Research Project No. 2160004

Cost-effective phosphorus management on UK arable farms

Report on Work-Package 1:

Apparent soil phosphate requirements

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Abstract

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 super phosphate 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 required less P_2O_5 (additions or removals) to change soil P by 1 mg/litre than is suggested in RB209 (i.e. less than 40 kg/ha was needed).
- 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 Introduction

Better phosphorus (P) management strategies are required to reduce growing costs, preserve finite global P reserves and reduce export of P to livestock and in runoff from land, whilst also facilitating renewed enhancement of crop productivity. The underlying principle of the current philosophy for P management in the UK is to bring deficient soils up to a target 'index' that will be non-limiting for the rotation and then to maintain them at that level by applying fertiliser or organic materials to replace P removed in crops at harvest (Knight *et al.,* 2012). The soil is therefore treated as a store of P which is maintained at a 'critical P' level from which enough crop-available P will be released to satisfy requirements of crops throughout their lives.

In the last 30 years, inorganic P inputs to arable land have halved, mainly as a result of lower application rates (BSFP, 2015); whilst average crop yields have been maintained or increased. Despite these lower application rates, the overall P budget for UK fields in 2014 was still a surplus of 6 kg P/ha of managed agricultural land (i.e. inputs exceeded offtakes), although the size of the surplus is showing a downward trend (Defra, 2015). In addition, there is little evidence of decreasing soil P (mean soil P for arable land 29 mg/l; PAAG, 2013-14). However, some farmers are concerned that they may be approaching a 'cliff-edge' of P deficiency, so that yields may soon become reduced unless inorganic P applications are resumed or increased.

P recommendations for arable crops in England, Wales and Northern Ireland (RB209; Defra, 2010) treat all soil types the same in terms of soil analytical method, critical soil P levels, and advised rates of P fertiliser application. However, scientific knowledge, extensive farm experience, and some recent experimental results indicate that soils differ, at least in rates of soil P decline and P-balance (inputs minus offtakes) required to change soil P levels; so basing current P fertiliser policy on the same P-balance approach may not be right for all situations and can probably be improved. Also, those operating soil analysis services on farms have noted in recent years that the decline in topsoil Olsen P (a sodium bicarbonate soil extract at pH 8.5; as described in 'The Analysis of Agricultural Materials', MAFF RB427) varies with site, as well as with P level, such that the RB209 recommendation for repeat analysis every 4 or 5 years may allow some soils to decline too far for maintenance of optimal yield before they are reanalysed.

Services in support of commercial precision-farming, such as by SOYL, have generated large soil nutrient databases over recent decades and their careful analysis may provide a more precise assessment of factors affecting P decline than has been possible hitherto from experimental evidence. In reviewing past evidence on P decline, Syers *et al.* (2008) concluded that soils at Saxmundham, Suffolk showed a half-life for Olsen's extractable P of nine years (with a mixed cereal, beans and roots rotation from 1968-84) where no P was applied; soil P was reduced by crop uptake, but the decline relative to uptake was larger from high soil P levels (c.60 mg/kg Olsen P) than from

low soil P levels (<10 mg/kg Olsen P). Also, decline in Olsen's P concentrations may be greater in light-textured than in heavy-textured soils due to a smaller P buffering capacity (Heming, 2007).

So far AHDB has addressed these uncertainties by funding two projects: the Critical P Project (RD-2008-3554) led by NIAB which reported in 2014 (Knight *et al.*, 2014), and the Targeted P LINK Project (RD-2007-3454) led by ADAS, due to report in 2016. Both of these projects prepared reviews to summarise the current state of knowledge in each area (Johnston and Poulton, 2011; Edwards *et al.,* 2015). Only a brief summary is given in the following paragraph, because both reviews mainly concern aspects of crop P nutrition <u>other than</u> *rates of change of soil P*, the main purpose of this Work-Package.

Johnston and Poulton (2011) found that variation in critical P at three sites was substantial, and critical P levels of Index 2 or above occurred in only a minority of years (*Table 1*).

Table 1 Percentage of years with critical soil P at each soil P index for three long-term sites

Site	Soil P index	0-1	2	3
A well-structured silty clay loam at Rothamsted		87%	9%	4%
A poorly-structured sandy clay loam at Saxmundham, Suffolk		43%	36%	21%
A poorly-structured heavy silty clay loam at Rothamsted			75%	25%

However, the variation in critical P appeared to depend on soil conditions, and the number of sites is too few to formulate confident advice for the whole arable industry, so further evidence was acquired in the Critical P project (Knight *et al.,* 2012). Edwards *et al.* (2015) concluded that reliance on soil P storage rather than on fresh P (fertiliser additions) 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.* (2015) 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. RB209 recommendations are that fresh P additions cannot make up fully 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 from the Critical P project have not necessarily supported this.

Irrespective of our certainty or uncertainty in particular critical levels of soil P, if the soil is to be used at all as a store of P for crop growth, it is necessary to monitor and manage this store, so that it does not become 'empty' leading to reduced crop yields, or over-full through over-expenditure on fertiliser.

And it is the monitoring and management of soil P that is the prime concern of this Work-Package. At present the current version of the RB209 (Defra, 2010) again treats all soils the same as far as soil P maintenance is concerned; the salient section is on page 39, and reads:

> *Large amounts of phosphate and potash may be required to raise the crop-available phosphate and potash in the soil by one Index, and it is difficult to give accurate amounts. However, as an example, to increase soil phosphate by 10 mg P/litre may need 400 kg P_2O_5/ha as a phosphate fertiliser (i.e. 850 kg/ha of triple superphosphate). … To apply such large amounts in one dressing is expensive. Consequently, smaller amounts of phosphate and potash are shown as the build up applications … in the Tables in Sections 4 to 8. … Using these amounts in addition to the maintenance dressing should result in the soil Index increasing by one level over 10-15 years where arable crops and grass are grown and 5-10 years where vegetables are grown frequently.*

Thus RB209 currently suggests (what we call here) an 'Apparent Soil Phosphate Requirement (ASPR) of 40 kg/ha/mg/l, and whilst it indicates that this value is uncertain, there is no suggestion that this amount might vary consistently with soil type. The evidence supporting these suggestions comes from a very few sites where long-term experimental studies have been undertaken. However, Heming (2007) concluded (after analysing a dataset of 1,300 records from southern England) that calcareous and 'red' soils appeared to require additional quantities of fertiliser P if their soil P analysis was to be maintained. Also, organic materials are becoming an increasingly important, but have been a somewhat neglected component of P-balances; *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 digestate) (Defra, 2015), yet there is some uncertainty about the level of immediate P availability from organic sources.

The aims of the Work Package reported here were therefore to improve our understanding of the factors affecting the rates of change in soil P status as a result of P_2O_5 additions from both fertiliser and organic P sources. The Work-Package analysed data from two contrasting sources: (a) nine medium to long-term replicated field experimental sites (with differential P inputs as both fertiliser and organic materials and repeated measurements of soil P status), and (b) the extensive SOYL database from which P_2O_5 'balances' (inputs minus offtakes) could be assessed (using the method advised in RB209) and changes in soil P status could be calculated, all across a wide range of soil types and cropping conditions. Thus the idea being tested in this work-package is that soils might differ in the way soil P changes relate to P_2O_5 balances, as a result of both different types of input and different soil types. The results should help to refine future fertiliser policy by increasing the confidence with which P_2O_5 inputs from fertiliser and organic materials are used.

2   Materials and methods

2.1   Long-term experiments

2.1.1   Selection of experimental dataset

Data were obtained from seven long-term experiments (funded by MAFF/Defra and managed by ADAS since the early 1990s; *Table 2* & *Figure 1*). These experiments were designed primarily to compare other aspects of organic materials, such as their effects on soil organic matter or impacts of their heavy metal content on crop performance. However, their designs did also happen to allow assessments of the impact of phosphorus (P) inputs from both fertilisers and organic materials on crop P offtake and on soil P status across a range of soil types and crop rotations. These experiments compared a range of treatments including manufactured fertiliser P and organic materials (i.e. farmyard manure, slurry, poultry manure and biosolids), and had regular measurements of Olsen P status plus annual measurements of P offtake from replicated treatments.

The approach taken with the data was to calculate P_2O_5 balances for each of the site-treatment combinations and compare these with measured changes in topsoil Olsen P status in order to assess relationships between P_2O_5 balance (according to form of P input) and soil P.

2.1.2   Relationship between soil P and P_2O_5 balance

Phosphate (P_2O_5) balances were calculated for each of the 7 experimental sites on an annual and cumulative basis (for the whole experimental period) as follows:

P_2O_5 balance (kg/ha) = *P_2O_5 inputs (kg/ha: manufactured + organic) – Crop P_2O_5 offtakes (kg/ha: straw, grain, grass etc.).*

Details of annual manufactured fertiliser and organic (i.e. FYM, slurries, biosolids etc.) P_2O_5 inputs were available for all experimental sites, together with crop yields and the fate of crop residues (i.e. baled/incorporated). However, the P_2O_5 contents of harvested materials were not always measured. Where these data were not available, standard values for the P_2O_5 content of grain and straw were taken from the Fertiliser Manual (RB209; Defra, 2010) to calculate crop P_2O_5 offtakes. Treatments (i.e. fertiliser policy/organic material type; *Table 2*) were replicated 3-4 times, depending on the site; P_2O_5 balances were calculated using treatment means for P_2O_5 input and offtake calculations.

Soil extractable P (Olsen P mg/l in the top 0-7.5 cm for grass at Faringdon; 0-15 cm at Ropsley and SOIL-*QC* sites; 0-25 cm at the long-term sludge sites) was usually measured every 3-4 years (in line with RB209 guidance; Defra, 2010) on a plot by plot basis. Average soil P concentrations for each treatment were compared with the P_2O_5 balances as follows:

- For each measurement period, the following variables were calculated:
    1. Change in soil P (Δsoil P mg/l) between sampling at time 1 and resampling at time 2.

Table 2. Medium to long-term arable experimental sites included within the data analysis

| No	Site	Soil texture (% clay)	Treatments	Rep-licates	Start date	End date	Project
1	Ropsley	Sandy clay loam (27%)	Phase I: 4 manufactured P fertiliser policies (nil, low, replacement and build-up)	4	1977	1985	HGCA Targeted P (and previous HGCA project Report No. 224)
				3	1986	1996	
			Phase II: 0, 70 or 100 kg/ha P_2O_5				
2	Gleadthorpe	Loamy sand (6%)	Manufactured fertiliser, broiler litter (5 rates)	3	1994	2009	Defra SP0530 (SOIL-*QC*)
3	Terrington	Silty clay loam (28%)	Manufactured fertiliser, pig FYM, pig slurry	3	1994	2012	Defra SP0530 (SOIL-*QC*) & WR1212; WRAP OMK001-001 (DC-*Agri*)
4	Harper Adams	Sandy loam (12%)	Manufactured fertiliser, cattle FYM, cattle slurry	3	1999	2013	Defra SP0530 (SOIL-*QC*) & WR1212; WRAP OMK001-001 (DC-*Agri*)
5	Gleadthorpe	Loamy sand (6%)	Manufactured fertiliser, biosolids cake	3	1994	2010	Defra SP0130/39 (Long-term sludge experiments)
6	Rosemaund	Silty clay loam (30%)	Manufactured fertiliser, biosolids cake	3	1994	2005	Defra SP0130/39 (Long-term sludge experiments)
7	Bridgets	Silty clay loam over chalk (23%)	Manufactured fertiliser, biosolids cake	3	1994	2005	Defra SP0130/39 (Long-term sludge experiments)
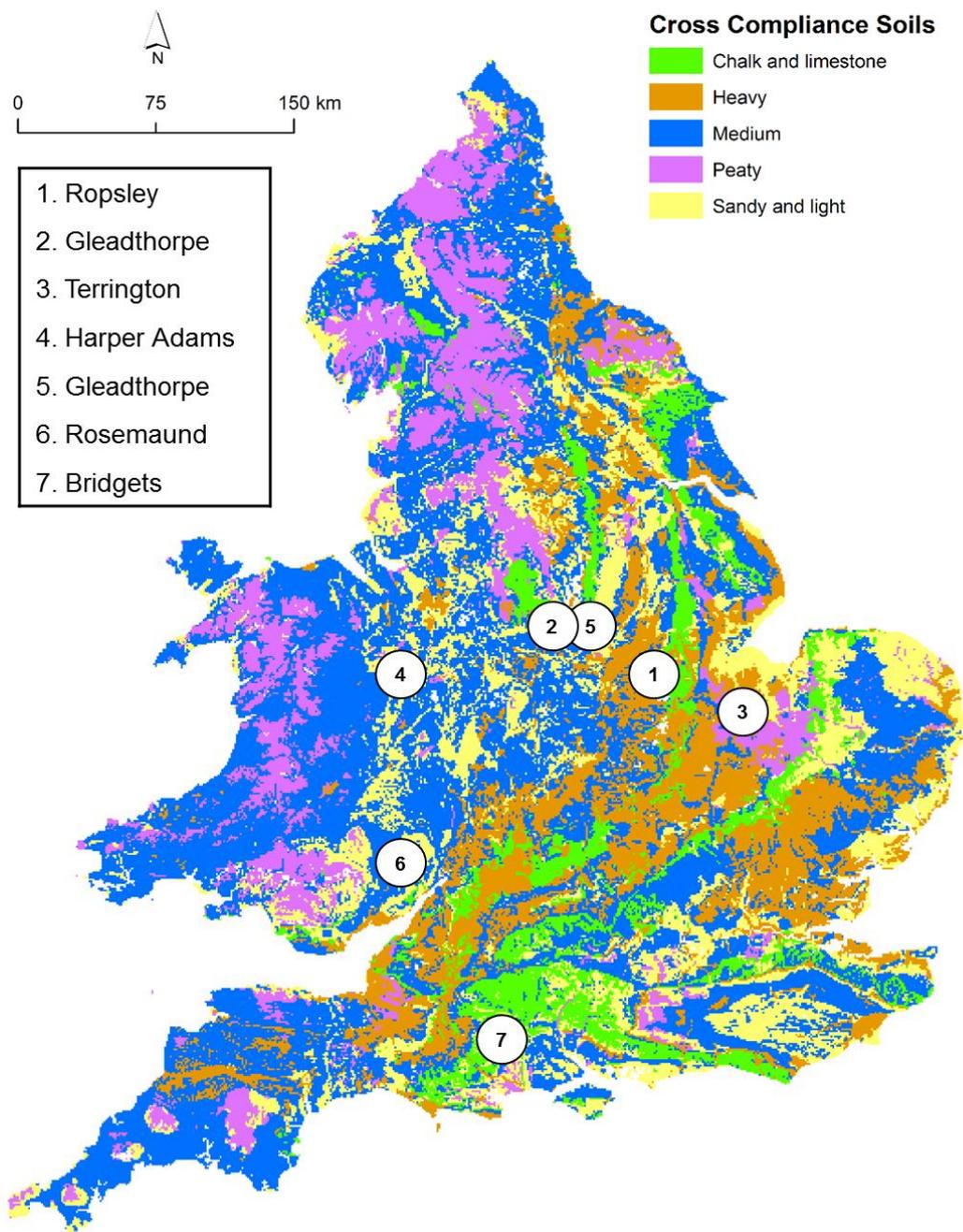
Figure 1. Map of long-term arable experimental site locations include in the analysis.

2. P_2O_5 balance kg (P_2O_5/ha): total P_2O_5 inputs (between time 1 and 2) minus total P_2O_5 offtake (between time 1 and 2).

- For each interval the Δsoil P and P_2O_5 balance were divided by the number of years between sampling times (to give Δsoil P in mg/l/year, and P_2O_5 balance in kg/ha/year).

- For each treatment at each site, Δsoil P (mg/l/year) was plotted against P_2O_5 balance (kg/ha/year) and the relationship evaluated by linear regression.

The results from each of the sites were then grouped to calculate an overall relationship for three types of P input:

1. Manufactured fertiliser P (i.e. Triple Super Phosphate;TSP) based on experiment 1 (*Table 2*),

2. Livestock manure (slurry, farmyard manure and poultry litter), based on experiments 2-4 (*Table 2*) and

3. Biosolids, based on experiments 5-7 (*Table 2*).

2.1.3 Calculation of apparent P_2O_5 balance for soil P maintenance and apparent soil P_2O_5 requirement

As detailed above, for each treatment at each site the change in Olsen P per year was regressed against P_2O_5 balance per year. The plotted regression line was used to calculate:

- The apparent soil P_2O_5 requirement (ASPR): the P_2O_5 input (kg/ha) required, in excess of crop removal, to raise the soil Olsen P concentration by 1 mg/l (i.e. the reciprocal of the slope), or the P_2O_5 removal (kg/ha) required, in excess of input, to decrease soil Olsen P by 1 mg/l.

- The annual change in soil P concentration (mg/l) when P_2O_5 inputs match crop P_2O_5 offtake (the Y intercept), and

- The P_2O_5 balance (kg/ha, positive or negative) for maintenance of soil P (PBSM; the X intercept).

In these regressions, if the plotted line does not pass through the origin it implies that Olsen P is not held constant when the P_2O_5 balance is zero (inputs equal offtakes); this is estimated by the intercepts on the Y-axis and X-axis (*Figure 2*).

In *Figure 2*, line (a) represents the model used in many fertiliser policies, passing through the intersect of the axes; i.e. a zero P_2O_5 balance gives no change in Olsen P (this implies that the soil P pools are at equilibrium), a positive P_2O_5 balance increases Olsen P and a negative balance decreases it (Heming, 2007). However, in practice the line may not pass through the origin. Line (b) in *Figure 2* is moved to the right, giving a negative Y intercept, indicating that the policy of matching P_2O_5 inputs to crop offtake is insufficient to maintain soil P status, possibly due to P loss or transfer of P into less available forms, such that additional P_2O_5 inputs are required (represented by the positive X intercept) to maintain extractable soil P at the current level. Alternatively, the line may be moved to the left (*Figure 2*, line c), with a positive Y intercept and a negative X intercept, implying that the full replacement of offtake is not required, possibly due to P release e.g. following the

mineralisation of organic P. It is important to recognise that intercepts that are significantly different from zero in these relationships may arise for reasons other than the dynamic relationships between soil P pools; for example various methodological factors could contribute to or even cause a significant intercept, any changes in the way soils were sampled or analysed, changes in the forms of P inputs, or changes in the way crop yields or their P_2O_5 contents were assessed.
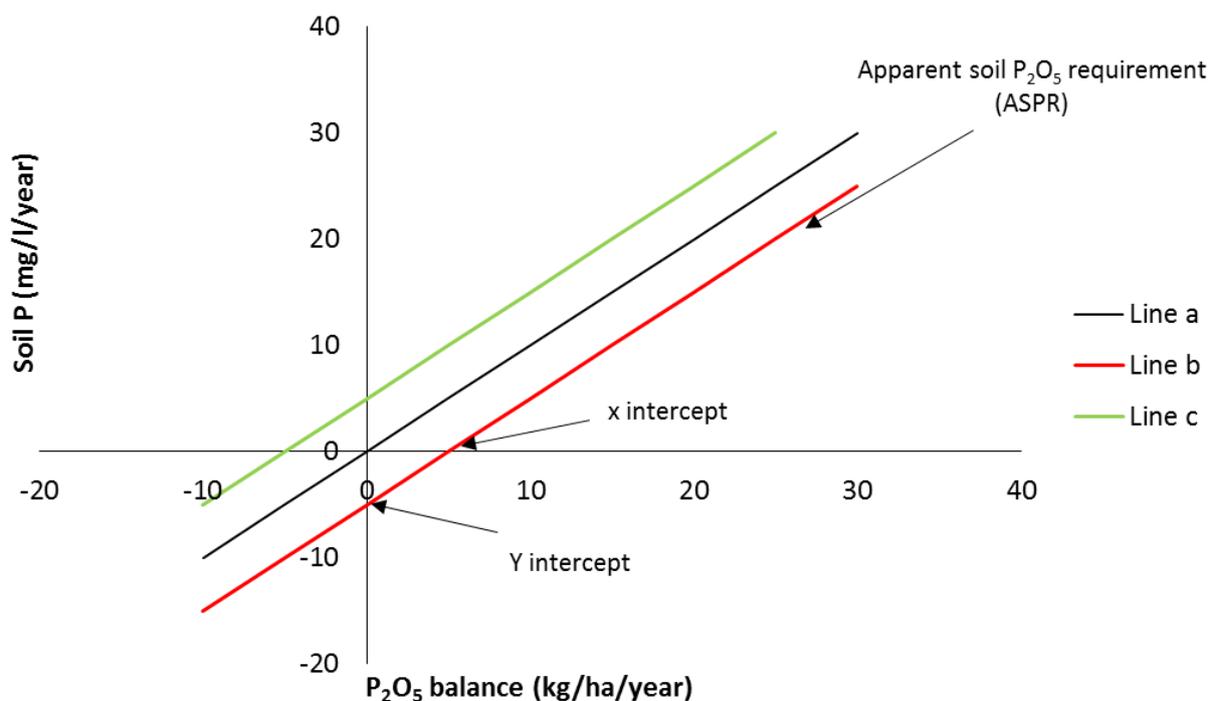
Figure 2. Relationships between phosphate balance and topsoil Olsen P concentration

However, to demonstrate how the slopes and intercepts of these relationships have been interpreted, an example regression equation is used here, $Y = 0.38x - 4.01$:

- The Y intercept is negative at -4.0 mg/l/year indicating a decline in soil Olsen P when P_2O_5 inputs = outputs.
- The X intercept is positive at 10.4 kg/ha/year (i.e.4.01/0.38), indicating a need for additional P_2O_5 inputs to be applied (over and above crop offtake) to maintain soil P status.
- The ASPR (or reciprocal of the slope) = 2.6 kg/ha/mg/l (i.e. 1/0.38), indicating that an additional 2.6 kg/ha P_2O_5 input would be required to increase soil Olsen P by 1 mg/l.

2.2 SOYL data

2.2.1 Selection of initial dataset

A dataset was collated from SOYL databases, initially comprising ~10,000 sampling points from 38 farms, the farms being chosen to exclude any use of organic manures. Using sampling coordinates,

points were selected where their positions were within 30 m of another sample taken on the succeeding sampling occasion. This approach resulted in 90% of repeat samples being within 8 m of the initial sample (*Figure 3*). Soil samples were all analysed by NRM throughout the period of study using Olsen's method.
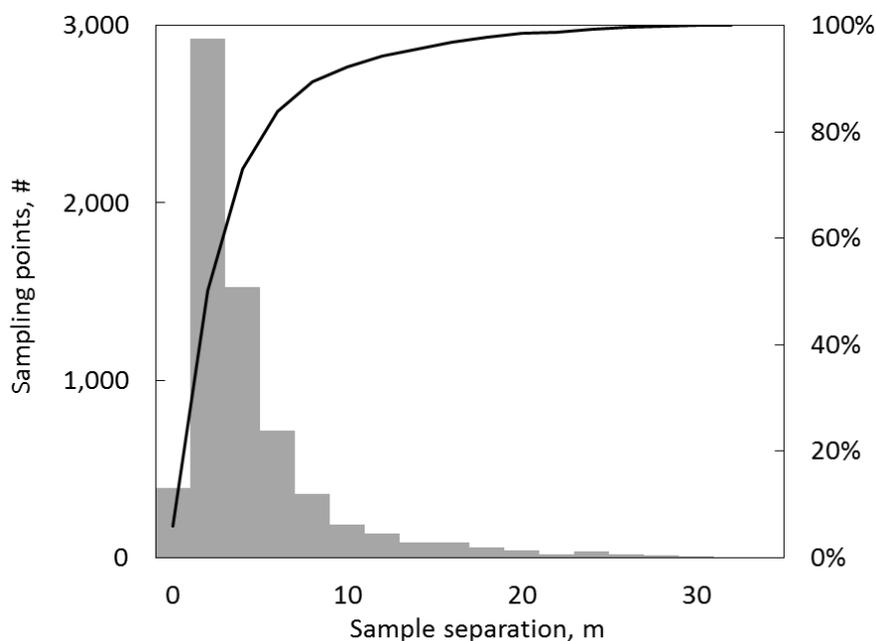

Figure 3. Variation in the proximity of successive sampling positions for all points included within the chosen dataset. Mean and median sample separations were 3.4 and 2.0 metres respectively.

2.2.2   Fertiliser P applications and P offtakes

P_2O_5 applications were not estimated from farm records but were calculated afresh using the bespoke information and algorithms that SOYL had recorded for each farm to regenerate the recommendations that would have been made for each sampling point. It was assumed that these amounts were actually applied because the whole purpose of SOYL's analysis service is to generate these recommendations for their clients, and to transit them to the farm where they are equipped to make (within field) variable applications. The algorithms used by SOYL to calculate the recommendations are based on the fertiliser strategy advised in the Fertiliser Manual (RB209; Defra 2010) but with particular modifications. The SOYL algorithms provide continuously adjusted P_2O_5 recommendations according to soil P analysis, rather than being stepped as in RB209 (not changing within one soil P Index). However, P_2O_5 recommendations by SOYL are constant (not on a 'sliding' scale) in the vicinity of the targeted soil P Index (normally but not always Index 2), hence there is a range of soil P values (around soil Index 2) for which the same amount of fertiliser P_2O_5 is recommended, and which has the same P_2O_5 balance. Also individual farms did not necessarily adopt the exact fertiliser strategy that is advocated in RB209 because they may have been trying to build soil P up or run it down at a different pace or to a different level than is advocated in RB209,

depending on farm circumstances; hence they have applied more or less than RB209 recommends for the particular P Index. This did not negate the value of this analysis because the algorithms used to derive appropriate recommendations had been preserved by SOYL so that it remained possible to work out what was actually applied, as well as how soil P had actually changed.

Similarly, the P_2O_5 offtakes were not recorded on farm but were re-derived (for each field i.e. with common values for all sampling positions within a field) from the target yields (and fates of crop residues) set by the farm for each crop when SOYL generated the recommendations. The P_2O_5 offtakes were estimated from yields and straw removals using standard P_2O_5 contents per tonne as given in the Fertiliser Manual (RB209 8th edition, Appendix 5, page 228).

2.2.3   Soil types

Detailed soil types were available from SOYL databases, but comprised too many overlapping classes for easy categorisation of all sampling points here. Hence soil types were obtained, according to latitude and longitude, from the 'cross compliance' soil type database held by ADAS which specifies four classes: shallow over chalk or limestone, heavy, medium and sandy (including light silt).

2.2.4   Data refinement

Initial soil P, soil P change, soil type, soil pH, easting and northing were acquired or calculated for each sampling point, along with P_2O_5 applied as fertiliser and total P_2O_5 offtake in crop produce (usually grain and straw) removed at harvest. Points were then filtered to retain only those (~6,500 points; *Table 3*) with a soil P value available for known successive dates 4 or 5 years apart, a soil type description available, all crops (with yield levels) known between sampling dates and fates of their residues known, hence P_2O_5 offtakes predictable for each of the 4 or 5 years, and a recommendation algorithm available for each year. Further points were omitted if cropping included potatoes or maize (in case recommendations were not followed exactly), and where pH was less than 5.5. Results of the sequential filtering process are in *Table 3* below.

Several rounds of statistical analysis were undertaken to make sense of these data:

1   In initial analyses, general relationships between 'P_2O_5 balance' and 'soil P change' could be seen but they were poorly defined and soil type effects were not significant.

2   Data were then consolidated to make field (or soil zone), rather than sampling point, the analytical unit (thinking that this would provide more robust estimates than individual sampling points), and excluding 'farm' from the analysis (because 'farm' cannot be generalised, when making recommendations). The main outcome of this approach was that consistent differences between soil types could not be detected.

3   Finally, a view was then taken that knowledge of a past soil P change/balance relationship for any particular field or farm might provide a basis for interpretation of future soil P analyses; i.e. future P application strategies could use farm-specific observations of 'soil P change' (based on

past farm data). Rather than using field or field-soil as the experimental unit in this third-round analysis, the spatial unit adopted was the single sampling point, as the view was taken that this would maximise the precision of any multi-variate analyses. It is this third approach to data analysis that is reported here (Section 3.2).

Table 3. Sample refinement process

Filter applied	Number excluded	Number left
None		10,210
With 2 P samples	1,523	8,687
With all crops known	1,332	7,355
With all equations recorded	580	6,774
Avoiding potatoes or maize in rotation	246	6,528
Low pH (<5.5) chalk and limestone	16	6,506

3   Results

3.1   Long-term experiments

3.1.1   *Manufactured fertiliser P additions: Ropsley*

Manufactured fertiliser P_2O_5 additions were monitored at a single site (Ropsley) where TSP was applied annually between 1978 and 1996. The experiment was run in two phases and cropping, inputs and experimental treatments for both phases are detailed in *Table 4* below.

3.1.1.1   *Change in soil P*

Soil extractable (Olsen) P was measured annually at Ropsley throughout Phase I and Phase II of the experiment. The overall change in soil P for each treatment is shown in *Table 5* and ranged from a decrease of 14 mg/l P in the Phase I maintenance treatment (annual application of *c.*45 kg P_2O_5 / ha for 8 years) to +5/6 mg/l P in the Phase II annual applications of 100 kg P_2O_5 / ha (for 11 years).

3.1.1.2   *Relationship between soil P and P balance*

The relationship between the change in soil P (Δ soil P) and P_2O_5 balance for each of the treatments is given in *Table 5*. For the majority of the individual treatments the relationship between soil P and P_2O_5 balance was non-significant ($P>0.05$) with a small R^2 (NB: R^2 here indicates how much of the variability in soil P was explained by the P_2O_5 balance). However, when all treatments were included in one regression there was a significant relationship ($P=0.03$): y = 0.015x – 0.60, albeit with a small R^2 of 10%, *Figure 4*. This relationship indicated:

- A change in Olsen P of -0.60mg/l/year when P_2O_5 inputs matched P_2O_5 offtakes

- A P_2O_5 balance of +41 kg P_2O_5/ha/year required for no change in Olsen P concentration
- An ASPR of 68 kg P_2O_5/ha/mg/l

Table 4. Ropsley: site details and treatments – a) Phase I and b) Phase II

a)	Ropsley Phase I (1978-1985)					
Soil	*Texture*	*% sand*	*% silt*	*% clay*	*pH*	*% OM*
	Clay loam	26	47	27	6.9	2.2
Cropping	Wheat, barley, sugar beet					
Inputs	Manufactured P_2O_5 fertiliser: triple super phosphate (TSP).					
Treatments						
Policy 0*	No application of P_2O_5 fertiliser[1]					
Policy A	'Maintenance' rates applied annually to each crop[2]. *(365 kg P_2O_5; c.20 kg P_2O_5/ha/year)*					
Policy B	'Periodic' maintenance rates applied every four years to the sugar beet crop. *(365 kg P_2O_5; c.180 kg P_2O_5/ha/year every four years).*					
Policy C	'Generous' rates (expected P offtake plus at least 50%) to gradually increase the soil P over several seasons[3]. *(810 kg P_2O_5; c.100 kg P_2O_5/ha/year).*					
Policy D	'Amelioration' rates to increase soil P within the first two seasons. *(890 kg P_2O_5; year 1 c.420 kg P_2O_5/ha and then c.70 kg P_2O_5/ha/year thereafter).*					

*No yield, offtake or soil P measurements were taken from these plots during Phase I

[1]Policy 0 plots used for nil treatments in Phase II. [2]Policy A (maintenance) plots used for low treatments in Phase II. [3]Policy C (generous) plots used for high treatments in Phase II.

b)	Ropsley Phase II (1986-1996)
Cropping	Continuous wheat
Inputs	Manufactured P_2O_5 fertiliser: triple super phosphate (TSP).
Treatment	
Nil[1] Nil	0 kg P_2O_5/ha/year
Nil 70	70 kg P_2O_5/ha/year
Nil 100	100 kg P_2O_5/ha/year
Low[2] Nil	0 kg P_2O_5/ha/year
Low 70	70 kg P_2O_5/ha/year
Low 100	100 kg P_2O_5/ha/year
High[3] Nil	0 kg P_2O_5/ha/year
High 70	70 kg P_2O_5/ha/year
High 100	100 kg P_2O_5/ha/year

[1]Nil on Phase I policy 0 plots. [2]Low on Phase I policy A plots. [3]High on Phase I policy C plots.

Note that changes in soil P were small with P_2O_5 in balance (-0.60 mg/l/year) compared to the errors, and there is no clear justification for applying additional P_2O_5 above that recommended to match offtake. Similarly the ASPR at Ropsley (68 kg P_2O_5/ha/mg/l) appears to exceed the suggestion of 40 kg/ha/mg/l in RB209 but the imprecision of the relationship indicates that these should not be taken as being significantly different.

3.1.2 Livestock manures

Livestock manure P additions were monitored at a three sites (Harper Adams, Gleadthorpe, and Terrington) where farmyard manure (FYM), slurry and broiler litter were applied annually between 1999 and 2013. Applied materials and application rates varied for each site; full details are given in *Table 7* to *Table 9*.

3.1.2.1 Change in soil P

Soil P was measured every 3-4 years at Harper Adams, Gleadthorpe and Terrington throughout the experimental period; the overall change in soil P for each treatment is shown in Table 11. There was no change in soil P following annual applications of slurry at Harper Adams for 15 years (the decrease of 2 mg/l P should be considered due to errors, rather than to an actual change in soil P). In contrast, at Gleadthorpe, soil P increased by 16-58 mg/l following annual applications of broiler litter at 5-25 t/ha (for 16 years). Also, at Terrington, soil P increased by 12 (slurry) and 32 mg/l (FYM) following repeated organic material applications for 19 years (note: inorganic P was also applied at Terrington).

3.1.2.2 Relationship between soil P and P balance

The relationship between the change in soil P (Δ soil P) and P_2O_5 balance for each of the treatments is given in *Table 10*. For the majority of the individual treatments the relationship between soil P and P_2O_5 balance was weak and non-significant ($P>0.05$) with a small R^2. Note that it was not possible to calculate the relationship between soil P and P_2O_5 balance for the individual treatments at Harper Adams due to lack of soil data (i.e. only 2 balance periods). However, combining all the sites and treatments into a single regression analysis resulted in a significant relationship ($P=0.006$); y = 0.01x + 0.18 (R^2 16%; *Figure 5*) which indicated:

- Soil P changed by +0.18 mg/l/year when P_2O_5 inputs matched crop P_2O_5 offtakes
- A P_2O_5 balance of -19 kg P_2O_5/ha/year was sufficient to maintain soil P concentration
- The ASPR was 105 kg P_2O_5/ha/mg/l.

For these livestock manure sites the change in Olsen P concentration when P_2O_5 inputs matched crop P_2O_5 offtake was only marginally positive and not significantly different from zero ($P>0.05$) whereas the ASPR is more than double that suggested in RB209 (Defra, 2010). However, this was not determined with great confidence ($R^2=0.16$), and it may be have arisen through the lower availability of P in livestock manures (50-60%) compared to manufactured P fertilisers (e.g. TSP >90% available). Note that overall, the addition of livestock manures (i.e. slurry, FYM and broiler litter) led to substantial build-up of soil P.

Table 5. Manufactured P_2O_5 fertiliser at Ropsley: P_2O_5 applied, regression equations and balance periods for individual and combined treatments.

Fertiliser strategy	Total P_2O_5 applied	Regression equation	R^2	P value	No of points	Balance period	No of years
Maintenance (annual applications)	365	y = 1.05x + 6.28	70.2	0.25	3	1978-1985	8
Periodic (applications to sugar beet every 4 years)	365	No fit	~	0.57	3	1978-1985	8
Generous (annual applications – P_2O_5 offtake plus at least 50%)	810	y = -0.02x + 0.17	~	0.76	3	1978-1985	8
Amelioration (annual applications, large applications in years 1/2)	893	y = 0.32x - 5.08	43.8	0.36	3	1978-1985	8
Nil[1] 0 (no annual applications of P_2O_5)	0	y = -0.12x - 4.21	96.7	0.08	3	1986-1996	11
Low[2] 0 (no annual applications of P_2O_5)	0	No fit	~	0.57	3	1986-1996	11
High[3] 0 (no annual applications of P_2O_5)	0	y = -0.13 - 5.98	46.7	0.35	3	1986-1996	11
Nil 70 (annual applications of 70 kg P_2O_5)	770	y = -0.09x + 2.94	98.8	0.05	3	1986-1996	11
Low 70 (annual applications of 70 kg P_2O_5)	770	No fit	~	0.97	3	1986-1996	11
High 70 (annual applications of 70 kg P_2O_5)	770	No fit	~	0.62	3	1986-1996	11
Nil 100 (annual applications of 100 kg P_2O_5)	1100	y = -0.09x + 6.31	7.1	0.48	3	1986-1996	11
Low 100 (annual applications of 100 kg P_2O_5)	1100	y = -0.06x + 3.86	26.9	0.41	3	1986-1996	11
High 100 (annual applications of 100 kg P_2O_5)	1100	No fit	~	0.94	3	1986-1996	11
All treatments	*Various*	y = 0.015x – 0.60	10	0.03	39	1986-1996	

[1]Nil on Phase I policy 0 plots. [2]Low on Phase I maintenance plots. [3]High on Phase I generous plots.

Manufactured P_2O_5 fertiliser

$y = 0.015x - 0.60$
$R^2 = 10\%. P = 0.03$

Annual soil P (mg/l/year)

Annual P_2O_5 balance (kg/ha/year)

▲ Maintenance ▲ Periodic ▲ Generous ▲ Ameilioration ■ Nil 0 ◆ Nil 70 ● Nil 100
■ Low 0 ◆ Low 70 ● Low 100 ■ High 0 ◆ High 70 ● High 100
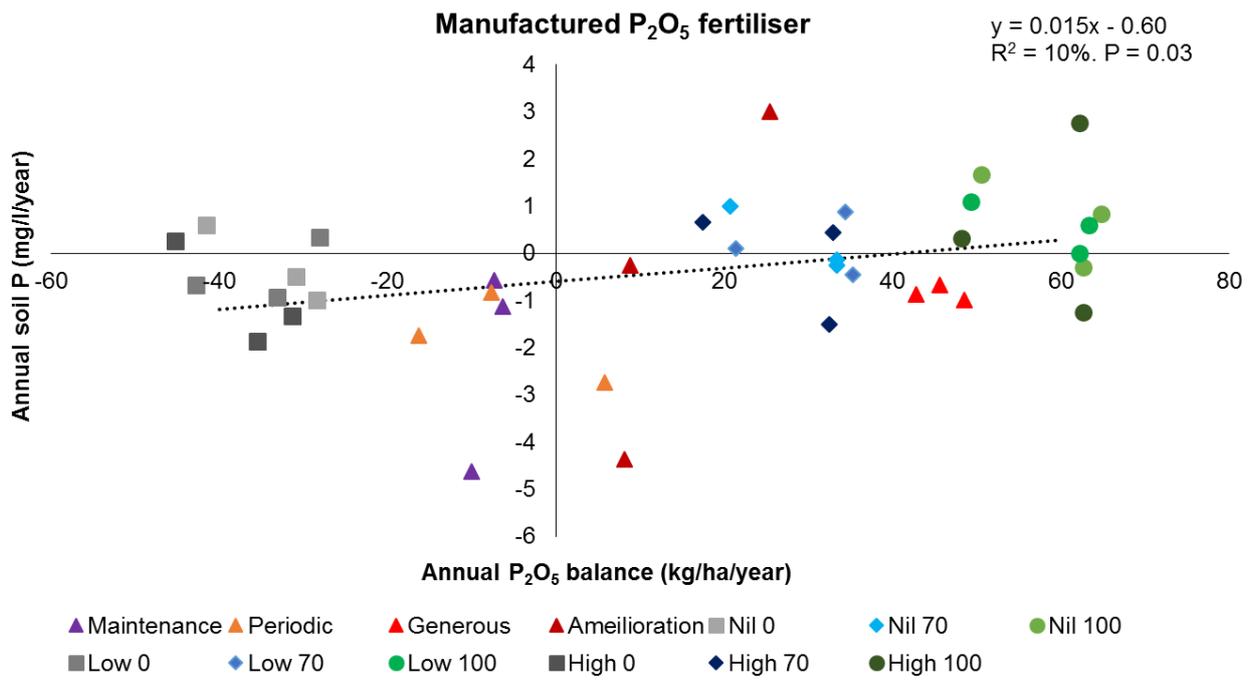
Figure 4. Manufactured P_2O_5 fertiliser: Relationship between P_2O_5 balance and soil P (all treatments). Y intercept = -0.6. X intercept = 41. ASPR = 68. Y intercept = reduction in soil P of -0.6 mg/l at 0 P_2O_5 balance (P_2O_5 input= P_2O_5 offtake). X intercept = +41 kg P_2O_5/ha/year balance required to maintain soil P unchanged. ASPR = 68 kg/ha of extra fertiliser required (in addition to crop offtake and 41 kg /ha/year) to raise soil P by 1 mg/l.

Table 6. Manufactured P_2O_5 fertiliser: summary of change in soil P over the experimental period

Fertiliser strategy	Total P_2O_5 input (kg/ha)	Soil P (mg/l start)	Soil P (mg/l finish)	Change in soil P (mg/l)	Change in soil P/kg P_2O_5	Balance period	No of years
Maintenance (annual applications)	365	30	16	-14	-0.036	1978-1985	8
Periodic (applications with sugar beet c.4 yearly)	365	30	18	-12	-0.032	1978-1985	8
Generous (annual applications)	810	30	24	-6	-0.007	1978-1985	8
Amelioration (annual applications, large applications years 1/2)	893	30	26	-4	-0.004	1978-1985	8
Nil 0 (no annual applications of P_2O_5)	0	13	10	-3	~	1986-1996	11
Low 0 (no annual applications of P_2O_5)	0	16	11	-5	~	1986-1996	11
High 0 (no annual applications of P_2O_5)	0	23	12	-11	~	1986-1996	11
Nil 70 (annual applications of 70 kg P_2O_5)	770	16	18	+2	0.002	1986-1996	11
Low 70 (annual applications of 70 kg P_2O_5)	770	18	19	+1	0.001	1986-1996	11
High 70 (annual applications of 70 kg P_2O_5)	770	25	22	-3	-0.004	1986-1996	11
Nil 100 (annual applications of 100 kg P_2O_5)	1100	16	22	+6	0.006	1986-1996	11
Low 100 (annual applications of 100 kg P_2O_5)	1100	16	21	+5	0.005	1986-1996	11
High 100 (annual applications of 100 kg P_2O_5)	1100	26	30	+4	0.004	1986-1996	11

Table 7. Harper Adams: site details and treatments

Harper Adams (1999-2013)

Soil	Texture	% sand	% silt	% clay	pH	% OM
	Sandy loam	74	14	12	6.6	2.6

Cropping	Wheat, barley, oilseed rape, oats, potatoes
Inputs	Cattle slurry, cattle FYM both applied at rates supplying *c.*250 kg N/ha (*c.* 40 t/ha FYM and 180 m^3/ha slurry).
Treatment	
Control	No applications of P_2O_5 during the experimental period.
Cattle slurry	Annual applications: 24-172 kg P_2O_5/ha. Total applied: *c.*1350 kg P_2O_5/ha
Cattle FYM	Annual applications: 50-420 kg P_2O_5/ha. Total applied: *c.*2300 kg P_2O_5//ha
Notes.	*No manufactured fertiliser P_2O_5 additions to treatments above.*

Table 8. Gleadthorpe: site details and treatments

Gleadthorpe (1994-2009)

Soil	Texture	% sand	% silt	% clay	pH	% OM
	Loamy sand	84	11	5	6.8	1.9

Cropping	Wheat, Barley, Oilseed rape, Oats, Rye, Linseed
Inputs	Broiler litter applied at 5, 10, 15, 20 & 25 t/ha (fresh weight)
Treatment	
Control	No applications of P_2O_5 during the experimental period.
Broiler litter 5 t/ha	Annual applications: 50-220 P_2O_5/ha. Total applied: *c.*1600 kg P_2O_5/ha
Broiler litter 10 t/ha	Annual applications: 100-430 kg P_2O_5/ha. Total applied: *c.*3200 kg P_2O_5/ha
Broiler litter 15 t/ha	Annual applications: 160-650 kg P_2O_5/ha. Total applied: *c.*4850 kg P_2O_5/ha
Broiler litter 20 t/ha	Annual applications: 220-860 kg P_2O_5/ha. Total applied: *c.*6500 kg P_2O_5/ha
Broiler litter 25 t/ha	Annual applications: 275-1100 kg P_2O_5/ha. Total applied: *c.*8100 kg P_2O_5/ha
Notes.	*No manufactured fertiliser P_2O_5 additions to treatments above.*

Table 9. Terrington (1994-2012): site details and treatments

Soil	Texture	% sand	% silt	% clay	pH	% OM
	Silty clay loam	10	62	28	8.2	2.4
Cropping	Wheat, Barley, Oilseed rape, Oats, Potatoes, Sugar beet					
Inputs	Pig FYM, pig slurry, both applied at rates supplying *c.*250 kg N/ha (c. 35 t/ha FYM and 115 m^3/ha slurry)					
Treatment						
Control	No applications of organic P_2O_5, *periodic manufactured fertiliser P_2O_5/ha additions (1995, 1998, 2001, 2003, 2006 and 2007). Total applied: c.750 kg P_2O_5/ha.*					
Pig FYM	Annual applications: *115-450* kg P_2O_5/ha. Total applied: *c.*4300 kg P_2O_5/ha.					
Pig slurry	Annual applications: *10-130* kg P_2O_5/ha. Total applied: *c.*1300 kg P_2O_5/ha.					
Notes.	*Manufactured fertiliser P_2O_5/ha additions were periodically applied to the livestock manure treatments (1998, 2001, 2003, 2006 and 2007). Total applied to each treatment: c.500 kg P_2O_5/ha.*					

Table 10. Livestock manures: P_2O_5 applied, regression equations and balance periods for individual and combined treatments.

Site	Fertiliser type	Fertiliser strategy	Applied P_2O_5 (kg/ha)	Regression equation	R^2	P value	No of points	Balance period	No of years
Harper	Control	No P_2O_5 applications	0	Only 2 values	n/d	n/d	2	1999-2013	15
Harper	Cattle FYM	Annual applications of FYM (no TSP)	2300	Only 2 values	n/d	n/d	2	1999-2013	15
Harper	Cattle slurry	Annual applications of slurry (no TSP)	1350	Only 2 values	n/d	n/d	2	1999-2013	15
GT	Control	No P_2O_5 applications	0	No fit	~	0.49	4	1994-2009	16
GT	Broiler litter	Annual applications of broiler litter: 5 t/ha (no TSP)	1600	y = 0.16x - 8.61	84.6	0.05	4	1994-2009	16
GT	Broiler litter	Annual applications of broiler litter: 10 t/ha (no TSP)	3200	y = 0.11x - 14.5	58.9	0.15	4	1994-2009	16
GT	Broiler litter	Annual applications of broiler litter: 15 t/ha (no TSP)	4850	y = 0.09x - 19.4	8.3	0.38	4	1994-2009	16
GT	Broiler litter	Annual applications of broiler litter: 20 t/ha (no TSP)	6500	No fit	~	0.82	4	1994-2009	16
GT	Broiler litter	Annual applications of broiler litter: 25 t/ha (no TSP)	8100	No fit	~	0.62	4	1994-2009	16
TT	Control	No manure application	750[1,2]	y = 0.10x – 0.53	51.4	0.11	4	1994-2012	16

Site	Fertiliser type	Fertiliser strategy	Applied P_2O_5 (kg/ha)	Regression equation	R^2	P value	No of points	Balance period	No of years
		s (+ periodic TSP)							
TT	Pig FYM	Annual applications of FYM (+ periodic TSP)	4300[3]	No fit	~	0.60	5	1994-2012	19
TT	Pig slurry	Annual applications of slurry (+ periodic TSP)	1300[3]	y = 0.05x - 2.00	45.4	0.13	5	1994-2012	19
All	*Manure*	*See individual entries for details*		*y = 0.01x + 0.18*	*16*	*0.006*	*40*		

[1]Inorganic P was applied in 1995, 1998, 2001, 2003, 2006 and 2007 applying, in total, *c.*750 kg P_2O_5/ha

[2]This treatment is not included in the calculation of the overall relationship by regression as the sole source of P_2O_5 was inorganic P.

[3]Inorganic P was applied in 1998, 2001, 2003, 2006 and 2007 applying, in total, *c.*500 kg P_2O_5/ha
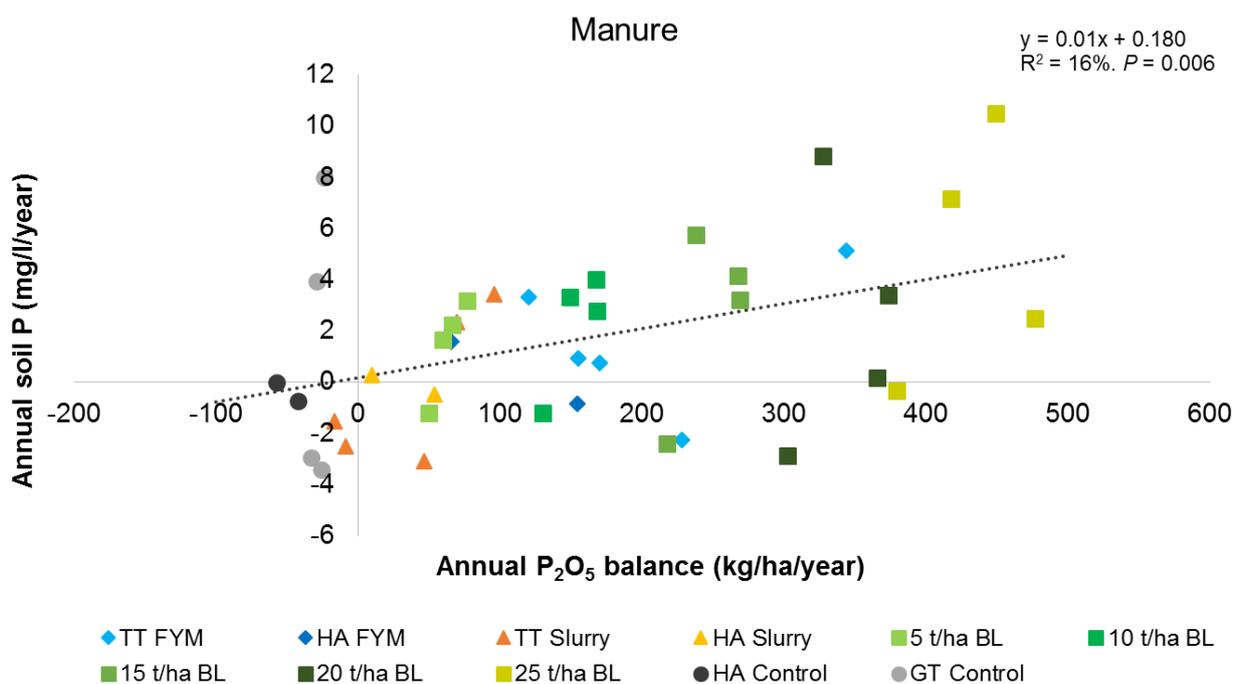
Figure 5. Livestock manure: Relationship between P_2O_5 balance and soil P (all treatments). Y intercept = 0.18. X intercept = 19. ASPR = 105 The X and Y intercepts are not significantly different from zero (P>0.05) and indicated that when inputs matched offtakes there was no change in soil P. Hence P applications in excess of offtake were not required to maintain soil P levels. ASPR = 105 kg P_2O_5/ha of extra fertiliser required to raise soil P by 1 mg/l.

Table 11. Livestock manure: summary of change in soil P over the experimental period

Site	Fertiliser type	Fertiliser strategy	Added P_2O_5 (kg/ha)	Soil P mg/l (start)	Soil P mg/l (finish)	Change in soil P (mg/l)	Change in soil P/kg P_2O_5	Balance period	No of years
Harper	Control	No P_2O_5 applications	0	76	72	-4	~	1999-2013	15
Harper	FYM	Annual applications of FYM (no TSP)	2300	81	89	+8	0.003	1999-2013	15
Harper	Slurry	Annual applications of slurry (no TSP)	1350	74	72	-2	-0.002	1999-2013	15
GT	Control	No P_2O_5 applications	0	49	52	+3	~	1994-2009	16
GT	Broiler litter	Annual applications of broiler	1600	46	62	+19	0.010	1994-2009	16

Site	Fertiliser type	Fertiliser strategy	Added P_2O_5 (kg/ha)	Soil P mg/l (start)	Soil P mg/l (finish)	Change in soil P (mg/l)	Change in soil P/kg P_2O_5	Balance period	No of years
GT	Broiler litter	litter 5 t/ha (no TSP) Annual applications of broiler litter 10 t/ha (no TSP)	3200	53	79	+26	0.008	1994-2009	16
GT	Broiler litter	Annual applications of broiler litter15 t/ha (no TSP)	4850	51	83	+32	0.007	1994-2009	16
GT	Broiler litter	Annual applications of broiler litter 20 t/ha (no TSP)	6500	55	90	+35	0.005	1994-2009	16
GT	Broiler litter	Annual applications of broiler litter 25 t/ha (no TSP)	8100	61	119	+58	0.007	1994-2009	16
TT	Control	No manure applications (+ periodic TSP)	750[1]	25	26	+1	~	1994-2012	19
TT	FYM	Annual applications of FYM (+ periodic TSP)	4300[2]	23	55	+32	0.007	1994-2012	19
TT	Slurry	Annual applications of slurry (+ periodic TSP)	1300[2]	22	34	+12	0.007	1994-2012	19

[1]Inorganic P was applied in 1995, 1998, 2001, 2003, 2006 and 2007 applying, in total, *c.*750 kg P_2O_5/ha

[2]Inorganic P was applied in 1998, 2001, 2003, 2006 and 2007 applying, in total, *c.*500 kg P_2O_5/ha

3.1.3 Biosolids

In the Biosolids experiments, materials were applied annually between 1994 and 2010 at three sites, Bridgets, Gleadthorpe and Rosemaund (*Table 12* to *Table 14*).

3.1.3.1 Change in soil P

Soil P was measured every 3-4 years at each site throughout the experimental period. Overall there was an increase in soil P as the added biosolids proved to be a good source of P. The overall change in soil P for each treatment is shown in *Table 16* and ranged from +8 (Rosemaund) to +24 mg/l/year (Gleadthorpe).

3.1.3.2 Relationship between soil P and P balance

The relationships between the change in soil P (Δ soil P) and P_2O_5 balance for each of the treatments are given in Table 15; these were non-significant ($P>0.05$) and nor was there a significant relationship for the combined dataset (*Figure 6*) probably because there were too few data points (10). This may also partly have arisen because the soils at all three sites were well supplied with P_2O_5 (P Index 3 or 4), and so may have had somewhat more measurement error than at other sites. This may also have been due to there being no treatments with nil P_2O_5 applied in these experiments, hence the range of P_2O_5 balance tested here was only 100 kg/ha/year compared to 500 kg/ha/year in the manure experiments (*Figure 5*).

Table 12. Bridgets: site details and treatments

	Bridgets (1994-2005)					
Soil	*Texture*	*% sand*	*% silt*	*% clay*	*pH*	*% OM*
	Silty clay loam	10	60	30	6.8	2.6
Cropping	Grass, wheat					
Inputs	Biosolids (annual application of *c.*3 t dry solids/ha)					
Treatment						
No biosolids control	Annual applications of manufactured fertiliser P_2O_5 (1999-2004). Total applied 270 kg P_2O_5/ha (30-70 kg P_2O_5/ha/year).					
Biosolids	Annual applications: *c.*45-190 kg P_2O_5/ha. Total applied: *c.*1550 kg P_2O_5/ha					

Notes.   *Annual manufactured fertiliser P_2O_5 applications to the biosolids treatment (1999-2004) supplying an additional 220 kg P_2O_5/ha.*

Table 13. Gleadthorpe (1994-2010): site details and treatments

Soil	Texture	% sand	% silt	% clay	pH	% OM
	Sandy loam	71	22	7	7.1	2.6
Cropping	Grass, wheat					
Inputs	Biosolids (annual application of *c.*3 t dry solids/ha)					
Treatment						
No biosolids control	Annual applications of manufactured fertiliser P_2O_5 (1999-2002, 2004, 2006-7 and 2009-10). Total applied 290 kg P_2O_5/ha (20-70 kg P_2O_5/ha/year).					
Biosolids	Annual applications: *c.*90-190 kg P_2O_5/ha. Total applied: *c.*2350 kg P_2O_5/ha					

Notes. *Annual manufactured fertiliser* P_2O_5 *(1999-2004) applications to the biosolids treatment supplying an additional 190 kg/ha P_2O_5/ha.*

Table 14. Rosemaund (1994-2005): site details and treatments

Soil	Texture	% sand	% silt	% clay	pH	% OM
	Silty clay loam	8	67	25	7.0	2.6
Cropping	Grass, wheat					
Inputs	Biosolids (annual application of *c.*3 t dry solids/ha)					
Treatment						
No biosolids control	Annual applications of manufactured fertiliser P_2O_5 (1999-2005). Total applied 230 kg P_2O_5/ha (30-60 kg P_2O_5/ha/year).					
Biosolids	Annual applications: *c.*80-145 kg P_2O_5/ha. Total applied: *c.*1600 kg P_2O_5/ha					

Notes. *Annual manufactured fertiliser* P_2O_5 *(1999-2004) applications to the biosolids treatment supplying an additional 130 kg/ha P_2O_5/ha.*

Table 15. Biosolids: P applied, regression equations and balance periods for individual and combined treatments.

Site	Fertiliser strategy	Total P_2O_5 (kg)	Regression equation	R^2	P value	No of points	Balance period	No of years
Bridgets	Annual applications of biosolids (+ periodic TSP)	1550[1]	y = 0.03x - 2.01	15	0.45	3	1994-2005	12
Gleadthorpe	Annual applications of biosolids (+ periodic TSP)	2350[2]	No fit	~	0.61	4	1994-2010	17
Rosemaund	Annual applications of biosolids (+ periodic TSP)	1600[3]	y = -0.03x + 3.64	19.2	0.44	3	1994-2005	12
All	*Annual applications of biosolids (+ periodic TSP)*	*Various*	*No fit*	*~*	*0.97*	*9*	*Various*	

[1]Inorganic P was applied annually between 1999 and 2004 supplying an additional 220 kg/ha P_2O_5.

[2]Inorganic P was applied annually between 1999 and 2004 supplying an additional 190 kg/ha P_2O_5.

[3]Inorganic P was applied annually between 1999 and 2004 supplying an additional 130 kg/ha P_2O_5.

Table 16. Biosolids: summary of change in soil P over the experimental period

Site	Fertiliser strategy	Added P_2O_5 (kg)	Soil P mg/l (start)	Soil P mg/l (finish)	Change in soil P (mg/l)	Change in soil P/kg P_2O_5	Balance period	No of years
Bridgets	Annual applications of sludge cake (+ periodic TSP)	1550[1]	33	52	+19	0.011	1994-2005	12
Gleadthorpe	Annual applications of sludge cake (+ periodic TSP)	2350[2]	40	64	+24	0.010	1994-2010	17
Rosemaund	Annual applications of sludge cake (+ periodic TSP)	1600[3]	30	38	+8	0.006	1994-2005	12

[1]Inorganic P was applied annually between 1999 and 2004 supplying an additional 220 kg/ha P_2O_5.

[2]Inorganic P was applied annually between 1999 and 2004 supplying an additional 190 kg/ha P_2O_5.

[3]Inorganic P was applied annually between 1999 and 2004 supplying an additional 130 kg/ha P_2O_5.
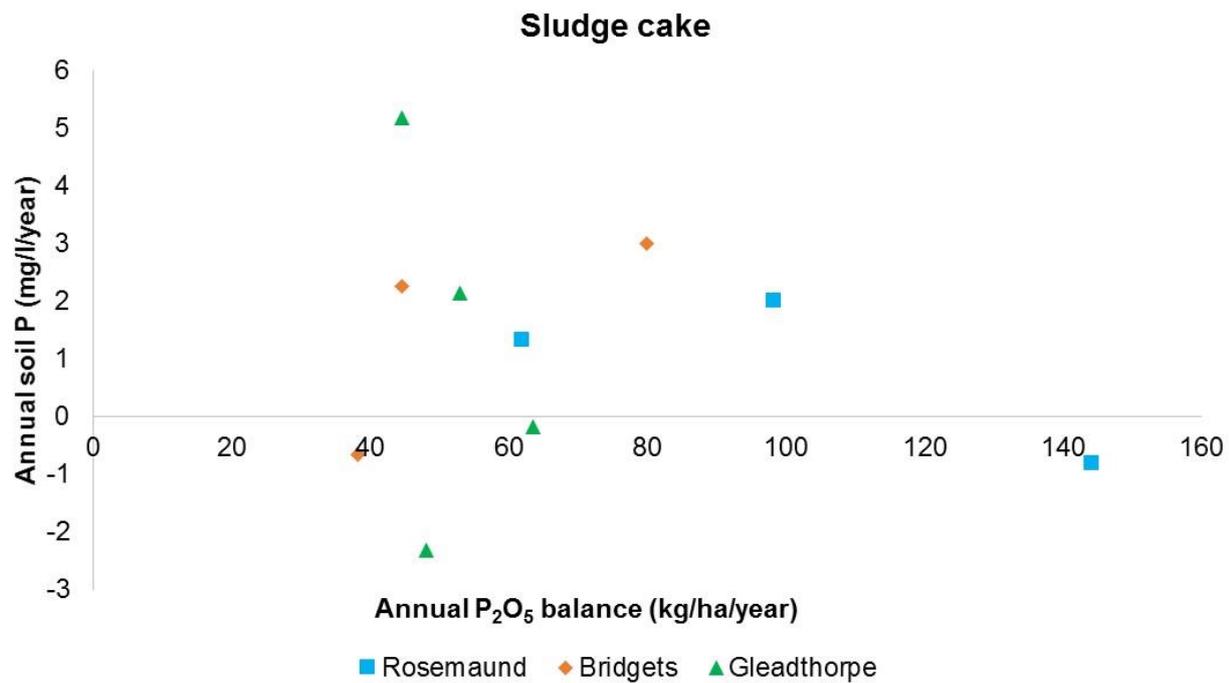
Figure 6. Biosolids: Relationship between P balance and soil P (all treatments).

3.1.4 Combined data analysis

Given the significant proportion of variation in the data from long-term experiments that remained unexplained, a combined analysis was performed, to test whether the three datasets for (i) inorganic fertiliser, (ii) manures and (iii) biosolids were significantly different. The full dataset is illustrated in *Figure 7*. The analysis of variance showed no significant difference between the three datasets.
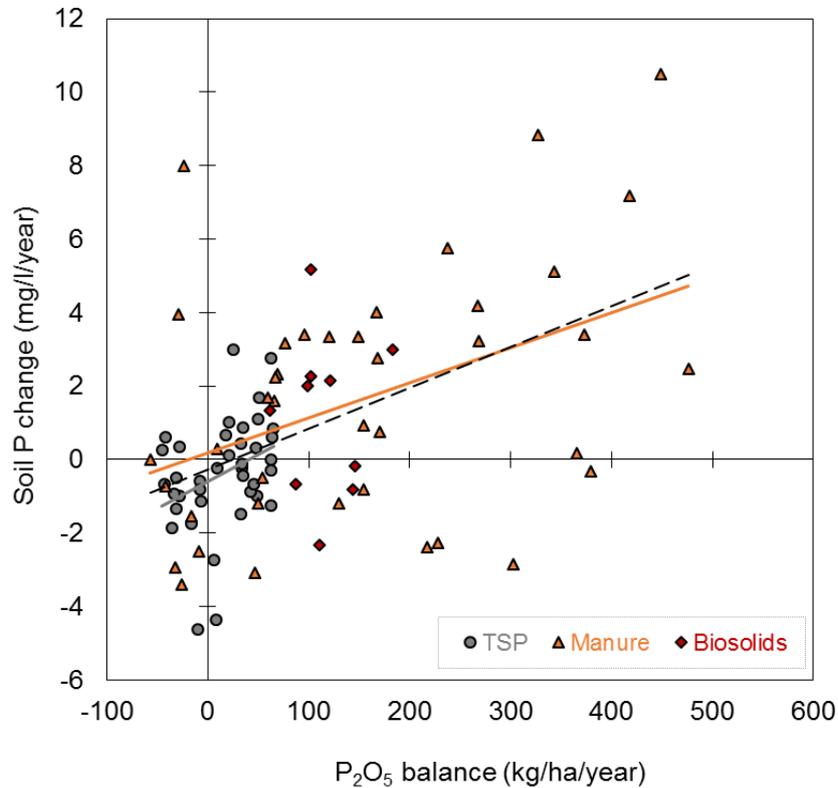
Figure 7. Combined results from all long-term experiments, with regression lines for inorganic fertiliser (TSP; grey circles; y = 0.0096x + 0.18; R²=18%; ASPR = 105 kg/ha/mg/l) and manures (orange triangles; y = 0.0146x – 0.60; R²=12%; ASPR = 68 kg/ha/mg/l); biosolids (red diamonds) gave no significant relationship. All the data combined gave an ASPR of 90 kg/ha/mg/l (black dashed line; y = 0.0111x – 0.28; R²=25%).

Indeed, the analysis of the combined data provided a greater degree of confidence in the relationship between soil P changes and P_2O_5 balances than the individual relationships, albeit still only 25% of the variation was explained. The slope of this relationship translated to an ASPR of 90 kg/ha/mg/l, but the SE on this value was 17 kg/ha/mg/l so, whilst it can probably be taken as being larger than the 40 kg/ha/mg/l suggested in RB209, its value cannot be used with any confidence. Further discussion on how to regard this value will be provided in Section 4, after analysis of the SOYL database has been described.

3.2 Analysis of SOYL data

3.2.1 Further data refinement

Using the initial dataset of 6,506 points, further minor changes or deletions were made leaving 6,455 data-points. The remaining data related to 36 of the initial 38 farms (*Figure 8*; *Table 17*) i.e. all data from two farms (PN & JS) were removed as a result of data filtering. On average there were 16.3 fields per farm (range 4-70 fields; total 387), and there were 16.8 sampling points per field (median 10); the distribution of sampling points per field was skewed due to a few very large fields with >100 sampling points. When the filtered dataset was split between the four 'cross-compliance' soils types the distribution of soils was 24% shallow over chalk or limestone, 36% heavy, 29% medium and 11% sandy (including light silt). All fields had only one soil type. However, whole farms often had more than one soil type (median 2, range 1 to 4).
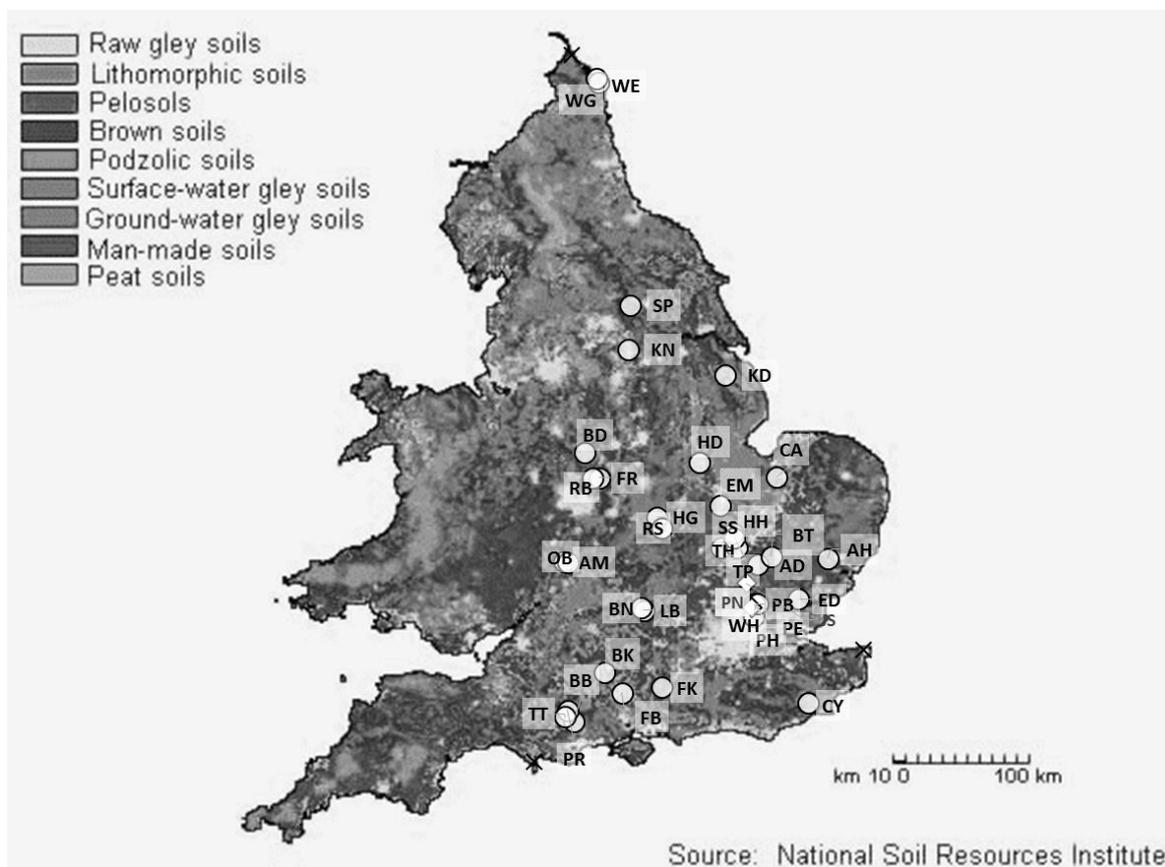
Figure 8. Map of England and Wales showing major soil types and locations of the 38 farms from which SOYL data were collated here (diamonds indicate farms eventually omitted: PN & JS).

Table 17. Summary details for the 36 farms from which data are analysed in this report. Soil pH values are the means of both sampling years; mean and SD of soil P (mg/l and Index) relate to the initial year of analysis.

Farm Code	Lati-tude	Longi-tude	Sample points	Fields	Main soil class	Mean soil pH	Mean soil P (mg/l)	Mean soil P (index)	Soil P variance (2SD mg/l)
AD	52.02	0.15	225	18	Shallow	8.0	24.5	2.4	14
AH	52.06	0.96	31	7	Heavy	7.9	25.2	2.3	22
AM	52.04	-2.10	161	28	Medium	7.4	27.8	2.4	33
LB	51.68	-1.17	239	16	Medium	6.7	29.3	2.6	28
BN	51.70	-1.20	135	11	Medium	7.0	20.9	1.9	20
BT	52.08	0.31	469	45	Heavy	8.0	19.3	1.9	11
BK	51.23	-1.62	91	7	Shallow	8.0	20.0	2.0	12
BD	52.84	-1.86	290	14	Medium	6.7	22.4	2.2	16
BB	50.86	-1.99	79	9	Shallow	8.1	18.4	1.8	13
CA	52.67	0.37	174	17	Sandy	7.8	14.5	1.3	11
CY	51.00	0.73	110	10	Heavy	8.0	29.4	2.9	12
ED	51.76	0.63	202	25	Medium	7.6	23.2	2.1	24
EM	52.46	-0.28	83	8	Heavy	6.6	21.6	2.2	15
FK	51.11	-0.96	175	15	Medium	6.8	31.3	2.8	26
FB	51.07	-1.42	258	17	Shallow	7.9	24.3	2.4	16
FR	52.66	-1.69	318	31	Medium	6.9	30.7	2.6	33
HH	52.14	-0.27	159	12	Heavy	6.9	18.5	1.9	12
HG	52.37	-1.02	111	14	Medium	6.8	21.1	1.7	24
HD	52.77	-0.53	107	9	Shallow	7.4	21.3	2.1	21
KN	53.60	-1.36	42	7	Medium	6.8	34.8	2.9	30
KD	53.41	-0.22	222	16	Shallow	8.2	21.3	2.1	10
OB	52.03	-2.06	721	66	Shallow	7.7	22.7	2.2	15
PB	51.64	0.11	148	11	Heavy	7.0	23.9	2.3	20
PE	51.73	0.14	127	9	Heavy	7.2	31.6	2.8	23
PH	51.73	0.12	226	14	Heavy	7.5	27.4	2.6	23
PR	50.94	-2.05	219	34	Shallow	7.5	20.5	2.0	15
RB	52.65	-1.77	77	14	Sandy	5.9	25.3	2.4	18
RS	52.29	-0.96	108	23	Medium	6.8	25.0	2.2	23
SS	52.14	-0.09	415	20	Heavy	7.4	15.7	1.6	8
SP	53.93	-1.32	30	4	Medium	5.8	16.3	1.6	12
TT	50.90	-2.08	125	14	Shallow	8.1	22.7	2.0	21
TH	52.25	-0.14	187	9	Heavy	7.7	15.9	1.6	8
TP	52.22	-0.12	115	7	Heavy	7.8	14.7	1.4	8
WE	55.57	-1.70	208	13	Medium	6.4	14.4	1.3	9
WG	55.60	-1.71	182	22	Medium	6.9	14.5	1.4	10
WH	51.73	0.15	55	6	Heavy	7.3	48.2	3.6	35

3.2.2   Soil P levels

In considering soil P values (*Figure 9*), note that zero or near-zero soil P never occurred; the minimum of all soil P values was 4.6 mg/l, so P Index 0 soils extended from 5 to 9 mg/l (5 units). Also, note that the soil P Index largely reflects a log-transformation. Thus higher P indices extend respectively by 6 units (Index 1), 10 units (Index 2), 10 units (Index 3), 20 units (Index 4), 25 units (Index 5), 30 units (Index 6) and 40 units (Index 7); the maximum soil P measured was 196 mg/l (P Index 7). Presentation of all soil P values according to their Soil P index thus appeared as a normal distribution (*Figure 9*) due to the <u>non</u>-normal distribution of soil P data. Thus the analysis of soil P data sometimes required log-transformation.

The variation in initial soil P is shown overall in *Figure 9* and by farm in *Figure 10* and *Figure 15*. The median soil P was 18.0 mg/l and the mode was 13.8 mg/l, reflecting the negatively skewed distribution of soil P (mg/l). Farm means varied from 12.4 mg/l (low Index 1) at TP to 37.5 mg/l (Index 3) at WH. There were no farms with average soil P less than Index 1 or more than Index 3; there were 19%, 50% & 31% of farms with averages at Index 1, 2 and 3 respectively.
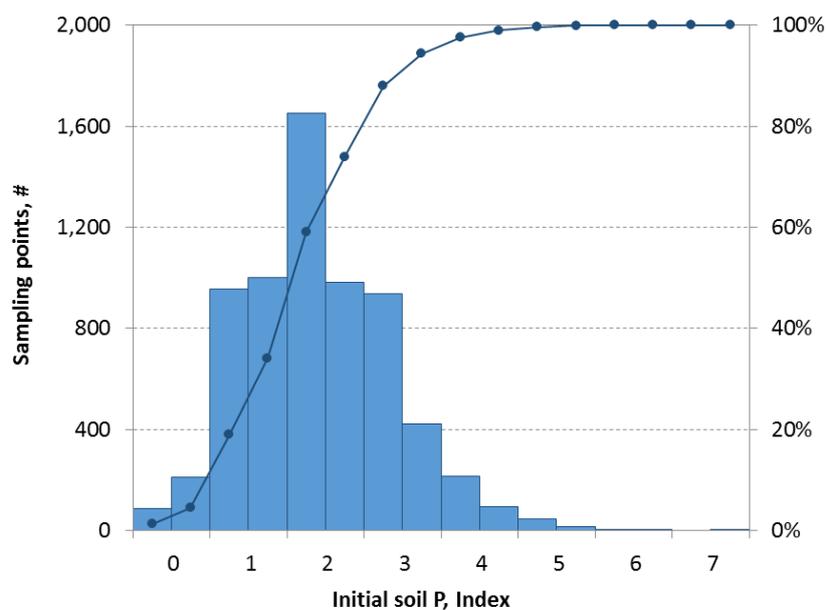
Figure 9. Frequency distribution (histogram) and cumulative frequency (full circles) of initial soil P at all sampling positions. Note that the P Index scale is near-exponential in terms of mg/l P.

However, variation in initial soil P between farms was less than variation within farms; all farms showed significant within-farm variability, which may reflect that all farms served by SOYL were seeking a sampling service to detect and correct soil P variability. Taking two standard deviations (2SD) as an index of within farm variability, this exceeded 16 mg/l P on most farms. On only five farms (SS, TH, TP, WE & WG) was 2SD less than 10 mg/l. The extent of variability in initial soil P within the farms did not relate to their mean soil P levels (*Figure 10*); i.e. farms with high soil P didn't

not necessarily have most variation. Discounting farms with few data-points, farms with most variation (2SD >30 mg/l P) were WH, FR, KN & AM.
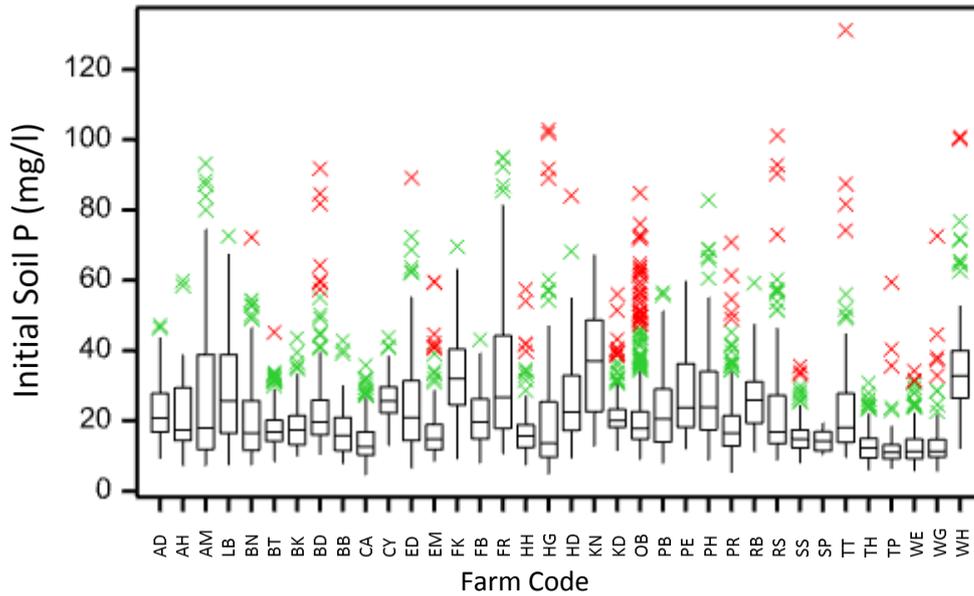
Figure 10. Boxplots showing variation in initial soil P (mg/l) by farm. The boxes extend from the lower to the upper quartile with the median indicated in-between, the whiskers indicate 1.5 times the interquartile range beyond the quartiles, the green crosses indicate outliers, and red crosses indicate 'far outliers' as specified in Genstat according to Tukey (1977).
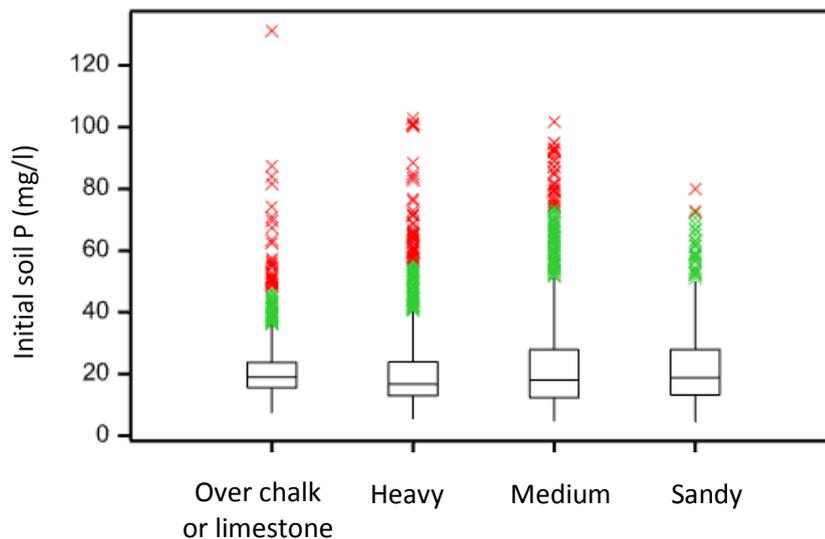
Figure 11. Boxplot showing variation in initial soil P according to soil type. Key as in Figure 10.
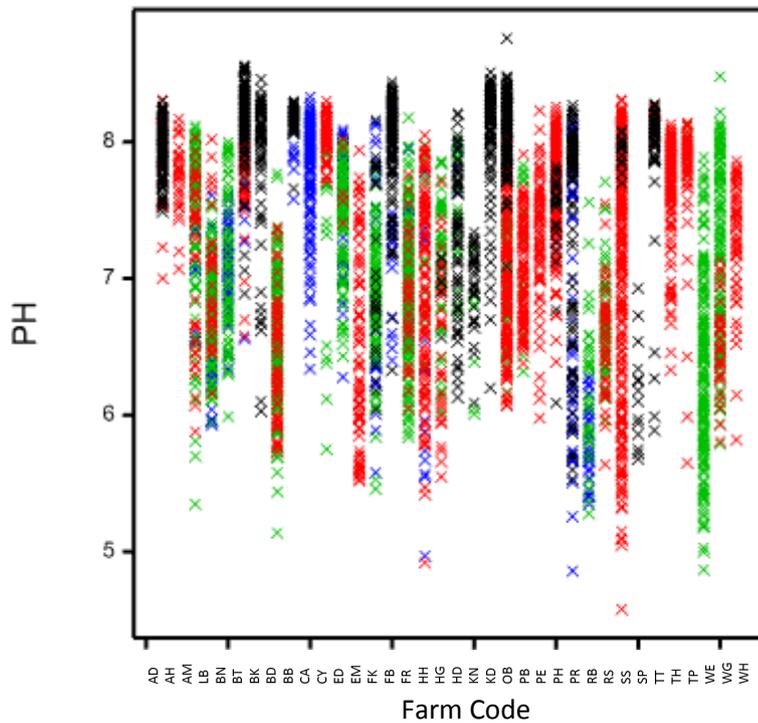
Figure 12. Soil types and soil pH on each of the 36 farms. Colours indicate soil type, with shallow over chalk or limestone (black), heavy (red), medium (green) and sandy (blue). For Farm descriptions according to Farm Codes see Table 17.
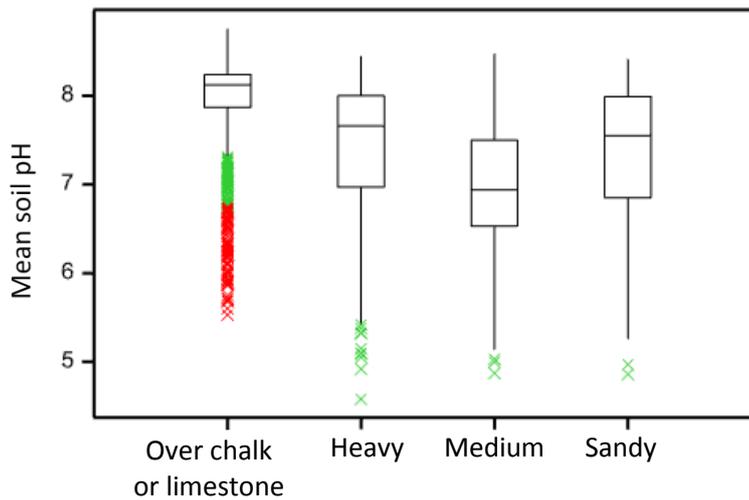
Figure 13. Boxplot showing variation in soil pH (mean of both sampling occasions) by soil type. Symbols are as Figure 10. Values of less than pH 5.5 were excluded from the analysis.

The range of soil P was large for each soil type (*Figure 11*) but on average there was a small significant difference in initial soil P between soil types (*Table 18*), with heavy soils showing slightly lower values than other soils and medium and sandy soils showing slightly larger values.

Soil types differed more significantly for pH than for soil P with, as expected, the shallow soils over chalk or limestone showing a high mean value of 8.0 which compares to 7.4 for heavy clay soils, 7.2 for sandy soils and 6.9 for medium soils. However there were nevertheless some soils classed as calcareous which had a low pH (*Figure 13*). This may be due to inaccuracies in the soil type database rather than in pH determination in the laboratory. There was no significant correlation between mean pH values and initial soil P levels.

Table 18. Analysis of initial soil P values according to main soil type.

Soil type	Sampling points	Mean initial Soil P (mg/l)
Shallow over chalk or limestone	1551	21.1
Heavy, clay	2371	20.4
Medium	1862	23.0
Sandy and light silt	722	22.6
Probability		<0.001
Max SED		0.563

3.2.3 P_2O_5 applications, offtakes and balances

Relationships between initial soil P and P_2O_5 fertiliser use and between initial soil P and crop P_2O_5 offtake are shown for the whole dataset in *Figure 14* (a & b respectively). Here it is clear that quantities of fertiliser P_2O_5 applied varied largely as a result of initial soil P but that expected P_2O_5 offtake also had an influence, and different farms operated different strategies in how to adjust for soil P. There was clearly no relationship between crop P_2O_5 offtake and the initial soil P. Variation in P_2O_5 offtake (maximum 90, minimum 37 kg/ha/year P_2O_5) was much less than variation in P_2O_5 applied (which ranged from nil to 122 kg/ha; *Figure 14*) so the balances between P_2O_5 applied and P_2O_5 offtake can be expected to be largely driven by the levels of P_2O_5 fertiliser used. Mean and median values for P_2O_5 offtake were both 64 kg/ha.

Overall, farms managed their P_2O_5 balances according to the initial levels of soil P (*Figure 15*) i.e. farms with average soil P at Index 0 or 1 used P_2O_5 applications in excess of estimated P_2O_5 offtake and farms with soils exceeding P Index 1 tended to apply less P_2O_5 than the P_2O_5 offtake they estimated. Some farms with low soil P were maintaining a high P balance (e.g. TP, TH, WE & WG), whilst others were trying to run down soil P (e.g. FR, HD, KN, PE, WH).
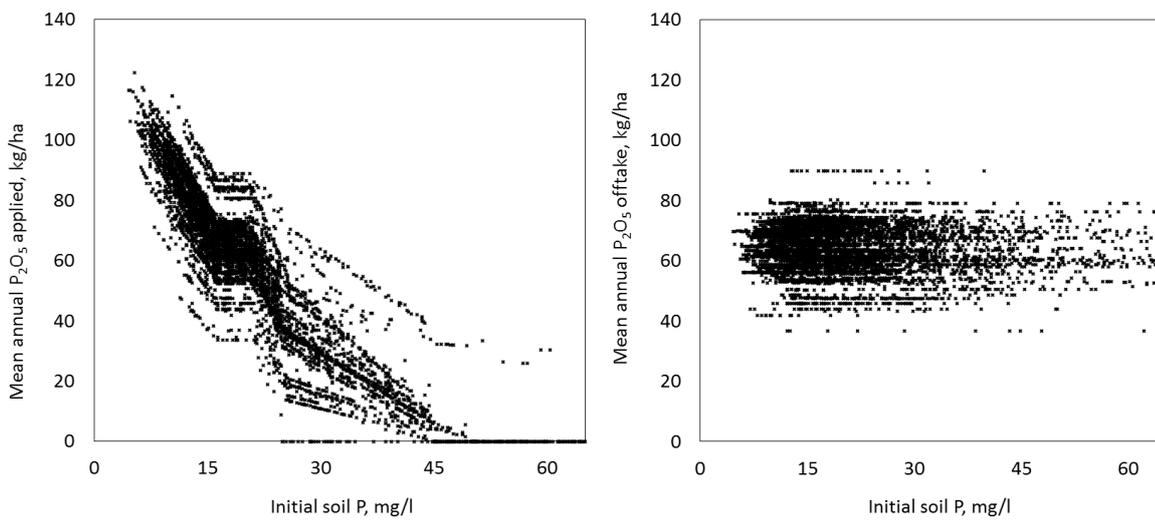
Figure 14. Relationships with initial soil P of (a) average annual P₂O₅ applied over 4 or 5 years or (b) average annual P₂O₅ offtake over 4 or 5 years for all sampling points with less than 65 mg/l P. Adjustments of applied P₂O₅ for soil P was continuous, not stepped, except at P Index 2- (16-20 mg/l P). Vertical variation related to crop type, crop yield or fate of crop residues.
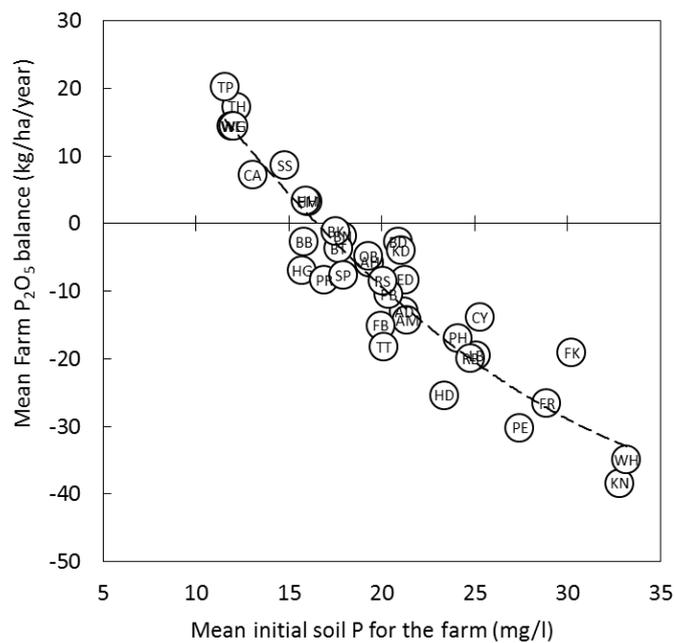

Figure 15. The relationship between mean P₂O₅ balances maintained on 36 farms (coded as in Table 17) and their mean initial soil P, showing that farm P₂O₅ balance strategy was set largely according to initial soil P; most farms with initial average soil P at Index 2 or more maintained a negative P₂O₅ balance.
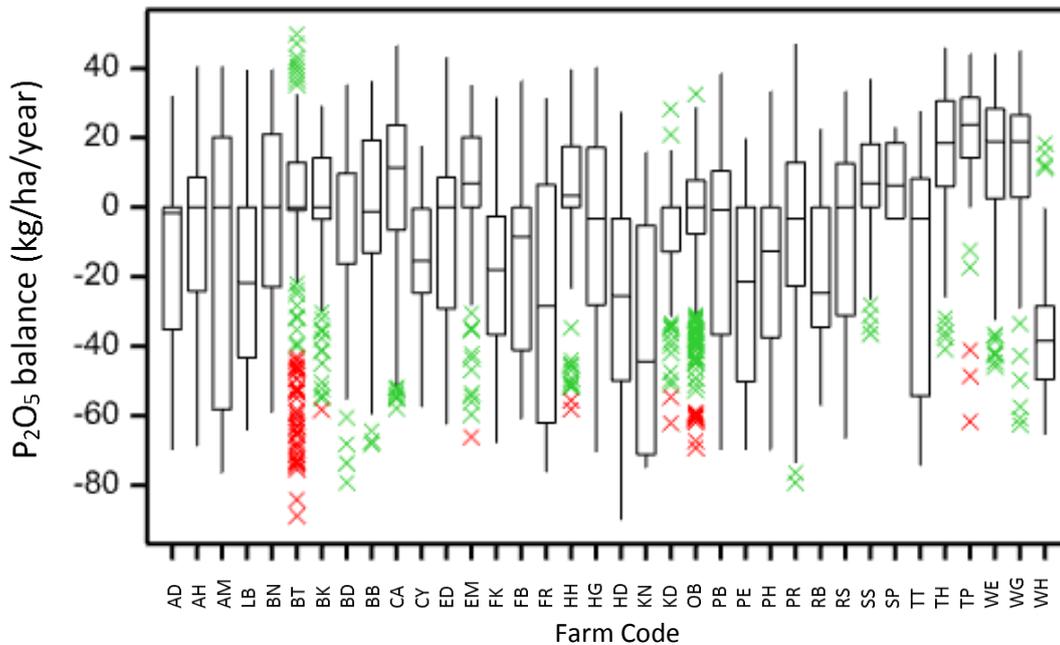
Figure 16. Boxplot showing variation in annual P_2O_5 balance for each farm (the key is the same as for Figure 10).

Perhaps the most aggressive farm P_2O_5 balance strategy in relation to soil P was farm HD where average soil P was within P Index 2 yet the P_2O_5 balance was -25 kg/ha/year. Note that farms with initial soil P within Index 2 generally maintained negative P_2O_5 balances of around -10 kg/ha/year P_2O_5 so there was a general tendency to be more frugal with P_2O_5 than is recommended in RB209. Individual sampling points had average P_2O_5 balances ranging between -92 and +51 kg/ha/year, and averaged at -6 kg/ha/year (median 0 kg/ha/year). The farms' median balances were zero for about half of the farms (*Figure 16*).

3.2.4   Soil P changes

Soil P values for the initial samples have been subtracted from those for the second samples and divided by the intervening period (four or five years) to give the soil P change in mg/l/year. Mean soil P levels on each farm at both the start and the end of the period considered are shown according to sampling year in *Figure 17*. The expected pattern here was for lines starting at low soil P to increase and for lines starting at high soil P to decrease. Surprisingly, overall, most farms tended to show increases in soil P. On only a few farms (FK, FR, HD & SP) was there a significant reduction in soil P, and (except for farm SP) these were all amongst the farms maintained with a significantly negative P_2O_5 balance (*Figure 16*). However, there were a number of other farms which also had significantly negative P_2O_5 balances but which did not show obvious decreases in soil P (e.g. LB, FK, KN, PB, PH, RB & WH). In fact WH showed large *increases* in soil P, by far the largest of any of the farms,

despite its initial high soil P value. WH was also one of only two farms for which the second sampling fell in 2015 (the other being BT); farm BT only showed a modest soil P increase, but it is just possible that the results for farm WH were affected by some aberrant sampling or laboratory conditions in 2015, and should thus be regarded as questionable.

It is worth noting that if data from the initial and second samplings were combined, average soil P tended to increase by year of analysis (*Figure 17*), despite the negative P_2O_5 balances maintained by most farms; even excluding the first and last year's when only one or two farms submitted samples, there was a statistically significant (P>0.05) positive trend of +0.7 mg/l/year in average farm soil P over these years. There could be a range of causes, including trends in cultivation practices (e.g. less ploughing), climatic trends, or possibly laboratory trends resulting from inaccurate standardisation. Note that analyses in December tended to exceed analyses in other months (*Figure 18*).

Despite having initial soil P Indices in Index 3, and despite maintaining P_2O_5 balances of -14 and -30 kg/ha/year respectively, Farms CY and PE showing large increases in soil P between their two sampling occasions (*Figure 17*). This contrasted with Farms FK & FR which had somewhat greater initial soil P levels (around 30 mg/l), and which maintained similarly negative P_2O_5 balances of -19 and -27 kg/ha/year respectively but for which soil P levels decreased slightly. On the other hand, Farms BD, ED & KD had initial soil P levels at around 21 mg/l and had much less negative P_2O_5 balances (-3, -8 & -4 kg/ha/year respectively) but only maintained soil P at around this level.
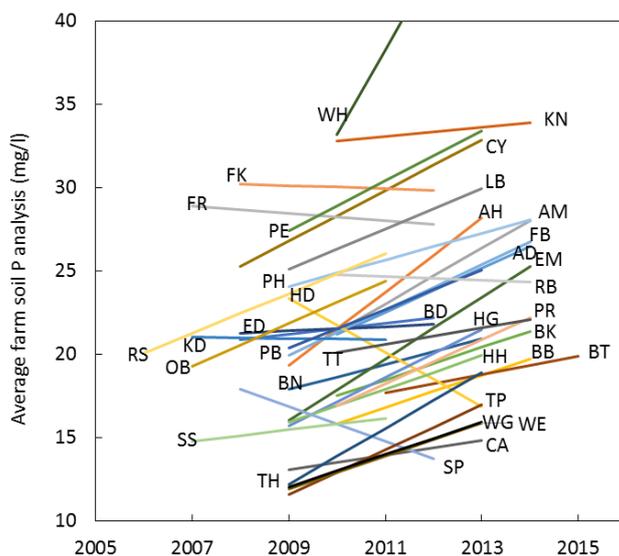

Figure 17. Changes in average soil P by farm, in relation to the years when sampling occurred. The Farm code (Table 17) is indicated for each line. Apparently, a mean analysis of 58.9 mg/l was achieved for Farm WH in 2015, despite maintaining a negative average P_2O_5 balance.
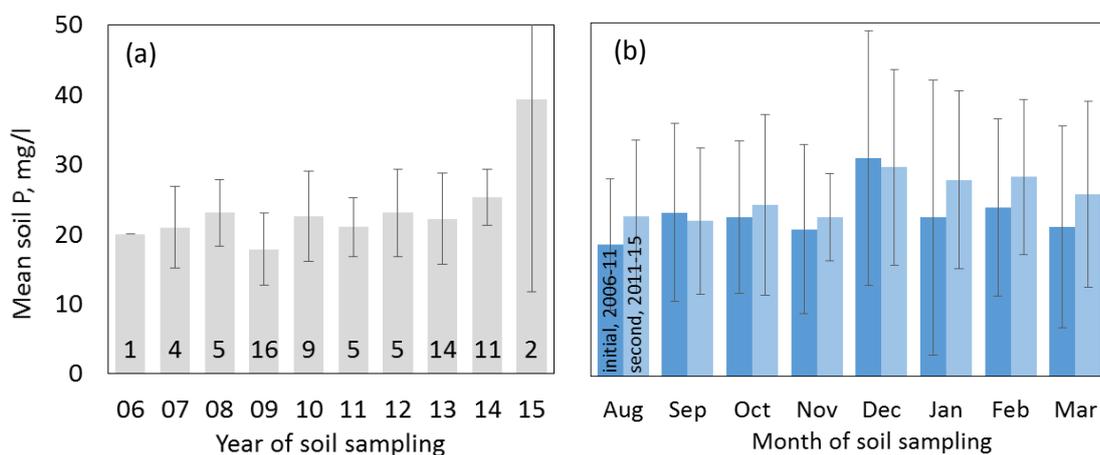
Figure 18. Average soil P (a) by year and (b) by month of analysis. Soils on each farm were analysed twice, four or five years apart. The number of farms analysed in each year is indicated at the base of each column, and one 2SD is indicated by each error bar.

The boxplots of intra-farm variation in changes in soil P in *Figure 19* are expressed on an annual basis. In comparison with the farm to farm variation, intra-farm variation was large, such that although most farms showed positive changes overall, all farms showed some negative changes. Again farm WH stands out as having the largest inter-quartile range, with almost all changes here being positive.
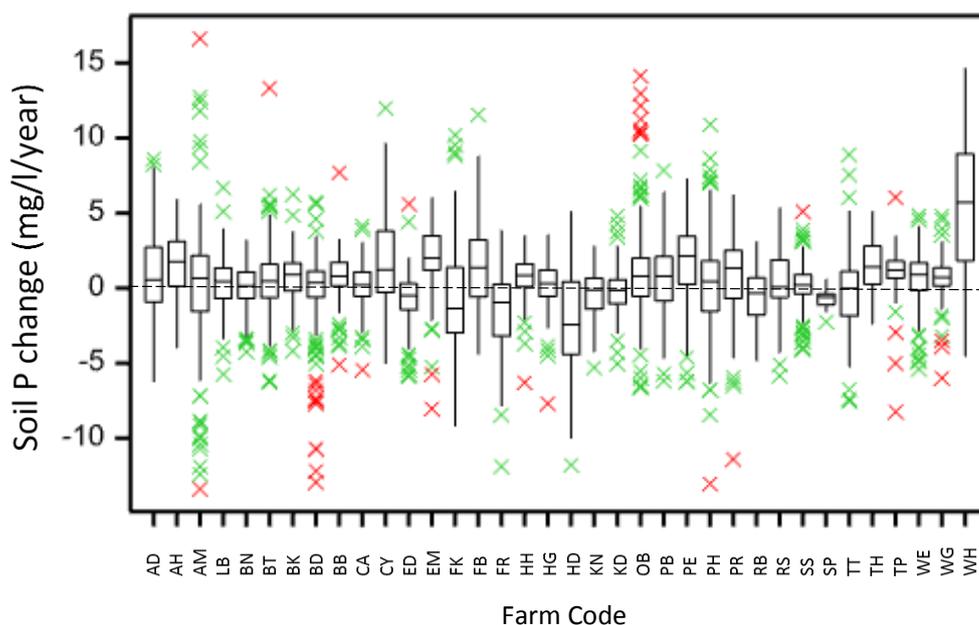
Figure 19. Boxplots showing variation in soil P changes per year farm by farm. The key is as for Figure 10. Farm codes are defined in Table 17.

Examining the data farm-by-farm, the general finding was that farms maintained a slightly negative P_2O_5 balance whilst achieving a positive soil P change. However, these underlying farm effects were small in relation to relationships in the dataset as a whole; because the variation within farms was so large, overall there was a dominant positive relationship between soil P changes and P_2O_5 balances (d).

In exploring the variation in soil P change within the dataset as a whole, a significant number of possible explanatory factors was considered in addition to P_2O_5 balance, including soil type, soil pH and initial soil P (*Figure 20*). However, other than the obvious and inherent dependence of P_2O_5 balance on initial soil P (*Figure 20a*), and the relationship between successive soil P analyses (*Figure 20c*), none of these was clearly having a dominant effect. The association between initial and second soil P analysis was sufficiently loose (*Figure 20c*) that there was a poor relationship between P_2O_5 balance and second P analysis (compare *Figure 20a* with *Figure 20b*). There were some boundary effects between soil P change and its component soil P analyses (*Figure 20e* and f) just because it is impossible to have a negative soil P change smaller than the initial value or a positive soil P change larger than the second value. There was a tendency for high soil P levels to occur more commonly at high rather than low soil pH (*Figure 20h* & i) but soil type and soil pH were not generally helpful in explaining the soil P changes observed here. Thus the main explanatory factor for soil P change was P_2O_5 balance.

A multivariate analysis of soil P change was undertaken to try to combine explanatory factors in one model. The aim was to test whether factors other than P_2O_5 balance were useful in explaining the soil P changes. Using just annual P_2O_5 balance and initial soil P only 29% of the variance in soil P change was accounted for, but when farms were treated as an additional explanatory factor 46% of the variance was accounted for. Including soil type as well as farm increased this to 49% but this may have been just because the number of explanatory categories (degrees of freedom) increased from 72 to 134. The contribution of northerliness (expressed as latitude) was explored but lacked value. Thus it was concluded that initial soil P and P_2O_5 balance were useful, but that there was significant value in including 'farm' itself, if this could be considered as a predictor.

3.2.5   Soil P 'responsiveness', or soil P_2O_5 'requirement'

We coin the term soil P 'responsiveness' here to describe the extent to which soil P changed in relation to the concurrent P_2O_5 balance maintained at that point (position); the units of responsiveness are mg P/litre soil/kg P_2O_5/ha, and are independent of time. The reciprocal of soil P responsiveness is possibly more meaningful to farming practitioners and we call this soil P_2O_5 requirement here, its units being kg P_2O_5/ha/mg P/litre soil. The intention of the analysis of soil P responsiveness (or requirement), and the subsequent discussion below, is to answer the question "Does land differ in the amount of phosphate (balance i.e. fertiliser input less crop offtake) required to change its soil P analysis?" i.e. Can differences in soil P requirements be explained?
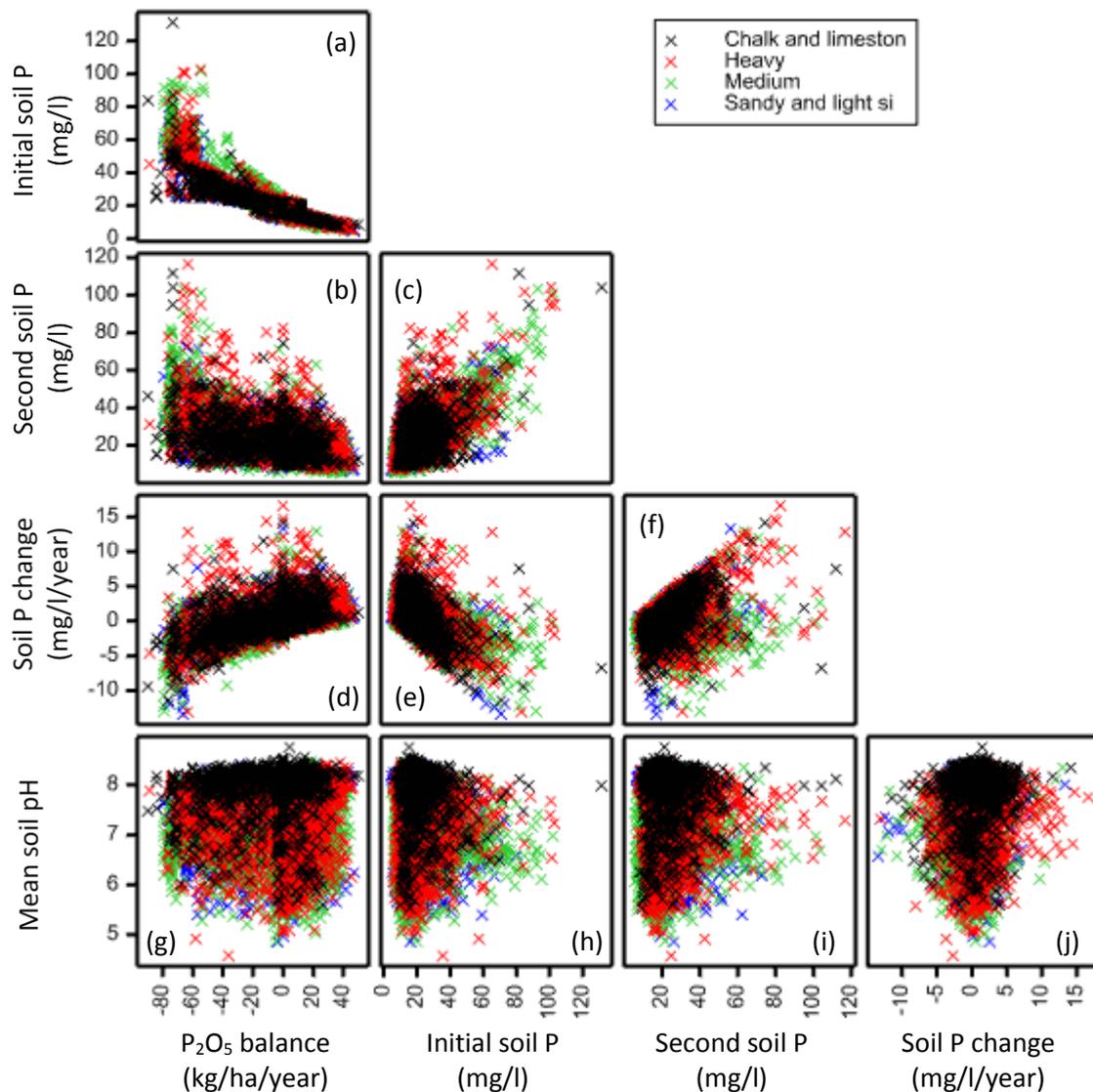
Figure 20 (a-j). Scatter plots showing inter-relationships for individual data-points between annual soil P changes and potential explanatory factors. Points are coloured by soil type (see legend top right).

Statistical analysis of the farm by farm correlations between soil P change and P_2O_5 balance showed significant positive relationships in every case. In only two cases (farms AH & RS) were the relationships less certain than $P<0.001$, but these were still significant at $P<0.05$. Correlation coefficients between soil P change and P_2O_5 balance ranged from 22% to 86%, the median being 64%. Slopes and intercepts were determined from the data for each farm; an example is shown in *Figure 21*. As explained above these coefficients are expressed in terms of P_2O_5, the intercept being an estimate of the annual balance of P_2O_5 required to maintain soil P unchanged, and the slope being an estimate of the amount of P_2O_5 required to raise soil P by one mg per litre. Thus in *Figure 21* the slope converts from 0.0775 mg/l/kg/ha to 13 kg P_2O_5/ha/mg/l and this with the intercept converts from 3.43 mg/l to -44 kg P_2O_5 /ha/year. Note that there are a set of points in *Figure 21*

aligned with the y-axis. This arises here (and in most other farm datasets) because, for the full breadth of P Index 2, a policy of exact P_2O_5 balance is maintained, whereas at other (initial) soil P levels the P_2O_5 balance is adjusted from zero on a continuous basis, with the intention of building up or running down soil P.

Considering the data from all farms (*Figure 22*) P_2O_5 intercepts were largely negative; apart from Farm AH which was the principal outlier at -96 kg/ha/year; otherwise they ranged from -52 to +26 kg/ha/year, with the mean being -17 kg/ha/year. As already stated, P_2O_5 slopes were all positive, but slopes and intercepts did not relate to each other i.e. the outliers were at different farms in each case. For the P_2O_5 slopes, the two principal outliers were farms LB & RS at 56 & 69 kg/ha/mg/l respectively. Other P_2O_5 slopes ranged from 7 to 38 kg/ha/mg/l, the mean and median being 22 and 21 kg/ha/mg/l respectively.

Whilst 'farm' appeared to explain a large part of the variation in soil P2O5 requirements here, earlier examination of variation in soil P change showed initial soil P to have some explanatory value. Thus initial soil P was examined here also. *Figure 23* shows that, if the two farms with the largest soil P_2O_5 requirements are omitted, there was a tendency for farms with larger initial soil P values to have smaller soil P_2O_5 requirements i.e. it was easier (took less P_2O_5) to change soils with large P reserves than soils with small P reserves. However, this relationship is not strong or sufficiently precise to be adopted as a quantitative predictor.
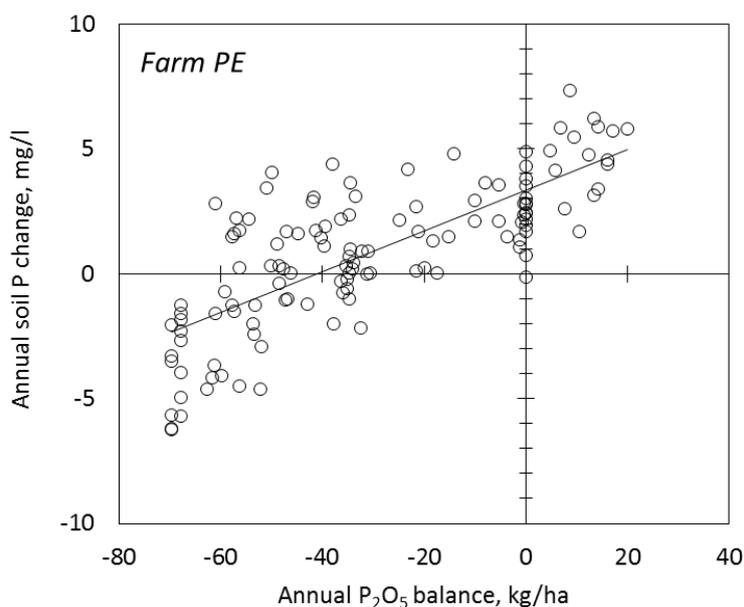

Figure 21. Example relationship (for farm PE) between soil P change and P_2O_5 balance. The y axis intercept is 3.43 mg/l and the slope is 0.0775 mg/l/kg/ha. These values expressed in terms of soil P_2O_5 requirements are (x-axis intercept) -44 kg/ha/year and (slope) 13 kg/ha/mg/l.
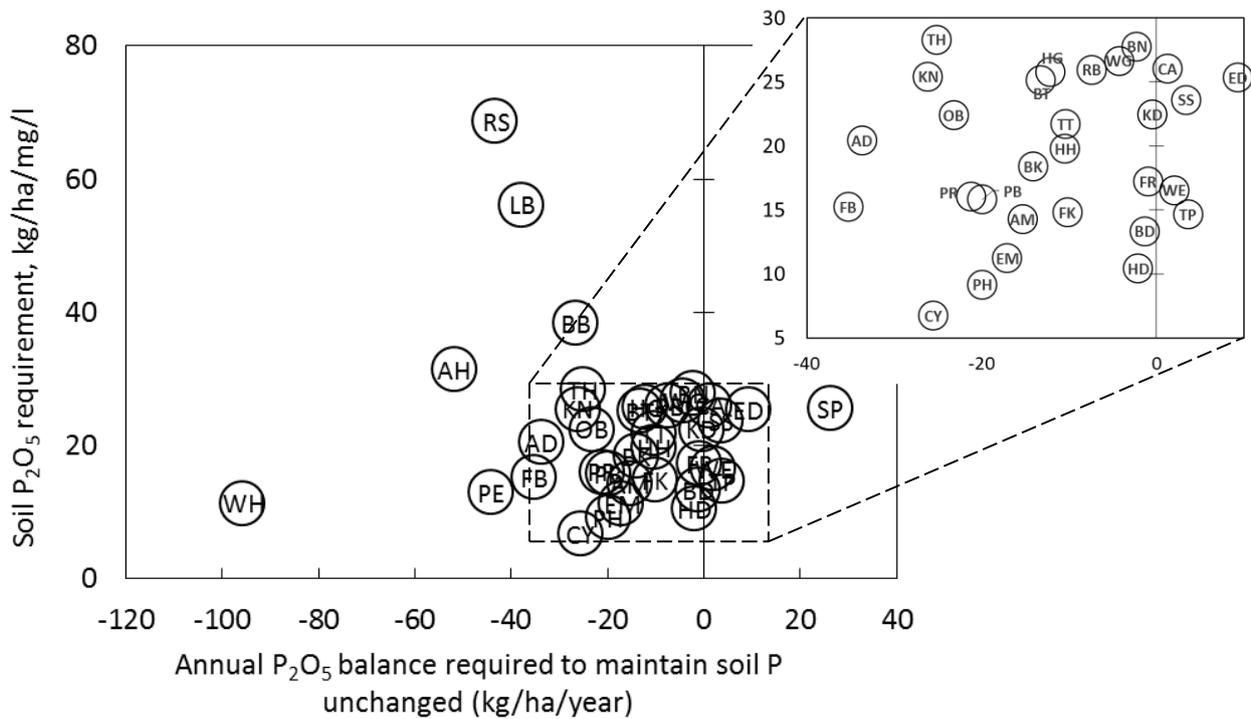
Figure 22. Intercepts (x-axis) and slopes (y-axis) of farm-by-farm relationships between soil P change and P_2O_5 balance. Intercepts and slopes are expressed in terms of P_2O_5 requirements. Farm codes (as described in Table 17) are indicated for each point and overlapping points are differentiated in the expanded section, inset.
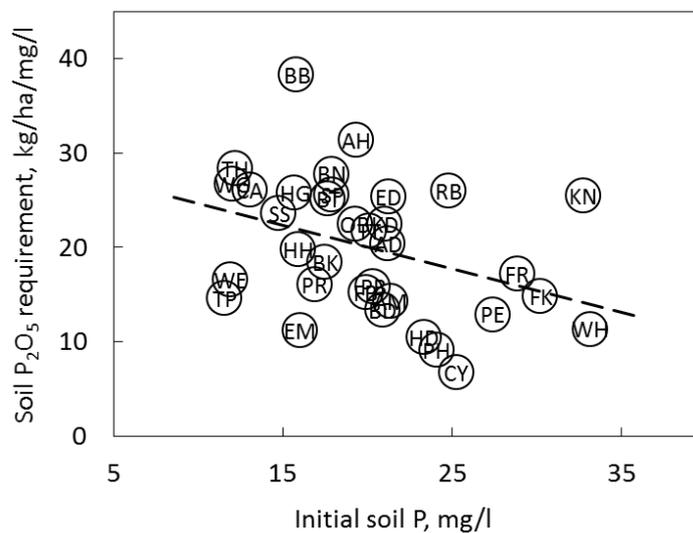

Figure 23. Tendency of soil P_2O_5 requirement to decrease on farms with increasing levels of initial soil P. Two farms (RS & LB) with extreme soil P_2O_5 requirements (Figure 22) but medium initial soil P have been omitted from this relationship. The negative correlation is significant ($R^2 = 0.137$; $P<0.05$).

Overall, the P_2O_5 requirements determined here were surprisingly small. They compare with a large soil P_2O_5 requirement quoted in the Fertiliser Manual (RB209, pp. 39-42) where it says: "Large amounts of phosphate and potash may be required to raise the crop-available phosphate and potash in the soil by one Index, and it is difficult to give accurate amounts. However, as an example, to increase soil phosphate by 10 mg P/litre may need 400 kg P_2O_5/ha as a phosphate fertiliser (i.e. 850 kg/ha of triple superphosphate)." This example translates to a P_2O_5 requirement as defined here of 40 kg/ha/mg/l, almost double the requirement of the median amount found; only two of the 36 farms showed slopes exceeding this example.

4   Discussion

As set out in the introduction, questions that this Work-Package sought to address are: "Is the philosophy of monitoring and managing the soil as a store of P sound?", "Do soils differ in the way their P storage should be managed?", "How confident can we be in an ASPR of 40 kg/ha/mg/l, and a PBSM of zero, as suggested in RB209?", "Are there factors other than soil type which should be taken into account, when seeking to alter soil P?" and lastly "By withholding P applications, might we cross a 'cliff-edge' into perpetual P deficiency which will be difficult to correct?". Answers to these questions could clearly have considerable commercial importance, since the UK arable industry invests significant funds in monitoring soil P and in applying phosphate fertilisers, and the consequences of any inadvertent phosphorus deficiencies arising from poor appreciation of soil P maintenance requirements could be significant for crop productivity. However, before addressing these questions, it is appropriate to summarise some of the initial reasoning behind this work.

4.1   Theory and expectations

Soil P is understood as being divided into four pools: 1) mineral P (very slowly plant available), 2) strongly bonded/absorbed P (less readily plant available), 3) surface adsorbed P (readily plant available) and 4) soil solution P (immediately plant available), with reversible transfer between pools 2-4 (Syers, 2008). Soil P determined by Olsen's test (STP) only measures the P in two of these pools – the soil solution and the readily available pool. However, most of the P_2O_5 added to soil in water soluble fertilisers and the water soluble fraction of organic manures, quickly transfers to the less readily available pool (Johnston and Poulton, 2011), so will not be measured as part of the STP . It has been reported that the efficiency of added inorganic fertiliser P_2O_5 for increasing STP levels is typically <20% (Griffin *et al.*, 2003). As a result, the rate (and direction) of change in soil P will depend both on the P_2O_5 balance and the rate at which P is released from the less readily-available pool of soil P. The latter will depend on soil (texture, pH etc.) and P_2O_5 input characteristics (FYM, slurry, manufactured fertiliser etc.) as well as previous fertiliser management practices (nutrient status, organic matter levels etc.).

Plant roots take up P from the soil solution as orthophosphate ions, principally H_2PO_4 which move only very slowly in the soil solution; estimates suggest only about 0.13 mm per day. The two main factors controlling the availability of soil P to plant roots are the concentration of phosphate ions in the soil solution and the ability of the soil to replenish these ions when plant roots remove them, i.e. the P-buffer capacity of the soil. Buffer capacity denotes the ability of the soil to resist changes in solution P (Shirvani *et al.*, 2005).

Buffering capacity is an important factor influencing the P-supplying capability of soils to plants, because it controls the ease of P release into the soil solution (Holford, 1980). The size of the readily available P pool governs the amount of P available in solution for uptake, whilst the size of the less readily available P pool governs the buffering capacity of the soil to maintain the P supply (Withers, 1997). Soil type is an important determinant of soil buffer capacity. Sandy soils generally have a large, readily available pool (i.e. high STP), but often have a low capacity (i.e. low buffer power) to maintain this pool compared to soils with a higher clay content which build up less readily available P reserves. The texture of soil affects its capacity to hold P by adsorption. Most clay and silt soils have larger capacities to adsorb phosphate than coarse-textured sandy soils. As a result, soils with high buffer power (high organic matter and clay) are expected to need more P_2O_5 to increase their STP level than soils with low buffer power (low organic matter and low clay).

The potential variation in the amount of P_2O_5 required to increase STP, as a consequence of the buffer power associated with different soil types, is currently not recognised in fertiliser recommendations in England and Wales. However, the recommendations in Scotland have recently been updated (Sinclair *et al.*, 2015) to reflect inherent differences in 'P sorption capacity' (equivalent to buffer power) as a result of soil chemistry, texture, pH and organic matter content. For those soils (classified as having a high P sorption capacity) fertiliser recommendations are typically increased to reflect the reduced plant P availability. It is possible that variations in buffer power linked to soil type may have influenced the relationship between soil P_2O_5 balances and soil P in the datasets studied. However, factors other than soil type will also have influenced the observed relationships between P_2O_5 balance and soil P, particularly in the experimental dataset where the samples were taken over a long period of time.

4.2 Comparing P_2O_5 requirements of soils

Comparisons of soil types are not easy and are seldom precise. Because soils cannot be moved, their comparison is almost always confounded with other spatial variables such as farm type, rotation, husbandry, weather and variety. The long term experiments provided replication over many years but the analysis of say TSP effects was nevertheless restricted to one soil (of Ragdale series) on one field on one farm at Ropsley near Grantham, and cannot be taken with confidence to represent all Ragdale-like soils. Furthermore, the effects of manures were studied at three sites of contrasting soil type but the relationships between Δ soil P and P_2O_5 balance were insufficiently precise to tell responses apart, and even if relationships had proved different, those differences could

not have been ascribed to soil differences, rather than one of the other major site differences, with any confidence. The long-term experiments were thus best used to assess the degree of variation in ASPR and PBSM (the P_2O_5 balance for soil P maintenance), and to assess possible differences between inorganic and organic forms of applied P, and the much more numerous SOYL data were potentially more suited to testing for soil differences.

The analytical approach to quantifying soil P behaviour in this study followed the methodology of Heming (2007), both for the experimental data and the SOYL data. Data from the seven sites were grouped, based on input type, giving three overall regression relationships – i.e. manufactured P_2O_5, livestock manures (broiler litter, slurry and farmyard manure-FYM) and biosolids. However, these groups did not show convincing differences. For the experimental data as a whole, APSR was approximately 90 kg/ha/mg/l, and when P_2O_5 inputs matched P_2O_5 offtake, soil P was approximately maintained. However, the SOYL data (discussed later) showed all APSRs to be less than 90 kg/ha/mg/l and most of them were much less. In addition there was a general increase in soil P noted for the SOYL-sampled farms. The larger SOYL dataset is potentially more representative of commercial practice but does rely on some data assumptions (see later sections for details).

4.3   Comparing with previous studies – inorganic fertilisers

The clay loam soil at Ropsley would be expected to have a high buffer power and therefore require more P_2O_5 to increase STP than a coarser textured soil. However, the slope had a low R^2, and only 10% of the variability in soil P change was explained by P_2O_5 balance, meaning that it is not possible to draw any firm conclusions relating to the influence of soil type (or any other soil parameter). The calculated ASPR at this site was 68 kg/ha/mg/l. In comparison, Heming (2007) using the same methodology, reported ASPRs of 10-28 kg/ha/mg/l and Johnston and Poulton's (2011) results indicate APSRs equivalent to *c.*40 kg/ha/mg/l. [They report that 143 kg P/ha (*c.*330 kg P_2O_5/ha) at 'Exhaustion Land' and 133 kg P/ha (*c.*300 kg P_2O_5/ha) at Saxmundham (applied as TSP) were required to increase Olsen soil P by 8 mg/kg from Index 1 to 2.] For the SOYL data a mean APSR of 22 kg/ha/mg/l was found. The current RB209 suggestion of 40 kg/ha/mg/l was probably taken from Johnston and Poulton's (2011) analysis, and is c.45% of that estimated in the long-term experiments studied here, and *c.*180% of that calculated from the SOYL dataset. The estimates of Heming (2007) and from the SOYL data show most similarity; however, it is notable that these were obtained by a similar methodology, and may have been subject to similar artefacts. It is clearly of concern that there are these large variations in responsiveness.

4.4   Comparing P_2O_5 requirements with different P inputs

Livestock manures are commonly used in modern agriculture to supply phosphorus. The total P content in manure varies depending on the animal species, age, diet, and how the manure has been stored. Estimated values of P plant availability vary from 50 to 100%. The recommendations in the current edition of RB209 (Defra, 2010) are based on availabilities of 60% for solid manures and 50%

for slurries respectively. Some recent studies have found that livestock manures were equivalent to inorganic P_2O_5 fertiliser in P_2O_5 availability (e.g. Reddy *et al.*, 1999) whilst others have suggested that manure P_2O_5 was less available (e.g. Miller *et al.*, 2010).

Environmental factors such as temperature, soil moisture, and soil pH can have important effects on the P mineralization rate. Blake *et al.* (2000) suggested that manure P can be either less available or more available than inorganic P, depending on climate, soil, and availability of other plant nutrients. They advised careful consideration of environmental conditions when transferring conclusions about soil P availability from one environment to another.

The P_2O_5 inputs at the three long-term manure sites were not planned in accordance with the approach of soil P maintenance, rather the application strategy was to apply 250 kg N/ha. As a result, annual P_2O_5 applications in these manures ranged from 25 to 1,100 kg/ha. The modelled relationship between P_2O_5 balance and STP changes indicated that, as at Ropsley, there was no change in STP when P_2O_5 inputs equalled P_2O_5 offtakes. It is tempting to reason that the larger ASPR here compared to at Ropsley – 105 compared to 68 kg/ha/mg/l – arose because the livestock manure P_2O_5 was less available than manufactured P_2O_5. However, as for the TSP, the manure slope had a low R^2, and only 16% of the variability in soil P was explained by the P_2O_5 balance meaning that it was not possible to draw any firm conclusions in relation to soil P_2O_5 balance. Combining the two datasets together (along with data from the biosolids experiments) showed no difference between the materials.

The analysis of experiments involving biosolids here was inconclusive but a UK study by Withers *et al.* (2015) showed that biosolids applied to agricultural land can behave very differently to inorganic fertilisers in terms of their effects on soil P sorption dynamics and soil P availability because of the extensive stabilisation processes at wastewater treatment centres that make biosolids safe to apply. They showed that soil P increases (1-18% of total P applied) were greatest for lime stabilised biosolids, whereas the presence of high iron (Fe) in the biosolids, or thermal drying into pellets, significantly reduced rates of soil P increase. Thus it is suggested that the addition of biosolids containing large amounts of calcium (Ca) or Fe increases binding sites in the soil and hence increases soil P buffering capacity.

4.5 Monitoring and managing the soil P store

The analysis of the SOYL data here followed quite closely the strategy advocated in RB209 for soil P monitoring and management. Thus this work provides a significant test of the current philosophy. However, the analysis revealed some significant surprises and difficulties so it is clearly necessary to make some cautionary remarks about the data and the way that they could be analysed, before any practical conclusions are drawn.

In analysing the SOYL data, values from only two sampling occasions were collated for each farm; it would have been significantly more effective to have acquired data from a third (earlier) sampling,

so that the consistency of changes in soil P at each point could be checked. However, this would also have diminished the size of the dataset significantly, not only because it is less likely that three successive samples will have been spatially coincident but because land coverage by SOYL's sampling services has increased over recent years, and many farms amongst their current clientele will only have been sampled twice so far. That only two samplings were considered causes significant complicating factors to be confounded with 'farm' differences, including the two particular times of sampling (month, year, weather, soil conditions, and interval since fertiliser application), the sampler at each time, and the laboratory practices at each time.

As regards sampling regimes, there are significant difficulties in achieving comparable results on different occasions several years apart when the sampler will commonly differ on each occasion, the month of the year may differ (*Figure 18*b), and recent weather or differences in recent cultivation practices may affect P release or soil P distribution in the soil. As regards laboratory practices, Olsen's method is notoriously difficult to standardise, and although the same lab was used on all occasions, it should be noted that inter-laboratory checks have failed to eliminate inter-lab differences in recent years, so similar effects may also apply to comparisons of results from the same lab, but over time periods of several years, as here. Given these issues and those concerning the data below, it is only realistic to look for gross effects in these data.

It was reassuring to find that 90% of repeat samples were within 8 m of each other. Previous studies of spatial variability of soil P indicate that this level of proximity should be adequate to detect temporal differences (Oliver & Kerry, 2013), so positional effects can be taken to be minor. In calculating P_2O_5 balances it was less than satisfactory that the yields assumed here were as expected by the farmer rather than as observed in practice. Whilst it is difficult to see that a farmer would purposely or unwittingly set unrepresentative yields (since this would only serve to impose an inaccuracy on his fertiliser use) it was common that standard assumptions were made (a) for whole fields and (b) prior to their realisation, and this will have imposed significant imprecision on the results. Similarly the assumption of standard P_2O_5 concentrations in crop materials (grain and straw) rather than measured concentrations (as in the long-term experiments) will only have added to this imprecision.

Notwithstanding these cautionary issues, the dataset analysed here has certain advantages over research data in that it was collected in the course of commercial use, and therefore indubitably represents information such as is used by farmers in the course of their fertiliser management. It is also much more extensive than research data such as from the long-term sites reported here, and represents many more soil types than can normally be addressed by research experiments. Any conclusions drawn from the data should thus be versed in these terms, for example P_2O_5 balances are not measured balances as were derived from long-term experiments but are the only balances that a farmer can work with when making his fertiliser decisions; they are 'expected P_2O_5 balances'.

4.6 Conclusions and Recommendations

4.6.1 P_2O_5 balances

Most farms here were maintaining negative P_2O_5 balances (*Figure 15*), even at P Index 2, and the same appears to be true nationally for arable land (Withers *et al.*, 2016). The expectation is thus that soil P reserves of arable land must be running down. However, other evidence here is to the contrary, so it is important to resolve this discrepancy as far as possible.

4.6.2 Soil P assessments – Temporal versus Spatial comparisons

Comparisons between trial-sites (or farms) will almost always confound temporal differences with spatial (e.g. soil type) differences i.e. different sites are generally sampled (and analysed) at different times. Because cropping, soil conditions, weather, sampling and lab analysis are all subject to temporal variation, there is a high chance of artefacts affecting temporal comparisons, so comparisons between sites, as well as between dates at the same site, must continue to be recognised as crude. This conclusion applies to normal recommended practice for soil P monitoring.

Within farms, soils here were analysed in batches. It was thus possible to separate spatial differences (all of the samples taken from one farm at one time are affected by the same temporal differences) from temporal differences, which tend to be singular for each farm. For any one farm, temporal and spatial comparisons are represented respectively by the intercept and slope of *Figure 21* and the figures in Appendix 1.

If we focus initially on the slopes of the relationships within farms ('apparent soil P_2O_5 requirements' or ASPRs, i.e. as in *Figure 21*), these can be considered as comparing different positions across each farm, the main influential factors being soil characteristics and crop performance, all estimated on a *common* basis. Almost without exception, and as expected, these showed an increase in P_2O_5 balance associated with an increase (or less of a decrease) in soil P for all farms in the dataset. A similarly strong positive relationship was found in the data from the long-term experiments (*Figure 7*). Thus, unsurprisingly, this work strongly supports the capacity of the soil to act as a P store.

The temporal changes in soil P were generally positive (*Figure 17*). This implies that, generally across all farms, PBSMs (P_2O_5 balance for maintenance of soil P) were negative i.e. soil P supplies for crops could have been maintained with significantly negative P_2O_5 balances (mean -17 and median -14 kg/ha/year; range -96 to +26 kg/ha/year). In the light of the received wisdom (as in RB209) of a positive relationship between soil P and P_2O_5 balance, and in the light of the spatial comparisons, this implication seems improbable, and it will best be given little credence.

ASPRs from the long-term experimental data (*Figure 7*) did not allow the separation of temporal and spatial comparisons. It is possible that the smaller ASPRs for the SOYL data compared to the ASPR from the more complex long-term experimental data, arose because the former were solely derived

from spatial comparisons. Similarly it is possible that the more positive PBSMs for the SOYL data arose because these were solely derived from temporal comparisons.

Of course it is possible that spatial comparisons and temporal effects interacted to some extent, but there was no relationship between the slopes and the intercepts determined for the 36 farms (*Figure 22*), so interactions between the slopes (positional effects) and differences in date of determination seem unlikely.

4.6.3 ASPR variation

Given the differences between findings from the experimental and the commercial data, it is not possible to be entirely conclusive on whether ASPRs differ from the value of 40 kg/ha/mg/l suggested in RB209 (Defra, 2010). However, relationships derived from the SOYL data were determined with much greater confidence than from the long-term experiments; over the 36 correlations the mean R^2 was 60%, the minimum 22% and the maximum 86% (Appendix 1.), whereas *Figure 7* shows the mean R^2 was only 25% for all the experimental data.

Generally ASPRs from the SOYL data were 10-30 kg/ha/mg/l (*Figure 22*), smaller than suggested in RB209 (40 kg/ha/mg/l) and much smaller than the (more uncertain) ASPR of 90 kg/ha/mg/l for the experimental data. If the SOYL result can be credited as real, it could be seen as good news, meaning that it is easier and cheaper to change soil P levels than was previously thought.

However, a relatively small ASPR may also be seen as bad news, meaning that it is necessary to review soil P more frequently than once every three to five years, as is currently recommended. It means that soil P might change quite quickly if a farm's P_2O_5 balance strategy changes. As an example, if a soil was just within Index 2 at say 16 mg/l, and a decision was taken to reduce P_2O_5 applications by 25 kg/ha/year, so making the P_2O_5 balance more negative by 25 kg/ha/year, we could expect soil P to decrease by 5 mg/l in 5 years hence to change almost two P indices in that time.

The range of ASPR between farms was large, from 7 to 70 kg P_2O_5 per hectare per mg P per litre soil. On many farms, it appears that soils have been more responsive to phosphate removals or additions than is suggested in RB209 (which suggests an ASPR of 40 kg P_2O_5 per hectare per mg P per litre soil). If a field has a low ASPR it means that imbalances in P_2O_5 will change the soil P Index quickly, so more frequent soil P analysis may be necessary, and changes in soil P will be quicker and cheaper to make than if the ASPR is large.

Thus, where farms have enough data (e.g. through doing P&K mapping), it seems sensible for them to calculate their own ASPRs, so that they can deduce more accurate P_2O_5 management strategies for their land, and decide on the frequency of soil P testing. Whilst calculation of ASPRs is fairly straightforward, the necessary yield and crop P data are often not available for direct estimation of P offtakes; it will thus help the industry if Apps or other routines can be provided to support growers in making the necessary assumptions and calculations.

4.6.4 Accuracy, precision and uncertainty of soil P assessment

The vagaries of using Olsen P to manage soil P over time and thereby ensure crop P availability are all too evident from the results reported here, and it would be wrong to leave these unaddressed. On average, for the 6,500 sampling positions, the second P analysis was 4.5 mg/l more than the first soil P analysis in the SOYL dataset, despite most farms maintaining a negative P_2O_5 balance. This clearly requires investigation and explanation.

Thus further recent datasets (also created by NRM Laboratories) were examined to assess whether the subset of SOYL data chosen for analysis were atypical. These included mean annual averages of all samples from whole-fields, submitted for analysis since the 1994-5 sampling season (*Figure 24*a), and mean monthly averages of all point-based samples (taken to support variable rate P_2O_5 applications) submitted by SOYL to NRM for analysis between 2007 and 2016 (*Figure 24*b). In both cases the trends over time were positive and statistically significant for arable land, although with a steeper slope for the point-based than for the whole-field data. The trend over time for grassland also appeared slightly positive, but was only weakly significant. The positive trends were largely driven by large averages since 2010.
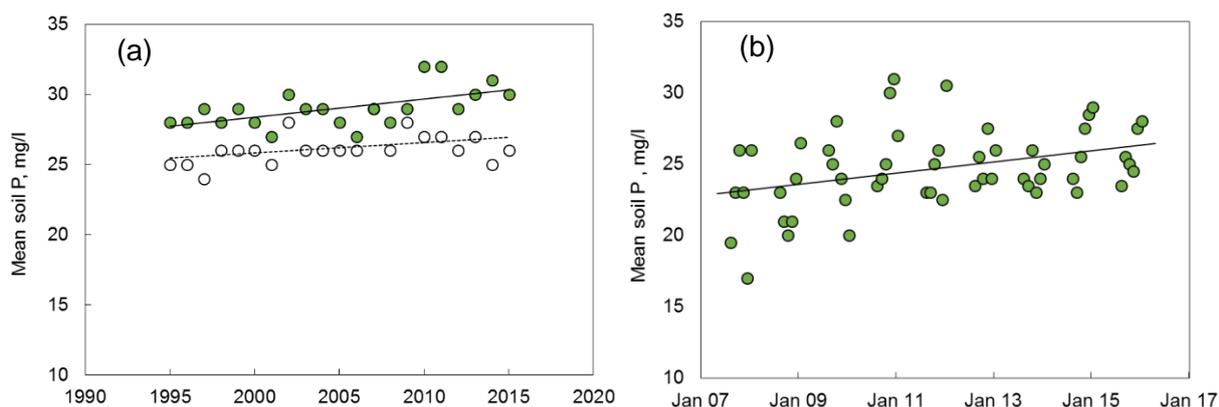

Figure 24. Mean soil P (by Olsen's method) from (a) whole-field samples received by NRM which had cropping details (arable, closed circles; grassland, open circles) averaged by sampling season since 1994-5, and (b) all point-samples submitted by SOYL for analysis by NRM averaged by month since 2007. Slopes (mg/l/year) are (a) + 0.07 for grassland (R^2=0.155; P<0.1) and +0.13 for arable (R^2=0.333; P<0.01), and (b) +0.40 (R^2=0.138; P<0.01).

Possible causes of the positive trends are listed below. These are informed by consultations during 2016 with the main parties involved (ADAS, AHDB, AIC / PAAG, Bangor University, FACTS, NIAB, NRM, Rothamsted Research and SOYL), but the brief assessments of the likelihood of each cause represent the views of the lead author (*RSB*) only, and are offered merely to initiate further joint deliberation:

1. **Climate change effects** on soil equilibria between extractable and non-extractable (both organic and inorganic) P, perhaps arising from soil warming, enhanced atmospheric carbon dioxide or

greater seasonality of rainfall affecting soil chemistry or biology (Dijkstra *et al.*, 2012). *RSB: The short time-scale of the soil P effects seen here make this cause seem unlikely.*

2. **Use of non-inversion tillage** increased from 10% to 40% of arable land from 2000 to 2007 and then stayed at 40% to 2010 (Knight *et al.*, 2012). There may have been further increases since then; however, to control weeds, much land under reduced tillage systems is ploughed every few years so it is only on the very small proportion of land (e.g. with zero-till) that applied P will have become significantly more concentrated within the 0-15 cm sampled horizon over this period. *RSB: The larger trends on arable rather than grassland soils make this cause seem feasible, but the changes from inversion to non-inversion do not appear to have been sufficiently widespread to explain the observed overall trend in surface P concentrations.*

3. **A consistent change in the protocol for soil sampling** between first and second dates. The same company and sampling team were responsible for the SOYL datasets, and these were working to the same protocol throughout, except that the time-delay between P application and soil sampling was increased from 3 to 6 months. *RSB: this cause seems unlikely.*

4. **Drift in laboratory analysis**, due to one or more changes, possibly slow and subtle, in analytical conditions. As well as their stringent internal quality assurance (QA) protocols, NRM and many other UK laboratories voluntarily operate within international QA 'ring test' procedures operated by WEPAL (the methodology is explained on the [WEPAL website](#)) and organised in the UK since 2009 by the Professional Agricultural Analysis Group ([PAAG](#)). These procedures are designed to alert any subscribing laboratory to any deviations in their results compared to other laboratory's results, so it should be possible to treat laboratory error as highly unlikely. However, sizable inter-laboratory differences (involving PAAG-participators) have been observed both during this project (Work-Package 2) and during the Targeted-P project (Appendix 2), and significant inter-annual fluctuations (reflecting sampling as well as laboratory analysis) have been observed from repeatedly sampling sites (Appendix 3). *RSB: It therefore seems possible that, despite current QA procedures, analytical errors could have played a part in the temporal trends found here.*

4.6.5   Improving procedures for monitoring soil P status

4.6.5.1   Support and interpretation

Farmers individually cannot be expected to undertake adequate QA for all aspects of soil P sampling and analysis. However, farmers commit substantial funds to the crop nutrition industry, and in return their service industries seek to provide reliable crop nutrition. The PAAG was formed to ensure continuing confidence in laboratory services. However, PAAG procedures do not check for effects arising from field management, fertiliser use, sampling methodology and even climate change. Thus the industry would be well served by an appropriate organisation, ideally independent of the main commercial interests, undertaking regular monitoring and validation of soil sampling and analysis protocols and results, and it could also possibly offer accreditation. Ideally this agency would report

for the whole industry the appropriate level of trust and certainty that should be attached to the services that the nutrition sector provides. One example component of this could be for soil results from the set of four 'run-down' experiments (Appendix 3; Figure 26) to be published annually, so that the industry can easily examine examples of the repeatability and season to season variation that affect their soil P monitoring. This requirement applies internationally, so may best be addressed internationally. It follows that somehow, without undermining their faith in the importance of monitoring soil P status, farms should be supported in maintaining a realistic view of the precision of soil P testing.

4.6.5.2 On-farm

Farms should strive to maintain as consistent an approach to soil sampling and analysis as possible. A protocol needs to be developed for this, in which the following possible features should be considered:

- **Use soil analysis for two purposes**

  - To determine the best <u>average soil P</u> level (from at least three samples, over time or over points) hence (using the Fertiliser Manual) to deduce the Soil P Index and any fertiliser P Requirement, and

  - To determine the <u>rate of soil P change per year</u>, hence how long it could take before the risk of crop deficiencies becomes serious.

- **Organise analysis for soil P** (also K, Mg & pH) **in 'campaigns'**

  - Do not sample within 6 months of any application of P-containing materials

  - Maintain a constant strategy for soil P sampling & analysis: target the same rotational position, the same calendar month (and the same stage in cropping cycle i.e. cult-sow-fert-harvest), the same location(s) within each field, the same soil-sampler, the same soil depth, the same sample transport arrangements, the same analytical lab., the same analytical method, and analysis on the same date.

  - Sample as many fields on the farm as is possible within one campaign. Note that the more extensive a campaign the better; average results can then be established with greater confidence and smaller differences can be detected. On smaller farms it could be useful to employ an agent who can arrange analyses of many fields on several adjacent farms all on the same occasion. The agent could also offer joint interpretation of the results.

  - Repeat any puzzling results, along with some 'normal' samples as double-checks.

- **Do double-checks with crop P analysis.** For soils at P Index 0, 1, or 2 (less than 26 mg/l), and especially on any soils recently 'built up' to P Index 2, use routine P analysis of *harvested crop* (grain or root). Grain or root P concentrations can be determined with more precision than soil P, and they can validate how close crops have come to being P deficient.

5   Acknowledgements

6   References

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Appendix 1. All SOYL data used

Data for all 36 farms reported here (shown as in the example in Figure 21):
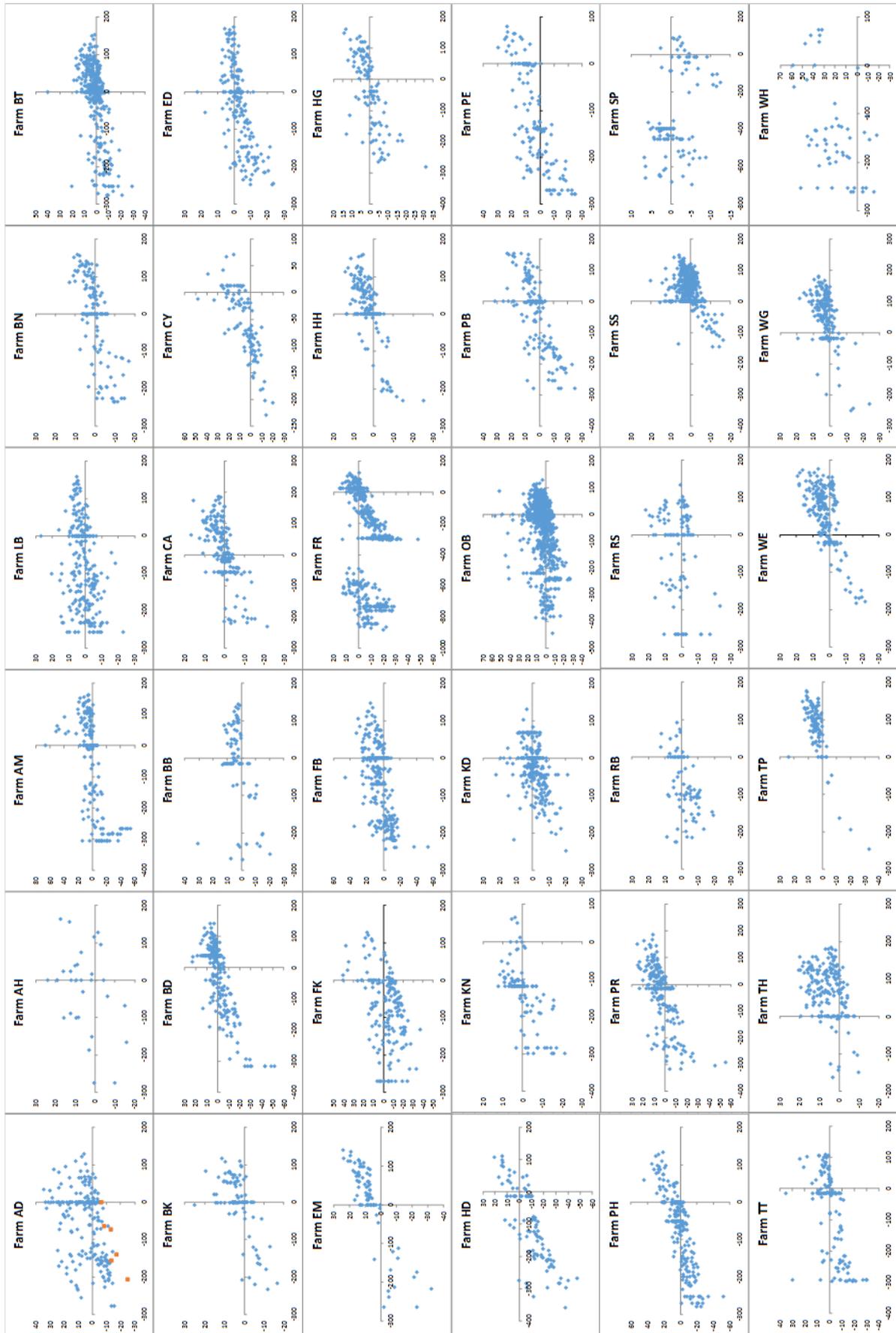
Appendix 2. Inter-laboratory comparison for soil P in 2014

In the Targeted-P Project (see AHDB Report, section 6.2.2.1) 99 soil samples were taken after harvest from the long-term site at Ropsley and were analysed by each of two laboratories. Results in Figure 25 show some outliers (circles), some apparently consistent discrepancies, and some variability.
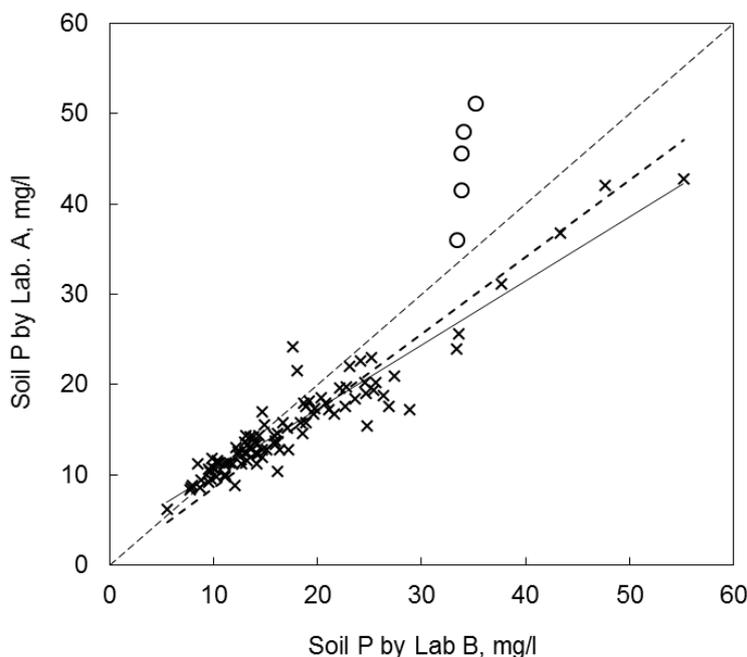

Figure 25   Soil P values for the same samples taken from plots of the long-term experiment at Ropsley, Lincs. after harvest 2014 and analysed by two different laboratories (A and B) both offering routine soil analysis services to UK farms. Points shown as circles were deemed to be outliers and were excluded from statistical comparisons.

Regression relationships were determined after removal of five outliers (Figure 25). The outliers were all for samples where Lab B reported around 35 mg/l, but Lab. A reported in excess of this.

The regression with no intercept showed

$$\text{Lab. A} = 0.852 \times \text{Lab. B}$$

the coefficient of determinations (R^2) being 0.852. Thus the discrepancy between labs was about 15%. However, the regression, including an intercept, showed

$$\text{Lab. A} = 3.11 + 0.708 \times \text{Lab. B}$$

R^2 being 0.897. Thus it appears that inclusion of an intercept improves explanation of the two datasets significantly, indicating that Lab A is positively biased in relation to Lab B where soil P levels are small (<15 mg/l) but negatively biased where soil P levels are larger (>15 mg/l).

Appendix 3. Annual soil P data from P 'run-down' sites

Four run-down sites were initiated in 2010 as part of the Targeted-P Project (see AHDB Report) and are now being maintained through this project (under Work Package 3). Methods are described in Section 6.2.3 of the Targeted-P Report and results in Section 6.3.3 where it is stated that 'there were no clear patterns of soil P decrease due to the 'run-down' treatment at any site' (Figure 26).
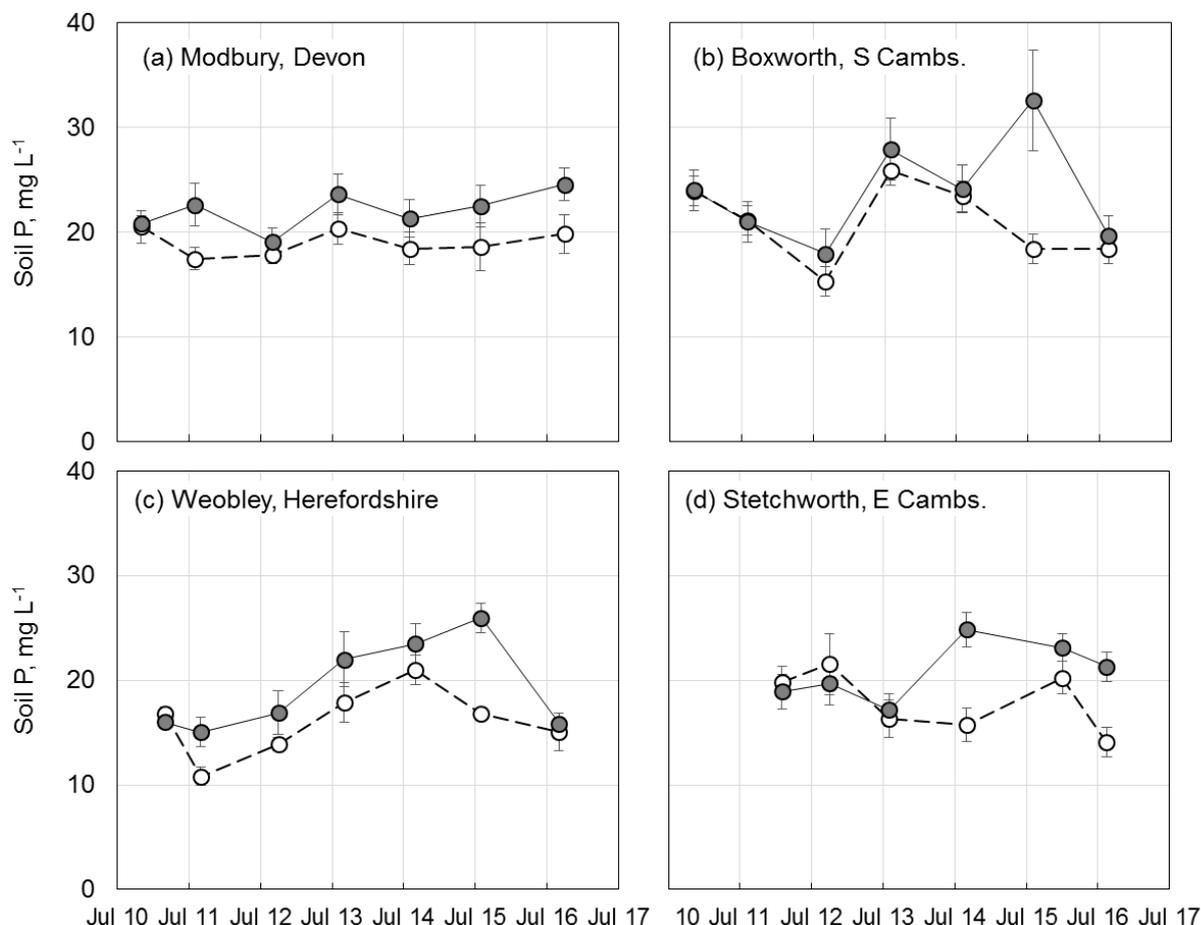

Figure 26   *Development of differences in soil P between 'maintenance' (closed circles) and 'run-down' (open circles) treatments at four sites from 2010 to 2016. Both treatments were cropped annually; run-down treatments had no P applied. Error bars = 2 SEs.*

These results relate not only to soil run-down but to the level of confidence that may be placed in routine soil P testing, as recommended in the Fertiliser Manual (RB209) and elsewhere. Note that in interpreting these results, each determination arose from one plot of 0.5 ha rather than from a whole field, and each point is the mean of four determinations, variation between replicate determinations being indicated by error bars. Clearly errors between simultaneous determinations were commonly small compared to differences between dates, whether these were real or due to error. It is clear that the variability through time at sites where soil P stability (maintenance) or trends (run-down) were expected, reflects on the confidence that may be placed in routine soil P testing, where advice is to compare a single determination from each field with another four years later, and with standards.