barsham showing (a) soil P levels (mg/L), (b) fertiliser P treatments, and (c) wheat yields in 2017 ranging from 8 (red) to 12 (blue) t/ha. Treatment boundaries are shown by pink lines.

Table 10. Effects of phosphate fertiliser treatments on yield of winter wheat at Long 13 Field, Barsham in 2017 with spatially corrected differences (SCDs) and LSDs.

	Treatment	Yield, t/ha	Yield SD, t/ha	Comparison	SCD, t/ha	LSD, t/ha
T1	Nil	11.12	0.703	T4 v T1	-0.126	0.478
T2	24 kg/ha P_2O_5 placed	10.76	0.898	T4 v T2	+0.244	0.502
T3	70 kg/ha P_2O_5 placed	10.88	0.904	T4 v T3	+0.134	0.487
T4	70 kg/ha P_2O_5 broadcast	11.01	0.721			

The final Agronomics analysis only detected small treatment differences which were not statistically significant, and SDA on the treatment boundaries also could not detect any significant effects (Table 10).

3.4.7 2017 CT14: Ashley

Wheat was sown on Coleman Field, Ashley, Kent with an 8m wide combine drill in autumn 2017. The field has a silty clay loam soil with topsoil P levels varying from very low (5) to 12 mg/L, and with one southern high-point of 19 mg/L (Fig. 17a); potassium and magnesium levels were also generally low (Index 0-1), especially in the eastern half of the field and soil pH showed wide variation from 6.0 to 8.5 (Fig. 17b). Unfortunately, this field had been merged from two former fields of different soil types (lighter to the east) and the treatments were laid out so that comparisons were confounded with the previous field and soil differences. There were four treatments (nil, 24 kg/ha P_2O_5 placed, 70 kg/ha P_2O_5 placed, and 70 kg/ha P_2O_5 broadcast) each 32m or 40m wide (with tramlines 36m wide), replicated twice in that order (starting in the east; Fig. 17c).

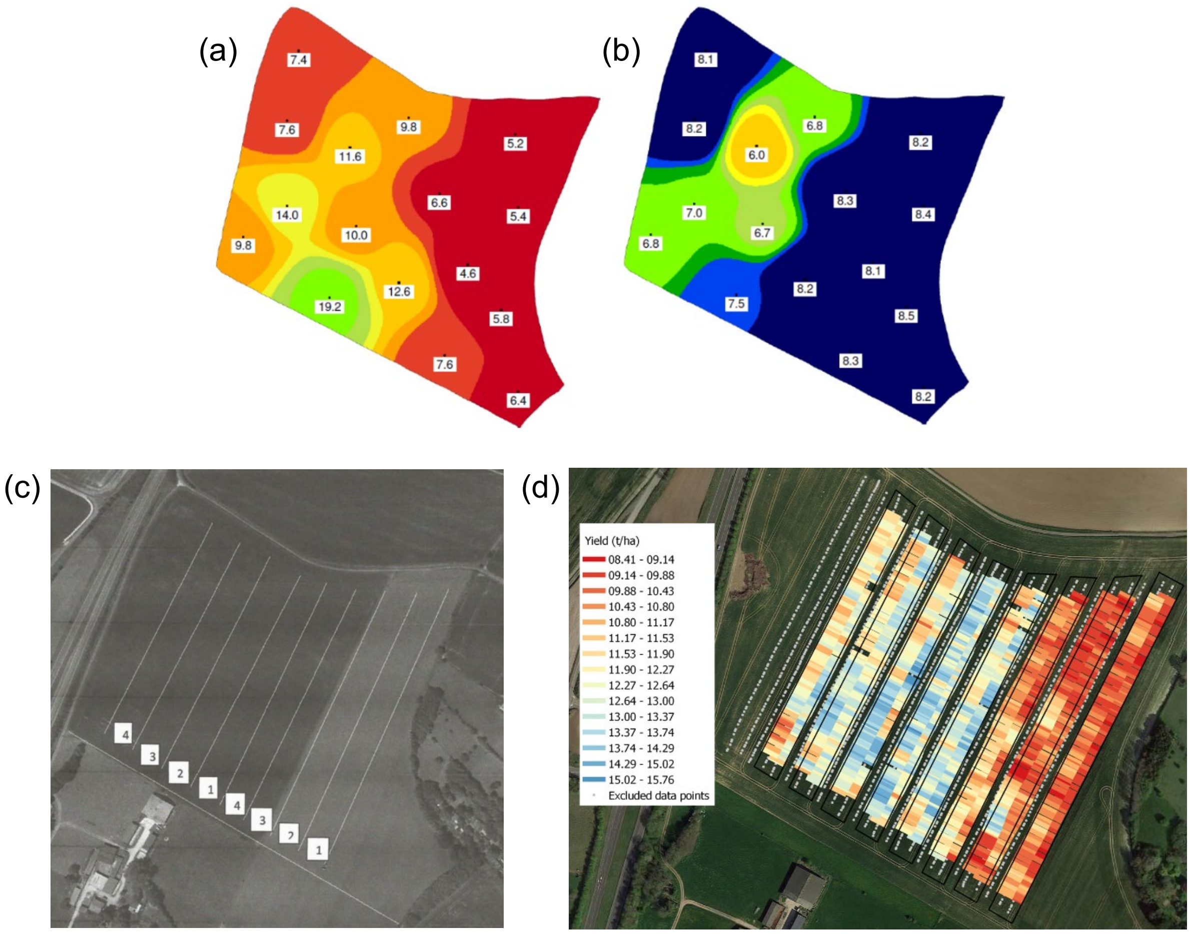

Figure 17. Maps of Coleman Field, Ashley showing (a) soil P levels (mg/L), (b) soil pH, (c) fertiliser P treatments (1, nil; 2, 20 kg/ha P2O5 placed; 3, 70 kg/ha P2O5 placed; 4, 70 kg/ha P2O5 broadcast) and the visible contrast in previous (2013) crop performance, and (d) wheat yields in 2017 ranging from 9 (red) to 15 (blue) t/ha.

The field was harvested on 15th August 2017 using two passes of a harvester with a 12m cut width, and leaving all wheelings within discard bouts between the treatment bouts. Yields were generally good, but showed a big contrast from around 9 t/ha in the east to around 13 t/ha in the west of the field (Fig. 17d). It proved best to discard the three low yielding eastern-most tramlines from the analysis so that treatment effects were tested within the western part of the field with two replicate tramlines remaining only for Treatment 4 (broadcast 70 kg/ha P_2O_5), and only one tramline for other treatments. However, this part of the field also contained wide variation in soil P and pH (not so much variation in soil K and Mg).

After spatial correction (SCD), the broadcast treatment yielded most, its yield significantly exceeding the nil treatment by about 0.5 t/ha (Table 11). Differences between fertilised treatments were not statistically significant when tested with the SCD approach. The SDA approach showed quite small confidence limits (LSDs) with treatment effects changing along the treatment boundaries; however, these effects were not consistent with treatment.

Table 11. Effects of phosphate fertiliser treatments on yield of winter wheat at Coleman Field, Ashley in 2017 with spatially corrected differences (SCD) and LSDs.

Treatment		Mean Yield, t/ha	Yield SD, t/ha	Comp-arison	SCD, t/ha	LSD, t/ha
T1	Nil	11.55	1.701	T4 v T1	+0.53	0.158
T2	20 kg/ha P_2O_5 placed	11.49	1.657	T4 v T2	+0.28	0.167
T3	70 kg/ha P_2O_5 placed	11.67	1.235	T4 v T3	+0.08	0.168
T4	70 kg/ha P_2O_5 broadcast	12.45	0.954			

3.4.8 2017 PE8: Hemington

Airfield, on Hemington Lodge Farm, East Northamptonshire has a clay loam soil with P levels varying widely from 8 to 77 mg/L. Winter barley was sown in autumn 2016 with a combine drill. Unfortunately the fertiliser product purchased for the trial caused the drill mechanism to block frequently so it only proved possible to establish two replicates of three treatments (T1, nil; T2, 20 kg/ha P_2O_5 placed; T3, 70 kg/ha P_2O_5 placed) on the six southern-most tramlines within the time available. There was no broadcast treatment, as intended. Tramlines were 24m wide.

The trial was harvested on or around 10th July 2017 with a 12m wide harvester header. It was only possible to be sure that one of the harvester bouts was placed fully within each treatment area so only six harvester bouts were included in the statistical analysis. Average yields were about 8.6 t/ha (Table 12) with a band of higher yields across the middle of the trial where the soil P levels were highest; however, there were also high yields to the west of the northern replicate, where soil P levels were low, so some of the yield variation did not relate to soil P. Yields with fertiliser were slightly more than those from treatments without but neither of the SCD effects was significant (Table 12).

SDA on treatment boundaries at this site showed some significant effects, particularly to the east end of the boundaries where T3 (70 kg/ha P_2O_5 applied) was next to either T2 (20 kg/ha P_2O_5 applied) or T1 (nil P applied) (Figure 19).

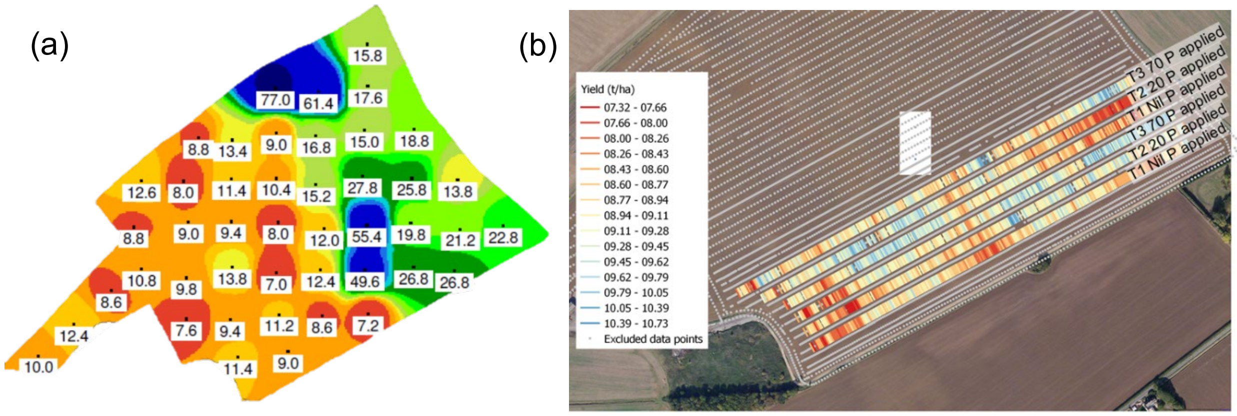

Figure 18. Maps of Airfield, Hemington showing (a) soil P levels (mg/L), (b) treatment allocations and barley yields in 2017 for the tramlines comparing fertiliser P treatments (T1, nil; T2, 20 kg/ha P_2O_5 placed; T3, 70 kg/ha P_2O_5 placed) ranging from 7 to 10 t/ha (red to blue).

Table 12. Effects of phosphate fertiliser treatments on yield of winter barley at Airfield, Hemington in 2017 with spatially corrected differences (SCD) and LSDs.

Treatment		Mean Yield, t/ha	Yield SD, t/ha	Comp-arison	SCD, t/ha	LSD, t/ha
T1	Nil	8.51	0.489	T2 v T1	0.12	0.495
T2	20 kg/ha P_2O_5 placed	8.61	0.541	T3 v T1	0.32	0.499
T3	70 kg/ha P_2O_5 placed	8.84	0.503			

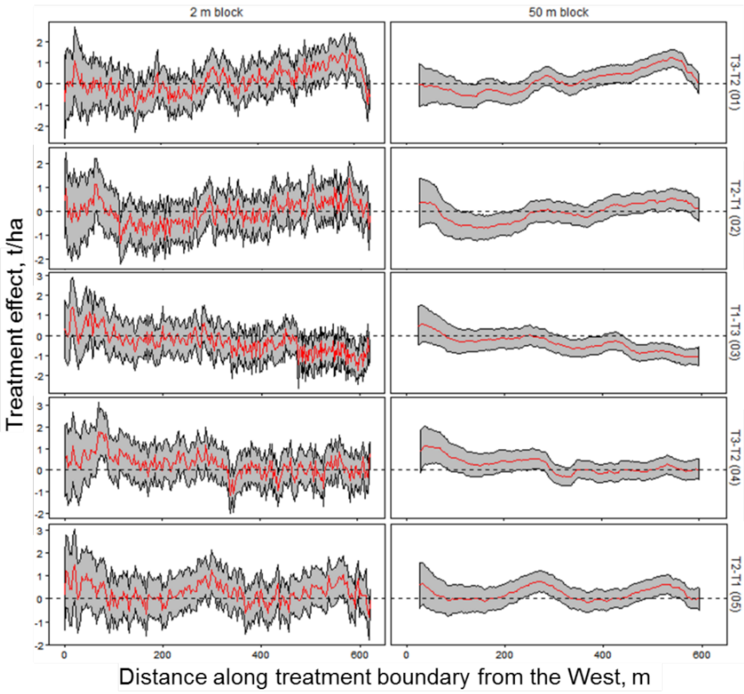

Figure 19. Results of SDA for the five successive treatment boundaries from north to south (top to bottom) in the trial on Airfield, Hemington in 2017 showing the treatment difference (red line) and its 95% confidence limits (grey band) with averaging of yields over 2m (left) and over 50m (right).

3.4.9 2017 NN7: Quinton

Great Holt field near Quinton, Northampton has a clay loam soil with P levels varying widely from 9 to 43 mg/L (Fig. 20a). Wheat was sown in autumn 2016 with a combine drill, and four treatments (T1, nil; T2, 20 kg/ha P_2O_5 placed; T3, 70 kg/ha P_2O_5 placed; T4, 70 kg/ha P_2O_5 broadcast) were laid out and replicated three times in the eastern part of the field where there were no trees (Fig. 20b). Tramlines were 24m apart. The trial was harvested by a 12m Claas combine on 11th August 2017 – after the rest of the field.

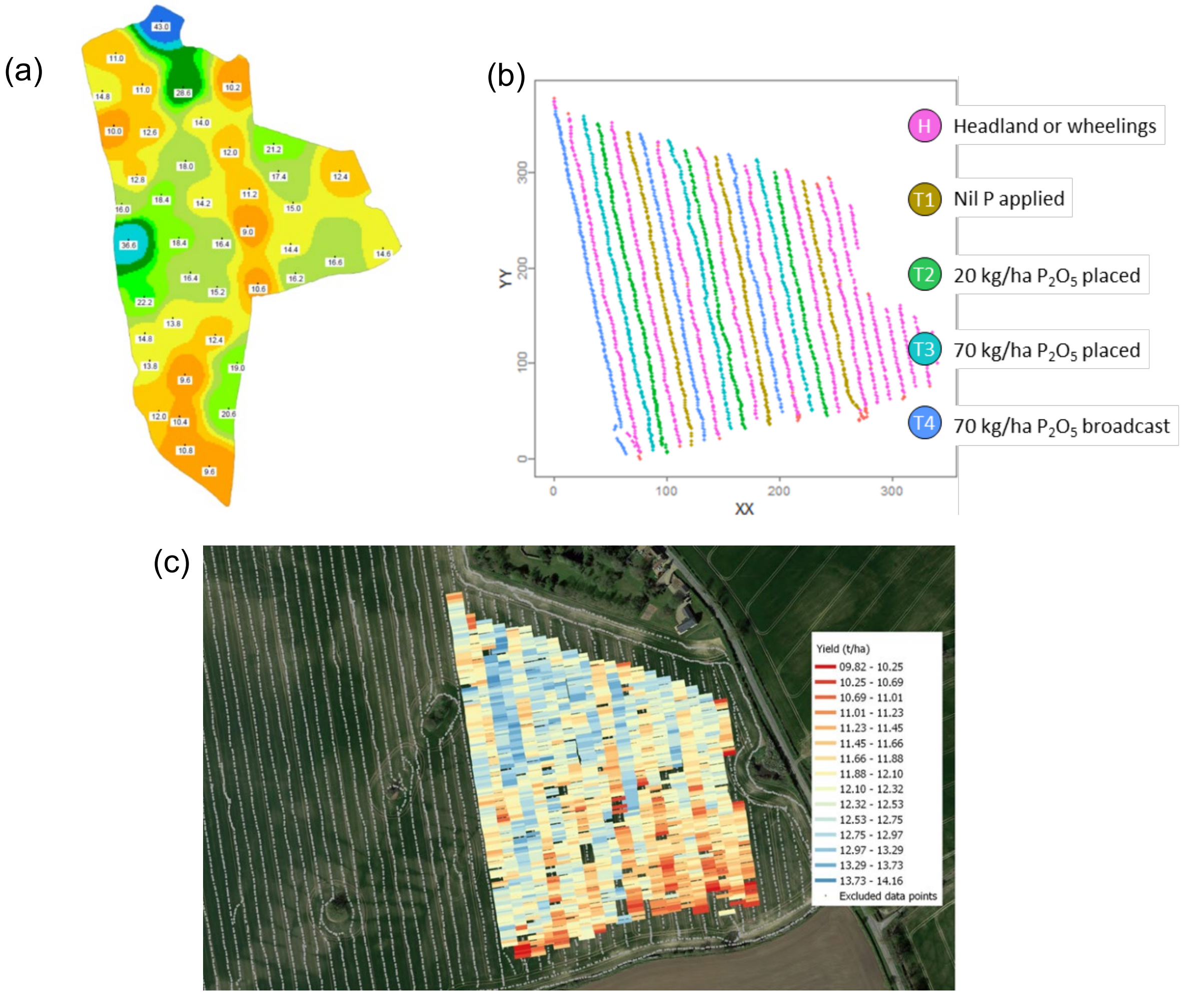

Figure 20. Maps of Great Holt, Quinton showing (a) soil P levels (mg/L), (b) treatment allocation to harvester bouts in the east part of the field (T1, nil; T2, 20 kg/ha P_2O_5 placed; T3, 70 kg/ha P_2O_5 placed; T3, 70 kg/ha P_2O_5 broadcast), and (c) wheat yields in 2017 ranging from 10 to 14 t/ha (red to blue).

Grain yields within the trial area varied from 10 to 14 t/ha (Fig. 20c) with an overall positive trend running from south-east to north-west. Tramlines including wheelings were noticeably low so treated as a separate treatment, along with headland areas, within the statistical analysis.

Average yields of all treatments were similar, but the trial was very precise and spatially corrected differences showed tramline bouts with wheelings (or in headlands) to yield significantly less than the nil P treatment (T1; Table 13); yields from the placed treatments did not differ significantly from T1 but the broadcast P treatment yielded 0.4 t/ha more than T1 (Table 12). Treatment boundary analysis with SDA supported these comparisons and did not show much evidence of changes in treatment differences with position across the field.

Table 13. Effects of phosphate fertiliser treatments on yield of winter wheat at Great Holt field, Quinton in 2017 with spatially corrected differences (SCD) and LSDs.

Treatment		Mean Yield, t/ha	Yield SD, t/ha	Comp-arison	SCD, t/ha	LSD, t/ha
T1	Nil	12.15	0.525	T1 v H*	0.62	0.132
T2	20 kg/ha P_2O_5 placed	12.20	0.583	T2 v T1	0.11	0.182
T3	70 kg/ha P_2O_5 placed	12.10	0.542	T3 v T1	0.06	0.183
T4	70 kg/ha P_2O_5 broadcast	11.78	0.458	T4 v T1	0.41	0.152

*headlands

3.4.10 2018 SO24: Northington

Slipsgate field, Northington in Hampshire is a 39 ha field having a chalky silty clay loam soil ranging in soil P from 12 to >40 mg/L (Fig. 21a). Aerial photographs show some variation in depth to chalk. The field was sown on 5th October 2017 with winter wheat using a 4 m wide Horsch Focus drill which places the fertiliser 2-3 cm below the seed and just to one side. Four treatments were established running east-west and replicated twice (Fig. 21b).

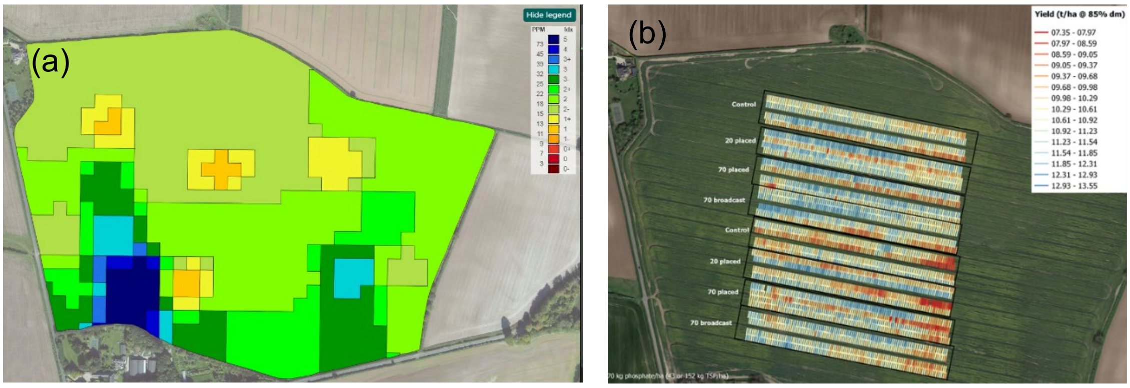

Figure 21. Maps of Slipsgate field, Northington showing (a) soil P variation and (b) treatment allocations and spring barley yields for the trial area in 2018, ranging from 8 to 13 t/ha (red to blue).

The trial was harvested on 25th July 2018 with yields ranging from 8 to 12 t/ha; the main area of low yields was to the east and through the centre of the field. The highest yields were associated with the more chalky areas (mainly North West). Mean yields of the treatments were all quite similar and when corrected for inherent spatial variation no differences were statistically significant (Table 14) because LSDs were too large. Boundary analysis with SDA supported this conclusion.

Table 14. Effects of phosphate fertiliser treatments on yield of winter wheat at Slipsgate field, Northington in 2018 with spatially corrected differences (SCD) and LSDs.

Treatment		Mean Yield, t/ha	Yield SD, t/ha	Comp-arison	SCD, t/ha	LSD, t/ha
T1	Nil	10.54	0.895			
T2	20 kg/ha P_2O_5 placed	10.77	1.063	T2 v T1	0.41	0.604
T3	70 kg/ha P_2O_5 placed	10.74	1.040	T3 v T1	0.36	0.623
T4	70 kg/ha P_2O_5 broadcast	10.86	0.866	T4 v T1	0.54	0.625

3.4.11 2018 CM5: Fyfield

Gypsy Field, Fyfield in Essex has a chalky boulder clay soil ranging in Olsen P from 10 to 20 mg/L (Fig. 22a). It was sown with spring barley on 10th April 2018 using a Horsch Sprinter drill 6 m wide which places liquid fertiliser containing 70 kg/ha P_2O_5 (as di-ammonium phosphate; DAP) about 2-3 cm directly below the seed. Two treatments were established running north-south in an area to the west of the field and replicated three times (Fig. 22b). The nitrogen from the DAP was balanced out with an application of liquid nitrogen on 16th May to the tramlines that didn't receive DAP.

The treatments largely ran across the soil P variation. The trial was harvested with yields ranging from 5.5 to 8.5 t/ha; one area of low yields also coincided with the area of lowest soil P to the south of the trial area (Fig. 22c). The apparent yield advantage of placed P over nil P applied was about 0.2 t/ha but this was within the confidence limits of this experiment (Table 15).

Table 15. Effects of phosphate fertiliser treatments on yield of spring barley at Gypsy field, Fyfield in 2018 with spatially corrected differences (SCD) and LSDs.

Treatment		Mean Yield, t/ha	Yield SD, t/ha	Comp-arison	SCD, t/ha	LSD, t/ha
T1	Nil	6.83		T2 v T1	0.229	0.444
T2	70 kg/ha P_2O_5 as placed liquid	7.05				

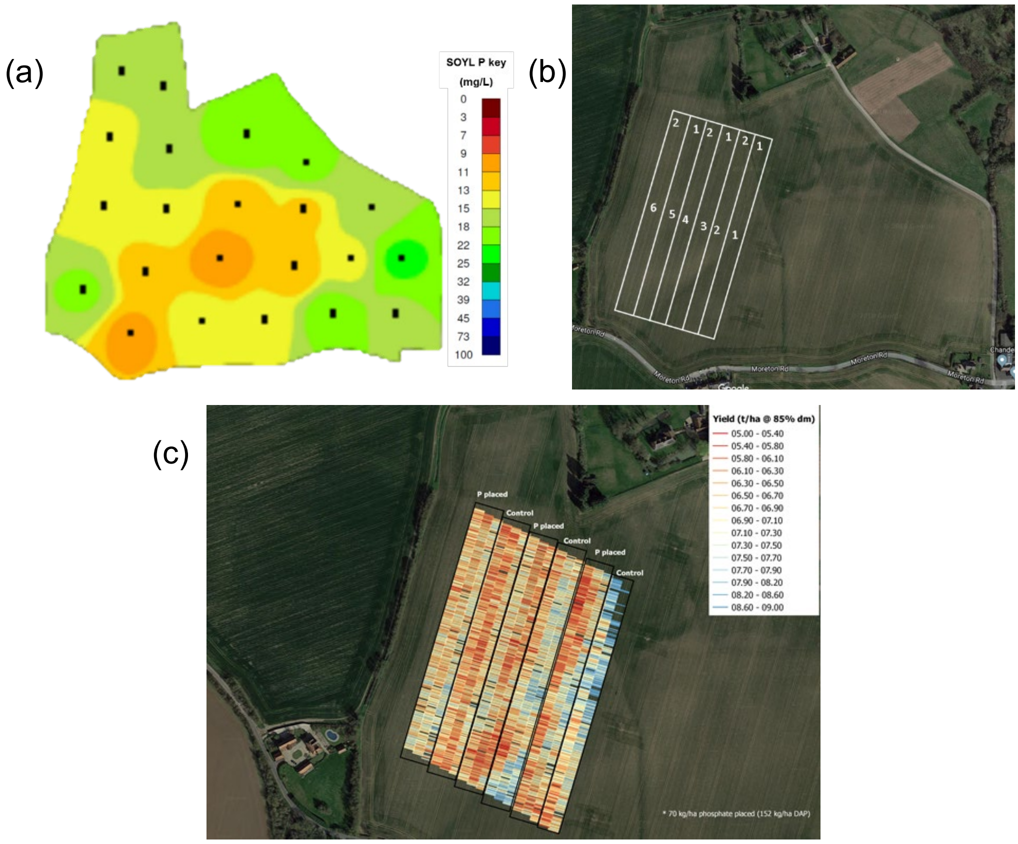

Figure 22. Map of Gypsy field, Fyfield showing (a) soil P levels (with colour key), (b) treatment allocation (top numbers: T1, nil P applied; T2, 70 kg/ha P_2O_5 placed with the seed at sowing as liquid DAP) and (c) spring barley yields, ranging from 5.4 to 8.6 t/ha (red to blue).

3.4.12 2018 LE10: Burton Hastings

Field BW D on Burton Field Farm, Burton Hastings near Hinckley is of 18 ha with a sandy clay loam topsoil ranging from 26 to 44 mg/l soil P (Fig. 23b).

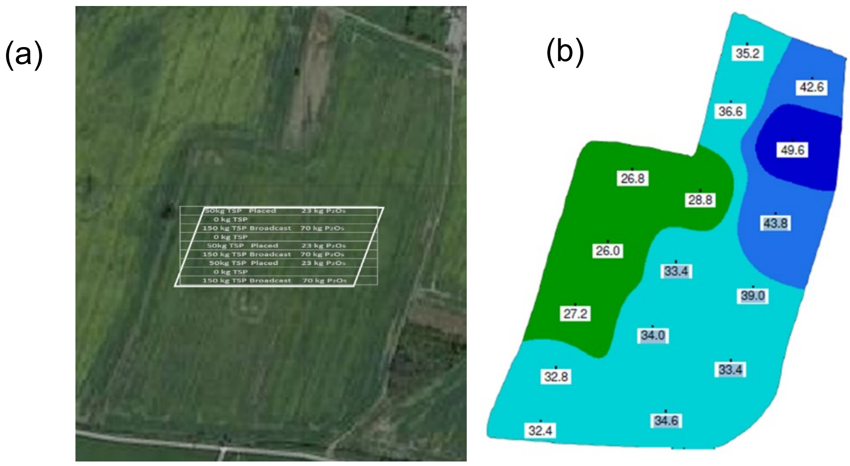

Figure 23. Maps of Field BW-D, Burton Hastings showing (a) layout of treatments (T1, nil P applied; T2, 23 kg/ha P_2O_5 placed; T3, 70 kg/ha P_2O_5 broadcast) and (b) soil P levels (mg/L). Grain yields lacked GPS data so cannot be mapped, but they ranged from 3 to 9 t/ha.

Barley was sown in spring of 2018 using a 6m drill. Nine plots were set up with two drill widths per plots, plots being drilled *across* direction of tramlines. The treatments were 0 kg/ha, 23 kg/ha P_2O_5 placed and 70 kg/ha P_2O_5 Broadcast. All top dressing and spraying followed 36m tramlines as normal, so these ran *across* the direction of the drilling and (unusually for this set of trials) the fertiliser treatments were not confounded with other husbandry operations. The trial was harvested with a 9m combine header, again running across the tramlines and through the centre of each plot. The yield data provided were separated into different soil P categories before transmission for reporting, and no GPS information was provided, so no spatial correction or analysis was possible, and no yield map could be drawn.

Table 16. Effects of phosphate fertiliser treatments on yield of spring barley at Field BW-D, Burton Hastings in 2018 with spatially corrected differences (SCD) and LSDs.

Treatment		Mean Yield, t/ha	Yield SD, t/ha	Comp-arison	SCD, t/ha	LSD, t/ha
T1	Nil	5.70	1.124	T2 v T1	NA	NA
T2	23 kg/ha P_2O_5 placed	5.71	1.163	T3 v T1	NA	NA
T3	70 kg/ha P_2O_5 broadcast	5.64	1.776	T3 v T2	NA	NA

3.4.13 Overview and Summary

Formal inclusion of farmer-managed tramline trials is a relatively novel way of conducting agronomic research so this section not only reviews the results themselves, but it includes an assessment of how successful this approach turned out to be, and whether it might offer potential for use in other projects on this or other topics.

3.4.13.1 Overview of effects of fresh P and P placement on cereal yields

The farms selected to conduct these trials were well-managed farms able to achieve above-average yields (mean grain yield of ~10 t/ha over all 12 trials), and inclined to invest in new technology and as evidenced by their use of combine drills able to place fertilisers adjacent to seed. Over recent decades combine drilling has generally been deemed economically unjustifiable on most arable farms. However, despite the good yields, field yield patterns showed large variation and the chosen fields all had low and usually variable soil P levels (fields were intentionally selected for this). The range of within-field spatial variation over all twelve fields was from 3 to 6 t/ha (mean 4.4 t/ha; Figs. 9c-23c). Visual inspection of the patterns of yield variation suggested that these were positively associated with soil P levels in at least half of these fields. On the other fields with no obvious P-related patterns, it is be assumed that P was not necessarily the first limiting nutrient and that other factors were responsible for within-field yield variation.

Compared to the spatial variation, yield differences between any of the P treatments were small (average 0.33 t/ha; maximum 0.81 t/ha; Table 17), so the challenge of achieving any degree of certainty that these differences were actually caused by the fertiliser treatments (and not by spatial variation) was considerable. Confidence intervals at $P<0.05$ between the spatially corrected yields ranged from 0.16 to 0.76 t/ha (Table 17) so only about 20% of individual treatment effects were statistically significant with 95% certainty.

Table 17. Summary of spatially corrected grain yields from tramlines after placing large (maintenance) or small (~20 kg/ha) amounts or broadcasting large amounts of fresh phosphate on 12 fields growing cereals in south and east England over 4 seasons. Yields were calculated by adding SCDs to the mean arithmetic mean yield of the control treatment. ND: not determined.

Harvest Year	2015	2016	2016	2016	2017	2017	2017	2017	2017	2018	2018	2018
Site code	NN7	CB21	NN7	CM5	CB21	NR21	CT14	PE8	NN7	SO24	CM5	LE10
Grain yields, t/ha												
Nil P_2O_5	11.23	9.72	12.93	7.19	9.45	11.12	11.55	8.51	12.15	10.54	6.83	5.70
15-24 kg/ha P_2O_5, placed	11.56	9.93	12.62	7.41	9.60	10.76	11.49	8.61	12.20	10.77	ND	5.71
40-70 kg/ha P_2O_5, placed	11.54	ND	13.06	7.55	9.64	10.88	11.67	8.84	12.10	10.74	7.05	ND
70 kg/ha P_2O_5, broadcast	11.64	9.82	12.77	ND	ND	11.01	12.45	ND	11.78	10.86	ND	5.64
Mean LSD:	0.761	0.354	0.305	0.318	0.367	0.489	0.164	0.497	0.162	0.617	0.444	NA

Nevertheless, compared to nil fertiliser, the effects of using either a large or a small dressing of fresh fertiliser P were positive in all but one of the fields and, across all sites, use of fresh P can be considered statistically significantly better than using none, with 95% certainty. This was despite the overall advantages being only small: +0.33 (±0.11) for P_2O_5 dressings equivalent to crop offtake (~70 kg/ha; Figs. 24a) and +0.19 (±0.14) t/ha for small dressings (20 kg/ha; Figs. 24b).

Only five of the 12 trials allowed comparisons of placement with broadcasting fertiliser at the same rate; here, spatially corrected yields after placement were generally worse than with broadcasting, but not significantly so (-0.17 ±0.17 t/ha; Fig. 24c). Further, yields after placing small dressings of fertiliser were not significantly different from after placing a large dressing (+0.04 ±0.14 t/ha; Fig. 24d), and compared to after broadcasting a large dressing, yields after placing small dressings were less four times out of five, but these were not significantly different overall (-0.26 ±0.10 t/ha; Figs. 24e).

Considering the economics of fresh P and how to apply it, with current fertiliser and grain prices, a 0.1 t/ha (1%) increase in a 10 t/ha yield would buy 23 kg/ha P_2O_5 so, although effects of fresh P were statistically significant, the profitability of applying either large or small fresh P dressings would have been marginal on the basis of the fresh P responses only; justification would partly have had to depend on factoring-in positive effects on subsequent crops.

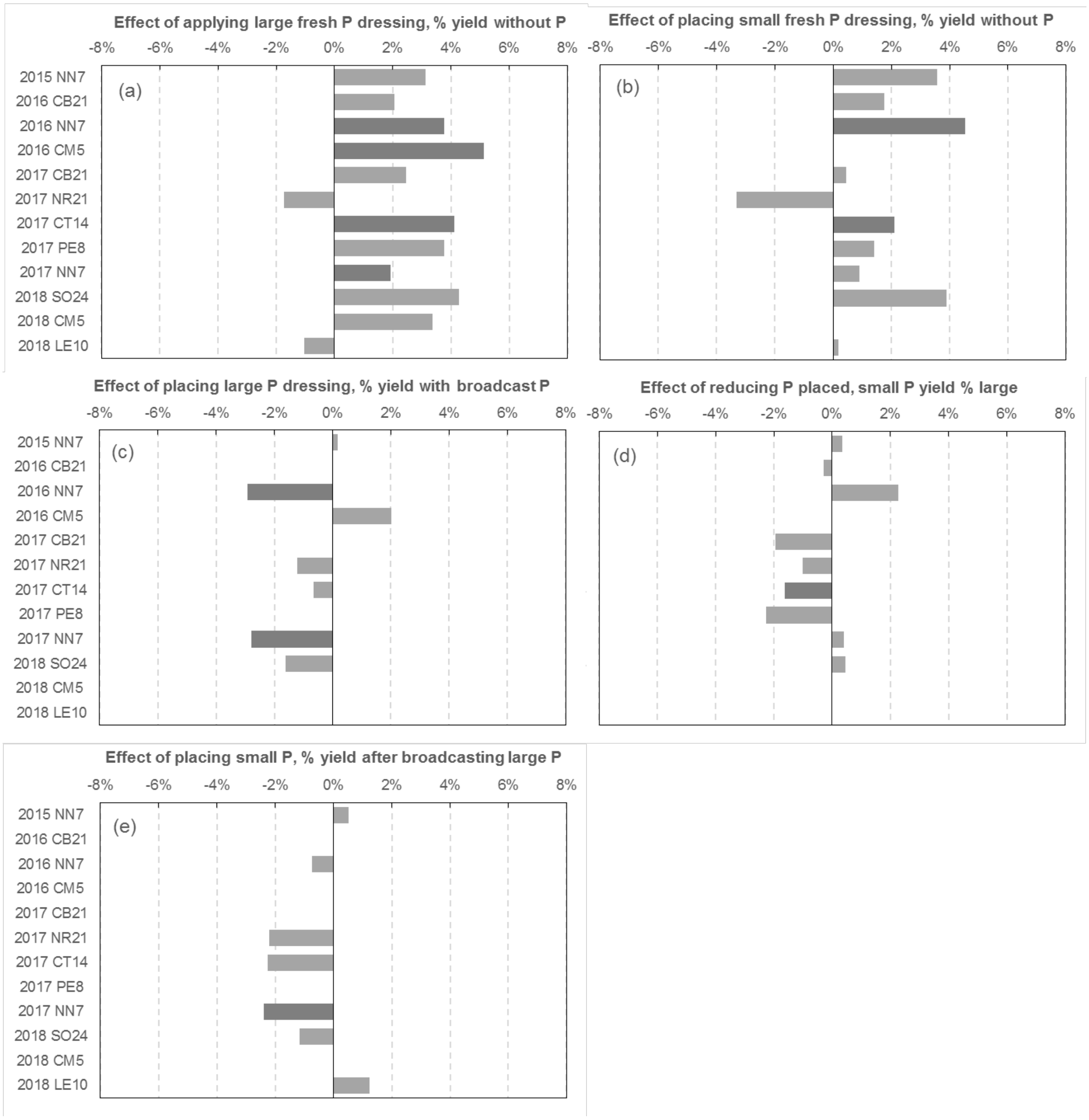

Figure 24. Summary of tramline comparisons over four harvest years from 2015 to 2018 in 12 fields (defined by site codes – see text) mostly with low levels of soil P, testing questions on size and placement of fresh phosphate dressings i.e. (a) is fresh phosphate use worthwhile? (b) is a small dressing (less than crop offtake) worthwhile, if placed? (c) is there an advantage in placing over broadcasting a large dressing (equivalent to crop offtake)? (d) what is the effect of reducing the amount of P placed? and (e) is a small placed dressing as good as a large broadcast dressing? Dark bars are statistically significant (P<0.05). Note that blank comparisons were not tested, and effects for site LE10 in 2018 were not spatially corrected.

3.4.13.2 Review of farmer-managed tramline trials

Some advantages were apparent from using tramline trials (as opposed to conventional small plot trials): primarily the farmers' tests were encountering the normal levels of spatial variability in soil P and grain yield that are experienced on these farms, so their results could be considered high relevant to this context. In addition, the farmers were also employing their actual every-day machinery, logistics, knowledge and data systems e.g. soil P maps, yield monitors on their harvesters, so there could be no doubt that the placement treatments and the crop responses to them were typical of commercial practice. Some farmers' machinery e.g. CM5, was set up for controlled traffic farming (CTF), which also happens to be best suited to tramline experimentation. This is because widths of drills, sprayers and harvesters match, and consequently the data analyst can be confident that any particular harvester bout has been driven in exact congruity with any particular treatment application, hence less data need be excluded from the spatial analyses. For example compare Figs. 13 & 22 with Figs. 11, 12 & 16.

However, the coordination of these tramline trials by Frontier proved to be a larger task than was anticipated. Various challenges arose: (i) suitability of sites depended on many conditions, so sites proved hard to find, (ii) the different characteristics of the sites and the machinery, and the need for careful trial layout often dictated that the coordinator should attend drilling, and (iii) data retrieval often required the help of busy farmers with a wide range of harvesters and data systems, so this required perseverance from the coordinators. Nevertheless the consistency in size and pattern of the results from just 12 trials (Fig. 24) was reassuring, and allowed conclusions to be drawn with satisfactory levels of confidence, which probably could not have happened with fewer small-plot experiments.

Given that this approach to agronomic research is relatively new, significant lessons were learned about logistics and practices that decrease time requirements from farmers, from coordinators and from data analysts and interpreters. Also, as hundreds of tramline comparisons are now being completed, it is becoming possible to deduce what are the key factors affecting precision of the comparisons, how the precision of comparisons can be increased, and how meta-data from Farmer Innovation Groups (FIGs) such as was created by Frontier here, are best analysed. Ever wider recognition and familiarity amongst farmers and their advisors about trial specifications and coordination will increasingly help to develop this cheaper and more relevant way of doing 'real-life' agronomic research.

4 Discussion of new findings

Initially this discussion will consider the results reported for the first time in this volume (the third volume of AHDB Report No. 570), i.e. the results arising from WP2 and WP3 of this Project.

However, publication of this report also marks the end of a series of projects (all supported by AHDB and managed by the present authors) which have extended continuously through the past ~10 years, so this discussion also offers overall conclusions from all of this work, as it concerns the efficiency of P use in UK arable agriculture. It then makes suggestions on (a) how fertiliser recommendations might now be revised, and (b) what might best happen next in terms of knowledge generation and exchange on P management in arable farming.

4.1 Soil P run-down

Rates of decrease in P levels were fast in the soils that had recently been built-up from Index 0 for the Critical P Experiments in WP2 (Fig. 3) compared to rates for the 'Run-Down' sites that had previously been maintained at P Index 2 (Fig. 8). Although no alternative approach could have determined critical P levels over a fairly short period of years, it appears that the soil P status in these experiments was not fully comparable with soils having similar Olsen P levels but after maintenance at those levels for a significant period. It therefore seems likely that the critical P levels determined in WP2 are pessimistic; i.e. values might have been smaller if they had been determined after a longer period of equilibration after the large fresh phosphate applications, because soils maintained at higher P levels for a longer period would have accumulated greater reserves of exchangeable P.

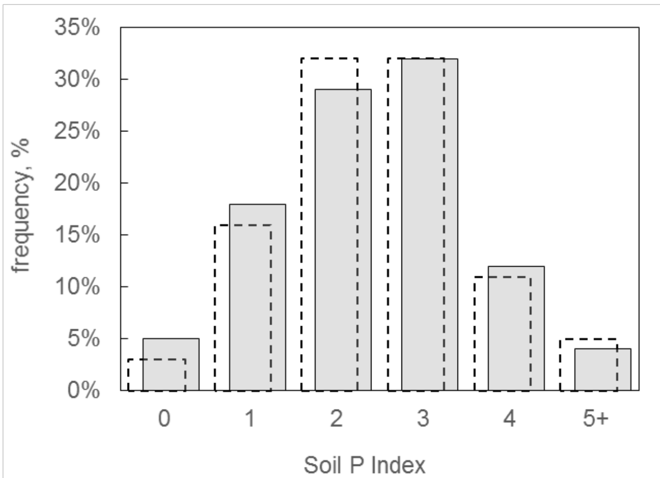

Figure 25. Frequency of topsoil P status of UK arable land averaged from 3,500 samples taken in the Representative Soil Sampling Scheme, 1995-1999 (broken line), and 65,000 commercial samples analysed in 2011-12 by members of PAAG (shaded, after Edwards *et al.*, 2012).

Given the distribution of soil P levels in the UK (Fig. 25), and the recent tendency of farmers to omit P applications that would be necessary to maintain soil P status more than in the past, it appears that more arable land in the UK is running down than has recently been built up.

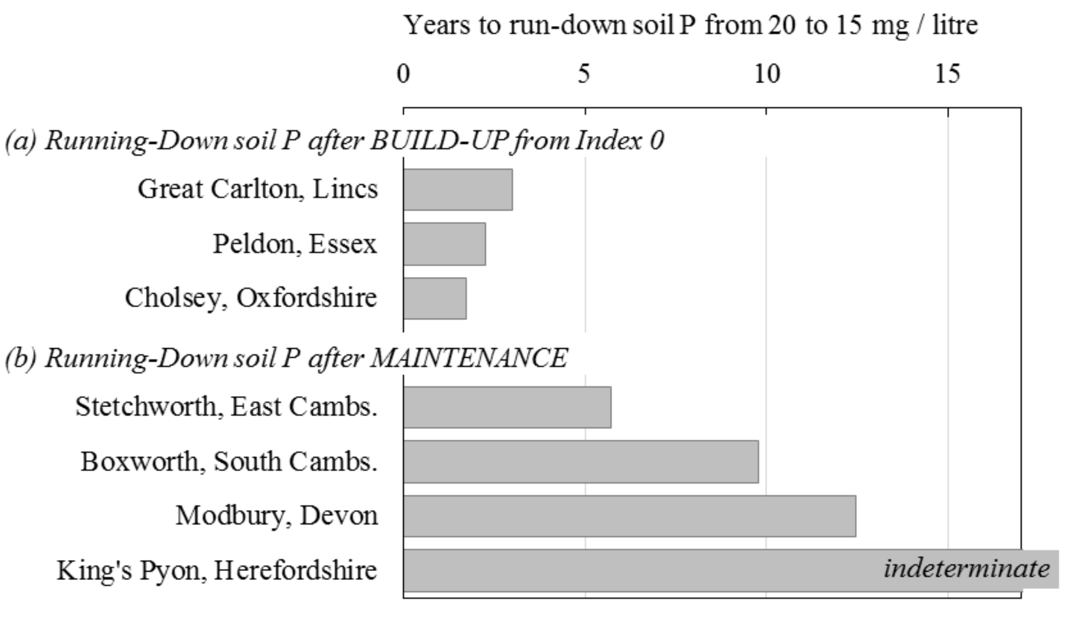

Figure 26. Periods needed to run-down Olsen soil P levels from 20 to 15 mg/l, estimated from linear slopes fitted to the data in Fig. 3 (a) where soils had recently been *built up to* Index 2, & in Fig. 8 (b) where soils had recently been *maintained at* Index 2.

The trends at the three Critical P sites and at the four Run-Down sites have been represented in Fig. 26 as the periods over which it would be expected for these sites to decrease by 5 mg/l, say from mid Index 2 to the top of Index1. They show large contrasts from 1-2 years at Cholsey to 12-13 years at Modbury, with King's Pyon yet to show a consistent negative trend even after nine years of nil P application. They also show the nine-year half-life that Johnston *et al*. (2016) adopted to summarise run-down rates in the Rothamsted experiments to be an unsafe standard for soil P management. It thus appears that new approaches should be advocated whereby land managers and their consultants can determine directly the rates at which soil P may change on any particular block of land.

However, as was noted when results from these sites were considered previously (Sylvester-Bradley *et al.,* 2016) the significant annual variations in the soil P levels at all sites blurred any interpretation of soil P trends through time, and prompted questions about how appropriate current advice is about soil P determination. Farmers are currently advised to collect one single sample per field (or part field if variation is known), to submit this for one single laboratory analysis, and to compare this result with a similar single result determined 3-5 years previously. The variability to be expected after following this advice must significantly exceed that seen in Fig. 8 because the latter arose despite a much more assiduous approach: in particular four, not one, samples were taken, each sample represented only 2-4 ha rather than a whole field, and sampling was repeated annually rather than every four or so years. With the experimental data showing such large perturbations, it is clear that significant additional factors were affecting the results, over-and-above variability due to sampling and analysis; probably concerning soil temperature and moisture conditions (Song *et al*., 2012), and probably also due to varying intervals since the most recent fertiliser application, variation in soil P sorption capacity (which is mapped in Scotland but not in the rest of the UK; SRUC, 2015), variation in mineralisation of P from soil organic matter (Saunders & Metson, 1971) and variation in soil bulk density, after drying and milling the sample (Drewry, 2013).

We suggested in our Report on WP1 (Rollett *et al*., 2017) that farms might over-come the uncertainties in temporal comparisons of 'soil test P' by making individual estimates of their Apparent Soil Phosphate Requirement or 'ASPR', largely arising from the many spatial comparisons that are possible with GPS-related data. Average ASPR values determined from the large SOYL dataset for 36 farms were 20-25 kg/ha P_2O_5 per mg/l change in soil P. These estimates can be compared with the rates of change indicated in Fig. 26. At this level of ASPR, a typical crop removing say 70 kg/ha P_2O_5 per year from the soil without any P additions would apparently reduce soil P by ~3 mg/l per year, indicating a run-down rate similar to the fastest examples illustrated in Fig. 26, and therefore indicating that ASPRs were probably underestimates. This may have arisen through using standard (RB209) assumptions about crop P concentrations and using farm estimated grain yields.

Turning to the insight of Johnston *et al*. (2016) in a soil P 'half-life', this inherently signifies that decreases in soil P (with continued cropping but no P applications) depend on the initial soil P level. Johnston *et al*. (2016) explain this largely through the model of Syers *et al*. (2008) which considers soil P being held in four pools defined by the range of exchangeabilities, thus availabilities. However, given the strong relationship between soil P, grain yield and grain P content (Fig. 5), it is equally feasible that a half-life of nine years could be fully accounted for by crop responses to soil P, with larger P offtakes occurring at higher soil P levels. It appears that responses akin to those illustrated in Fig. 5, and idealised in Fig. 27, would fully provide for this explanation.

Overall, the soil P data collated and studied within WPs 2 & 3 has revealed significant imprecision and uncertainty in the guidance available to land managers for managing the store of soil-available P, and thus crop P sufficiency. However, if responses such as in Fig. 27, particularly that of grain P, can be validated as typical, they could offer an additional, or even an alternative, approach to the diagnosis of crop P sufficiency, because crop P is still responding to soil P as grain yield reaches its maximum i.e. grain P could be used to indicate sufficient (or 'critical') P supplies. Thus the next section discusses the grain P concentrations measured here.

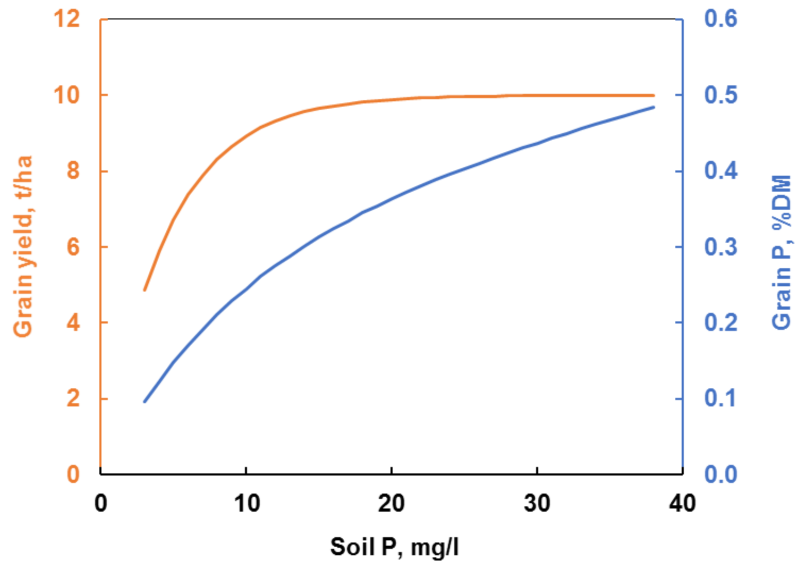

Figure 27. Typical responses of grain yield (orange line, Y) and grain P concentration (blue line, P) that would fully explain a soil P (S) half-life of nine years, where Y = 10 – 10 x 0.8^S and P = 0.3 – 0.3 x 0.9^S + 0.005 x S.

4.2 Grain P

Whilst assessments of grain nitrogen are common, grain P has been measured less habitually in agronomic research, even that focussed on P nutrition. Interest in crop P concentrations was initiated in the Targeted P project (Sylvester-Bradley *et al.*, 2016), and then extended into the Yield Enhancement Network (Sylvester-Bradley & Kindred, 2014) to explore the prevalence of low grain P across farms (Fig. 28). Data from the Critical P Project (Morris *et al*., 2016) then proved invaluable in studying grain P responses to soil and fertiliser P (Section 3.2) and data from past ADAS research and from the literature have been collated to set these findings in context (Fig. 29). All of this evidence leads to a conclusion that grain P analysis can be used both to assess crop P offtakes accurately, and to act as a more precise diagnostic of crop P sufficiency than is possible with soil P (Fig. 30).

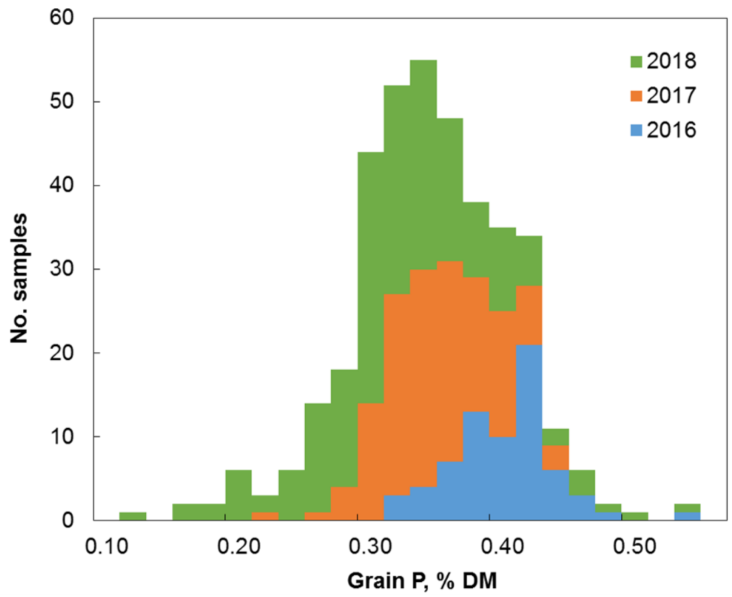

Figure 28. Frequency distribution for P in cereal grain (mostly wheat) over three recent seasons. Data are for farmer's crops entered in the Yield Enhancement Network (ADAS, personal communication).

Thus, within this Project, it now proves possible to propose crop P analysis as a new farmer-friendly tool to support and improve on-farm P management. This innovation is significant, and promises to facilitate further progress into the future.

Firstly, grain analysis showed clearly that P offtakes are generally less than is assumed in RB209 (Rollett *et al*., 2018). The RB209 value of 0.4% P in cereal grains (= 7.8 kg P_2O_5 / tonne @ 85% DM) does not represent typical grain P contents now; nor did it represent them in the 1970s. It appears that this value was chosen 'to err on the side of generosity' in the 1970s, when fertilisers were cheaper and environmental repercussions were rarely of concern. Secondly, because it appears that P in the grain represents most of the P taken up by the plant, grain P may be taken as an index of the success of the crop in capturing P. Thirdly, it seems that absolute values of grain P indicate whether or not crops would have responded to fertiliser P during their growth, as shown by the critical P experiments plus the results of similar experiments elsewhere (Fig. 29). Although the critical P experiments were probably pessimistic in estimating critical levels of soil P (see previous Section) and gave very varied results in terms of critical values (Fig. 30; Morris *et al*., 2016), the narrower range of values for *critical grain P* (Fig. 30), from across a much wider range of conditions (Fig. 29), indicates that cereal physiology offers a more stable system through which to judge crop P sufficiency, than soil chemistry and biology, so grain P should provide a new and valuable tool through which to manage P availability for cropping.

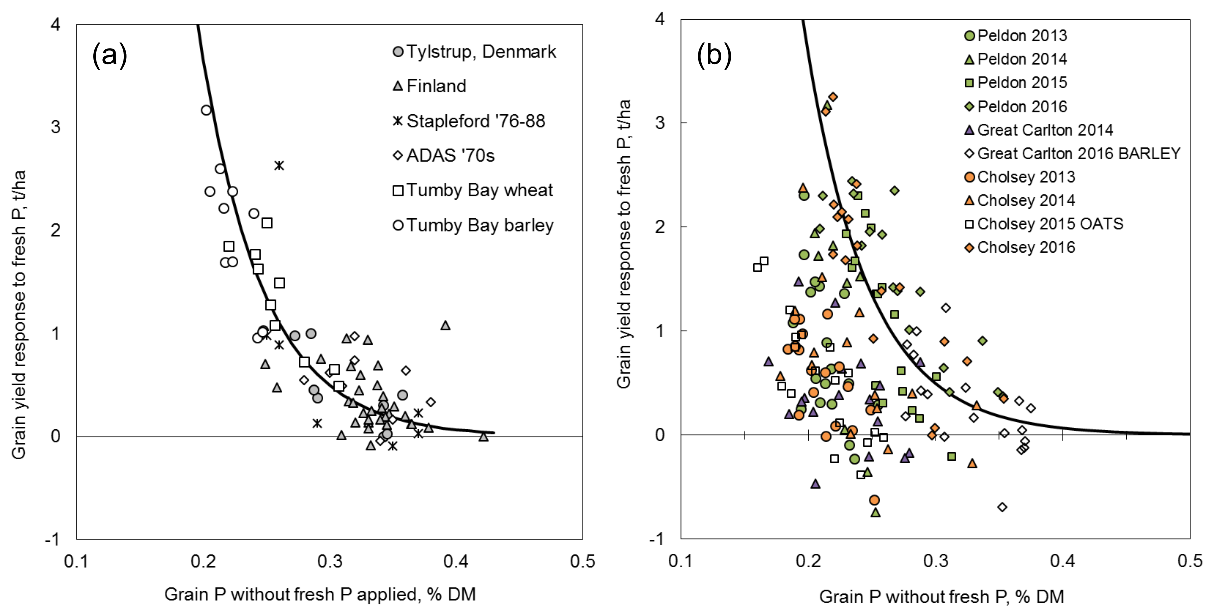

Figure 29. Grain P (a) from 57 site-seasons (published and unpublished data collated by Withers, personal communication), and (b) replotted from Fig. 6, showing how they related to yield responses to fresh fertiliser P. The line in both graphs shows Y = 200*e^{-20P}.

Not all grain P values from Fig. 6 (redrawn in Fig. 29b) conformed to the relationship derived from Fig.29a. Probably due to the analytical and sample storage issues noted in Section 2.2, grain P values determined in the first two seasons were less than would be expected from this function and must be regarded as inaccurately small. Values for the single experiment on oats at Cholsey in 2015 were also low and pose a question about oats responses differing from wheat (and barley). Even so, individual critical grain P values determined from linear fits shown in Fig. 6 were much less variable than the critical soil P values determined in the same series of experiments (Fig. 30).

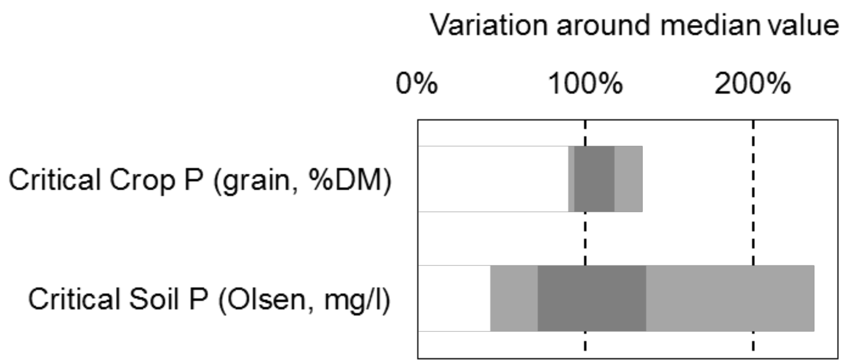

Figure 30. Distributions of critical levels of crop P (n=13; median 0.28%) and soil P (n=12; median 16 mg/l) determined from yield responses over harvest years 2010 to 2016 in the six critical P experiments reported by Morris *et al.* (2016) and here (Section 3.2).

Taking the fitted curve (Fig. 29) as the best approximation of the available data, 0.32% was the grain P level indicating a grain yield response of 0.3 t/ha, so sufficient to cover the cost of 60 kg/ha P_2O_5. Compared to this 'critical grain P value', grain P values from recent high yielding wheat crops (Fig. 28) averaged only 0.34%, and differed between years such that no crops had less than 0.32% grain P in 2016, 15% of crops had less than 0.32% in 2017 and 43% had less than 0.32% after the very dry summer of 2018; overall, 25% of grain P values from the YEN were less than 0.32%. It thus appears that a significant minority of wheat crops would currently respond to additional supplies of P. It is important that crops at risk of such deficiencies can be recognised, and it seems that this can be a role if routine grain P analysis can be adopted by the industry. The present cost of grain P analysis is approximately £20 per sample (or ~£30 if multiple nutrients are analysed), which compares with ~£11 per sample for soil analysis (for P, K, Mg & pH); if this extra cost were shared over a ten hectare field, if analyses were repeated through a four-year rotation, and if the occurrence of deficient samples was the same is in Fig. 28, if 60 kg/ha fertiliser P_2O_5 were applied accordingly, and if the crop responses were correctly anticipated as indicated in Fig. 29, a net profit (over the cost of analysis and fertiliser) from using grain P to predict the need for fresh fertiliser P would be approximately £40/ha.

Rollet *et al.* (2018) reviewed recent experimental data (including all the data arising from this project, and including 220 of the 380 YEN values presented in Fig. 28) in order to determine whether the grain P contents assumed within the Fertiliser Recommendations (RB209, which have remained unchanged for many decades) should be adjusted to reflect performance of modern crops. They suggested that the assumed offtake of 7.8 kg/t grain at 85%DM should be reduced. However, given that a critical grain P content of ~0.32% has been identified here, questions now arise of whether the P offtake assumed in RB209 should be informed by this critical value? It would seem important that assumptions about P offtake in RB209 are as accurate as possible, even if these imply that a proportion of crops are deficient. However, the distribution of data considered by Rollett *et al*. (2018) favoured sites with low levels of soil P supply compared to the existing distribution of soil P indices in arable land (Fig. 25) and, as there is a clear relationship between soil P levels and grain P contents (Morris *et al*., 2016), it may be necessary, in the absence of grain P analysis, for farms to assume a sliding scale of grain P offtakes (kg/t), according to the soil P status (such as is illustrated in Fig. 27).

4.3 P placement

The tramline trials reported here now add twelve site-seasons to the evidence-base of ten site-seasons testing placement, initiated within the Targeted P Project (Sylvester-Bradley *et al*., 2016). Fifteen of these tests have been on autumn sown crops; only four site-seasons were on spring sown cereals, plus three on potatoes. Only one of the ten to twelve comparisons of placement with broadcasting on autumn sown cereals has been statistically significant and positive, and three or four have been statistically significant and negative. One effect on winter oilseed rape was also negative whilst all effects have been small, 0.3 t/ha at most. So, along with the disappointing results from different fertiliser products tested in the previous project (Sylvester-Bradley *et al*., 2016), and different application techniques, no clear means of improving responses to fresh fertiliser P has been identified by this work, and this most obvious application method for targeting the crop has been shown quite clearly to be ineffective on autumn-sown crops. Two of the four site-seasons on spring barley proved positive for placement but further tests are required before firm conclusions can be drawn on the value of placement for spring sown crops.

One interesting observation arising from working with tramline trials rather than small plot trials was the ability to identify significant interactions between husbandry (in this case fertiliser placement) and soil characteristics (in this case soil P status; Figs. 13 & 14). Unfortunately most tramline trials were not conducted with machinery that was sufficiently accurate (as with ‘controlled traffic’) to replicate this, but it is to be hoped, as farms come to appreciate the value of and requirements for precise tramline experiments, such interactions could become a much more common topic of research.

5 Overall conclusions from recent UK P research (2009-2019)

This section summarises changes in understanding of optimum arable crop P nutrition during research over the past ten years, and suggests how the AHDB's Nutrition Management Guide (RB209) might now best be revised. The research has enabled a broad-ranging reassessment of the status of P nutrition across arable farming in the UK; in particular we have shown that:

- Around 25% of cereal crops in the UK appear to be deficient in P, and are therefore likely to respond to increased supplies of available P.
- Soil P analysis only achieved modest certainty in predicting crops that would respond to increased soil P status, whereas crop P analysis provided better confidence in identifying crops that would respond to added P.
- P-containing fertilisers provided 8% or less of their P to the arable crops to which they were applied, so (unless applications far exceeded amounts of P taken off) they had limited capacity to overcome anything exceeding a small P deficiency.
- Current P supply strategies for arable crops are therefore reliant on building a sizeable store of P in the soil which unfortunately (a) costs the industry ~£95 million per year just in fertilisers, (b) of which the P is never fully recovered, so transfers mined P into an unrecovered soil legacy, and (c) is associated with levels of reactive P in run-off and drainage waters that exceed EU targets.
- Whilst the current AHDB Nutrient Management Guide (RB209) makes little distinction between the efficiencies of different P fertilisers, other than to (apparently) favour water-soluble P forms, the fertiliser industry offers a wealth of fertilisers, differing in composition and form, which must differ also in efficiency. A further wealth of organic manures is available which (a) contain recycled P and (b) must enable different levels of P recovery by crops.
- Suppliers of fertilisers and bio-stimulants are now encouraged to provide evidence of their efficacies, so this information should ideally be used to inform choice of P fertiliser products.
- Conditions under which fertilisers and manures are used must be expected to affect their efficiencies, so end-users of fertilisers and manures must assume some responsibility for the efficacies of the crop nutrition products-cum-application-practices that they adopt, including comparison of alternatives where possible.
- There remains much scope to improve the cost-effectiveness and efficiency of crop P nutrition in arable farming, both through adoption of better practices and through generation of new knowledge to support better practices.

5.1 Suggestions for revisions to RB209

The current philosophy for P management advocated in the AHDB Nutrient Management Guide (RB209) originated in the first part of the last century, 'crystallised' in the 1960s (Johnston & Poulton,

2014) and has been perpetuated with only small modifications ever since. After the decade of recent research culminating here, a major shift in this philosophy appears merited, with this shift being seen as initiating (but far from completing) a transition to more efficient, cost-effective and sustainable management of P in arable agriculture. The principle feature of this shift must be <u>a change of focus from the soil to the crop</u>. The P being managed must be entirely predicated on maximising the profitability of crop performance; soil fertility should not be the end in itself. Ultimately the ambition for crop P nutrition might be for crop performance to be maximised with only attention to the crop, and without a need to attend to the soil; however, this is not feasible at present because no fertiliser has been identified as being capable of overcoming anything other than a small P deficiency, so the philosophy arising from research to date is to own this ultimate 'crop-centric' ambition, and to prepare for this through a hybrid strategy which is designed to evolve as crop P supply technologies improve; this strategy is to gauge and promote crop performance, whilst husbanding soil P fertility appropriately.

In broad terms, the new aims for RB209 being suggested here are to explicitly address each of the three key elements of any productive, profitable and sustainable nutrition system for arable cropping, as follows:

1. **The Crops:** Routinely gauge all crops' P sufficiencies.
2. **The Soil:** Maintain the minimum necessary soil P 'fertility'.
3. **P Fertilisers & Manures:** Directly feed each crop in the most efficient way.

The research reported here has shown, or has considered, a range of means whereby P status of crops can be monitored with confidence, including analysis of grain or other harvested materials, leaf analysis, and yield comparisons (mainly through in-field yield mapping). The research reported here has also exposed the modest confidence applicable to soil P analysis and its interpretation, and has proposed a range of ways to manage this, including particularly 'campaign sampling'. Lastly, the research reported here has also revealed massive opportunities for enhancement of crop recovery from P applications.

Given this proposed change in philosophy for arable cropping, plus the increasing prospect of more stringent environmental targets for P management on arable land, plus the increasing need to recycle P within agriculture, we suggest that AHDB should consider a new publication with a working title of 'The AHDB Phosphorus Management Guide', because the fundamental changes in philosophy will be difficult to communicate simply through modifications to the current text of RB209.

Nevertheless, a review of the current (2017) version of RB209 (Section 1, providing principles, as well as Sections 4 & 5 providing crop-specific recommendations) was undertaken so that points from the recent research could be identified for consideration in any future revisions of RB209. These suggestions are listed below, the primary over-arching suggestion being that P management on land growing arable crops should become crop focussed rather than soil focussed; so a farm-specific policy for P management should be developed that is tailored according to the expected crop rotation and the P responsiveness of those intended crops. Our suggested revisions to RB209 come under four sub-headings: (i) Develop P management primarily with a crop focus, (ii) Recognise that using the topsoil as a store of P is inherently inefficient and has environmental repercussions, (iii) Develop bespoke soil P management for this land. Interpret soil and crop P analyses with care, and avoid over-reliance on 'soil test P', and (iv) Maximise efficiency of P applications. Suggestions relevant to each sub-heading follow here:

5.1.1 Develop P management to have a crop focus

- For each field, determine whether P is sometimes or always restrictive of yield by:
  - Examining yield patterns and soil P patterns across each field to see if they coincide.
  - Spot-testing P contents of crop and soil where yields are known to be low and high.
  - Test for obvious effects of large P supplies on crop growth, either by manually treating a patch (apply say 500 kg P_2O_5 to say a one hectare square per field) and observe any plant effects, or treat whole tramlines differently[5].

Table 18. Suggested new layout and values for table providing default removals of phosphate and potash by arable crops in the UK.

		Phosphate (P_2O_5)	Potash (K_2O)
		kg/t of fresh material	
All Cereals	Grain only	6.5	5
	Grain and straw[a]	7	11
	Straw[b]	1.2	11
Oilseed rape	Seed only	14	11
	Seed plus haulm[a]	15	18
	Haulm[b]	2	13
Pulses	Field beans and Dried peas	10	11
	Vining peas	2	3
	Bean or pea straw[b]	3	16
Potatoes	Tubers only	1	6
Sugar beet	Roots only	0.8	1.7
	Roots and tops	2	7.5

a. Values are per tonne of grain or seed removed and include nutrients in straw assuming this is also removed without weighing.

b. These values to be used only when straw weight is known. Potash content of straw can vary substantially – higher than average rainfall between crop maturity and straw baling will reduce straw potash content.

[5] Note that seedbed applications of fertilisers containing water-soluble P rarely affect grain yields by more than 0.4 t/ha so visually obvious effects on crop growth are more telling than yield comparisons. Note that whole tramline effects can be inspected with little cost or trouble using satellite imagery.

- Where crop P status is moderate, low or uncertain, adopt annual analysis of P in all harvested produce – cereal grains, oilseeds, sugar beet roots, potato tubers, etc. – as well as occasional analysis of leaf tissues, to augment less frequent (and more laborious) soil P analyses. Note that crop analysis is multi-purpose: it both monitors crop P removals and predicts sufficiency of crop P supplies, whilst also providing useful intelligence on crop status for at least six additional nutrient elements[6].
- Crop P analysis is also useful where soil P status is high, because it measures offtakes and assesses crop status of non-P nutrients. However, if analysis is not undertaken, P removals may be estimated from Table 18[7].
- The industry needs to be working towards a future new P management philosophy which will rely less on fertiliser P inputs, less on soil P storage and more on directly feeding the crop (as with nitrogen). In particular farmers should be looking to change two key aspects of P nutrition:
  (i) Better monitoring techniques that reliably identify impending crop P deficiencies.
  (ii) Better application systems (fertilisers, manures, formulations & application methods and timings) giving more immediate recoveries of applied P by crops, and
- (Although not a subject of the research summarised here) it must also be recognised that recycling of P in UK agriculture has huge scope for improvement, and that recycling to arable land (rather than grassland) is commonly advantageous for the environment.

5.1.2 Develop bespoke soil P management for each field and its crop rotation

The following suggestions are made after finding large apparent differences in the capacities of soils on different farms to fix and re-release soil P for uptake by arable crops (Rollett *et al*., 2017), and having no capacity to estimate this (except in Scotland; SRUC, 2015) and recognising significant uncertainties in the precision with which available P can be measured in soil.

- Maintain a continuous field-log of crop yields, P in harvested materials, straw & haulm removals, soil P levels and P_2O_5 additions in fertilisers, manures or other amendments, so that soil P can be assessed and managed perennially.
- Set a target soil P status (index) according to all crops in the intended rotation (rather than for individual crops) and decide on a perennial soil P management strategy for each field (or sub-field zone), options being either: (i) run-down, (ii) maintain or (iii) build-up.
  - Soil P Index may be maintained at 1 for arable situations where only autumn-sown crops are grown, soil structure and crop establishment tend to be good, and some fresh P

[6] Analysis of P concentrations in grain or other harvested materials is normally accompanied by analyses of potassium, magnesium, sulphur, manganese, copper, zinc and other nutrients at no extra cost.

[7] Table 18 has been revised from Table 4.11 in the current version of RB209, taking into account the levels of precision that are justified for each value, and new evidence presented by Rollett *et al*. (2018) and in Figs. 28 & 29. Values have been included for potash for completeness, but these have not been reviewed here.

fertiliser can be applied each year. This strategy is likely to be economically and environmentally advantageous for rotations with just cereals and oilseeds. Fresh P fertiliser usually raises yields at P Index 1 to the same as at P Index 2, but seldom makes crops at P Index 0 perform as well as at P Index 2.

  - Soil P Index should be maintained at Index 2 for other arable situations e.g. including rotations including spring sown crops; this should ensure P does not limit yield even under adverse conditions and where fresh P may be omitted.
  - Soil P Index should be maintained at Index 3 for rotations which frequently include vegetables, potatoes or maize.
  - Soil P may be run-down from above Index 3 without risk of losing crop production. Crops on fields being run-down should be analysed regularly (at least every 1-2 years).
- Determine and differentiate between soils that are building up or running down – soils running down contain more ‘fixed’ P so, through equilibration, they are less likely to cause short-term deficiencies. Note that the amount of P required to change Olsen P varies from farm to farm and according to soil type so run down should be monitored.
  - Added P may be immobilised at different rates depending on soil type, for example fixation is fast on shallow soils over chalk or limestone. On soils such as these with high ‘buffer power’, it will often be uneconomic to build-up P status, and best to sustain soil P status using organic manures as well as inorganic fertilisers.
  - Soil P changes also appear to depend on farming practices due to differences in the ways crop yields, P contents, cultivation practices, depths and times of soil sampling, are estimated, so growers should not assume that standard recommendations, even if adjusted for yield, will necessarily achieve their intended effect; they should check.
  - Soil P should be maintained according to offtakes actually recorded, rather than to replace anticipated future offtakes. If crop P analyses are not known, assume P offtakes accord with the suggested revised values (see Table 18; working from new offtake data of Rollett *et al*., 2018 and additional data for 2018 in Fig. 28).
- Admit that the Olsen method for ‘soil test P’ is inherently less reliable than soil analyses for potassium or magnesium, or crop analysis for P, so it is important to standardise soil P testing closely, and double-check, as follows:
  - Take & consider many samples together, i.e. even if not GPS sampling, organise sampling in ‘campaigns’, whole farms or even several adjacent farms being sampled, analysed and interpreted together (this may be most convenient where a sampling agency is employed).
  - Standardise all sampling conditions (including previous crop, sampling month, sampler, sample positions, sampling depth, lab. choice, etc.).
  - Check soil results against crop data and past data, and repeat analyses showing large contrasts or surprises, or analyses for which differences are not corroborated.

- AHDB should work with PAAG on Quality Assurance for soil P sampling and analysis.

5.1.3 Maximising crop recovery from P applications

The key importance (for both economic and environmental efficiency) of successful crop recovery of applied P should be emphasised and as much guidance as possible should be offered, whilst acknowledging the considerable current uncertainties about relative efficiencies of different materials, products and methods, and pointing to the big scope to extend and improve industry information. The normally low recoveries (of <10% P) from most materials currently used should be acknowledged, and this should be attributed to fast soil immobilisation of available P especially on calcareous soils.

Table 19. Suggested new layout and values for table providing phosphate and potash recommendations for annual application to cereal and oilseed crops in the UK. Note that potash values are presented (in grey) to show their proposed format but their values have not been revised.

Crop & Yield level		Phosphate (P_2O_5)		Potash (K_2O)	
		Straw ploughed in / incorporated	Straw removed	Straw ploughed in / incorporated	Straw removed
To maintain the existing soil Index, kg/ha					
Cereals	6 t/ha	40	45	30	70
	8 t/ha	55	60	40	90
	10 t/ha	70	75	50	110
	12 t/ha	80	90	60	135
Oilseeds	1.5 t/ha	25	25	20	30
	3.5 t/ha	50	55	40	65
	5.0 t/ha	70	75	55	90
To increase the soil Index over 5-10 years, kg/ha[8]					
Cereals	6 t/ha	90	95	80	120
	8 t/ha	105	110	90	140
	10 t/ha	120	125	100	160
	12 t/ha	125	135	110	185
Oilseeds	1.5 t/ha	75	75	70	80
	3.5 t/ha	100	105	90	115
	5.0 t/ha	120	125	105	140

Factors that could be noted as improving crop recovery of P from fertilisers and manures should include:

- Annual P applications, as opposed to more infrequent 'rotational manuring'. Quantities for annual application are suggested in Table 19, either to build-up or to maintain soil P status. Smaller

[8] *See also RB209 Section 1, Page 29 and Table 1.6.*

annual applications than these may prove adequate if the total P applied through the rotation either exceeds of equals these amounts.

- Fertiliser distribution, with placement possibly being positive for yields of spring crops (e.g. potatoes & barley) but probably not for winter wheat or winter oilseed rape.
- Water solubility is not essential to P fertiliser efficiency; although some soluble P may help to support early crop growth, slow release from less soluble e.g. organic sources can give better P recovery overall than immediately soluble sources e.g. TSP. Manures, biosolids, etc. and products derived from them are also more sustainable than manufactured fertilisers because they recycle P, and their mineralisation during crop growth tends to match crop demand.
- Ammoniacal P fertilisers (DAP, MAP) may be more efficient than superphosphate but are usually restricted to being applied in spring (because of their N content).
- Products for direct application to crop plants (on seed or foliage) may be claimed to improve crop P recovery, and the immediacy of yield responses, but these are unproven, as yet.

5.2 Proposed further knowledge generation & exchange on P management

Of the three key strategies proposed by Edwards *et al.* (2015) at the start of this research to develop more sustainable P use [i.e. (i) minimising crop P requirements, (ii) maximising root recovery of soil P, and (iii) developing targeted fertiliser technologies with as complete P recovery as possible] only the third received any attention here and that was severely limited by the long period taken to run-down soil P levels and thus to create satisfactory conditions in which to test new technologies.

Meanwhile a new capacity to screen and interpret grain P has indicated that arable crops are quite commonly affected by P deficiencies. The biggest challenge is to identify new products and/or practices that can treat these deficiencies effectively.

After selecting sites with low available soil P, the small plot experimentation undertaken through the past ten years was able to show the inefficiencies of mainstream products and practices (e.g. broadcasting or placing TSP in the seedbed) and a few alternatives. However, the capacity of these small plot trials has been modest – only a few products and practices could be tested sufficiently thoroughly for conclusions to be made with at least modest confidence.

Development of P deficiencies at three of the four run-down sites (Fig. 8) now opens the way for more confident testing of new technologies because interactions with soil P status are now testable directly on these sites. It will therefore be important to secure these sites, develop site management plans and protocols, and select new technologies, along with appropriate funding, so that efficiency testing can proceed over the next few years (see Box). However, the availability of these sites is not yet certain, there are only three, and their capacity to address the urgent need for progress on-farms is modest. Given the evidence of farm-specific interactions, and the multiplicity of possible new technologies (for instance including breeding of new crop varieties, seed dressings, foliar sprays, formulated fertiliser products, enhancers, mychorhizae and other biologicals), an additional new, broad and open approach to future research is also required.

We therefore propose that a new farming-centric 'Phosphorus Efficiency Network' be formed, using similar principles to those governing the Yield Enhancement Network, or YEN (Sylvester-Bradley & Kindred, 2014) which has grown into a successful pre-competitive farmer-centric research operation over the past six years. The so-called 'PEN' would adopt the 'farm-centric' or 'bottom-up' philosophy described by Sylvester-Bradley *et al.* (2017; 2018); thus it would be an open, industry-wide collaboration between all parties interested in improving the efficiency, profitability and sustainability of P use in agriculture. Benefits to farmers would include provision of technical support, benchmarking of P status of their crops, and independent testing and intelligence of P-efficiency technologies. Benefits to the support industry would be access to proponents of on-farm testing, and active dissemination of independent evidence on their new or evolving technologies. Benefits to government would be availability of up-to-date intelligence of the efficiency of P use, and of progress in improving commercial practice. Proposed activities of the PEN would include:

EXPLOITING PAST INVESTMENT IN RUN-DOWN SITES

Three of the four run-down sites are now showing P deficiencies (see below) so can be used to test efficiency of varieties, products and practices which offer to overcome these.

However, work will be required to secure these sites, and address uncertainties, as follows:

- Future ownership and management preferences and costs of land use?
- Rotations and flexibility of cultivation and cropping?
- Numbers of treatments comparable each year?
- Likely precision of comparisons?

1. **Testing products & practices for P use efficiency**
   - Identify & maintain P efficiency-testing sites
   - Test Fertilisers, Biologicals & Application methods
   - Compare species, varieties and breeders' germplasm
2. **Improving and promoting P monitoring**
   - Promote farm use … & provide software
   - Establish metrics (of efficiency), standards and benchmarks
   - Develop Sensing, Monitoring & Analytical approaches
3. **Disseminating best practice and relevant science**
   - Develop a P Management Guide for all farms … Arable, mixed and grassland farms
   - Design more P-efficient farming systems
   - Develop relevant science e.g. effects of P additions and types on crop P status.
   - Liaise with academic initiatives on P, e.g.

ADAS is keen to work with all interested parties to establish the PEN over the coming year or so.

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Appendix 1.

Rundown sites: Mean soil P (mg/l) and standard error of the mean (SEM).

Year	Devon		South Cambridgeshire		Herefordshire		East Cambridgeshire	
	Mean	*SEM*	*Mean*	*SEM*	*Mean*	*SEM*	*Mean*	*SEM*
2010	20.5	1.55	24.0	0.98	16.8	0.62		
2011	17.5	1.06	21.1	1.78	10.8	0.89	19.8	1.52
2012	17.9	0.85	15.3	0.84	13.9	0.62	21.6	2.90
2013	20.4	1.50	23.6	2.88	17.9	1.89	16.4	1.78
2014	18.4	1.56	20.5	3.51	21.0	1.42	15.7	1.60
2015	18.6	2.29	18.4	4.25	16.9	0.25	20.3	1.56
2016	19.9	1.84	18.4	1.24	15.1	1.80	14.1	1.43
2017	14.0	1.29	14.9	1.45	17.4	1.22	12.9	1.21
2018	13.4	1.06	13.8	0.82	21.6	2.28	14.5	1.24