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(Supplementary)

Cost-effective Phosphorus Management on UK Arable Farms

Supplementary report on work package 3: rundown sites

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Contents

Abstract

We report recent phosphorus (P) levels and yields of arable soils and crops at four sites (Boxworth, Cambridgeshire; Modbury, Devon; King's Pyon, Herefordshire and Stetchworth, Cambridgeshire) after maintaining nil and replacement P application policies for up to ten years.

Initial soil P levels at the four sites were all within Index 2 (16–25 mg/l). Soil types ranged from sandy loam to clay loam, and pH values ranged from 6.8 to 8.1. At each site, soils in half of the large replicated plots had been allowed to run down their available P contents through no fertiliser or manure P being applied, whilst crop P removals continued (rundown treatment). In the other adjacent replicated plots, soil P levels were maintained at P Index 2 in plots which had received enough fertiliser P to replace crop P removals (maintenance treatment).

On the nil P plots, rates of soil P rundown were somewhat slower than the expected 9-year half-life observed in experiments at Rothamsted Research. However, by 2019, soil P at three of the sites (Boxworth, Modbury and Stetchworth) had decreased by 8-10 mg/l and had reached soil P Index 1 (<16 mg/l) after 5-7 years. (Inexplicable increases in soil P occurred at the fourth site, King's Pyon).

Despite good precision from four replicate soil P analyses on each sampling occasion at each site, there were large perturbations in soil P between years – casting doubt on the value of advice to routinely take just a single sample from each field once every 3–5 years.

Once differences in soil P had developed between maintenance and rundown treatments at each site, crop yield measurements showed differences of up to 0.9 t/ha (cereals), 1.5 t/ha (oilseed rape) and 2.0 t/ha (sugar beet), whilst also showing differences in P concentrations of grain and straw biomass.

In conclusion, three sites are now ready to host research on improving crop P use efficiency, by testing genotypes, products and practices with potential gains. The urgency of initiating such studies is high, given the very poor efficiency of P fertilisers revealed in earlier phases of this research programme on P nutrition.

1 Introduction

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

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

The project had three work-packages (targeting the three bullet points above), all of which have already been reported (Rollett *et al*., 2017; Morris *et al*., 2017 and Sylvester-Bradley *et al*., 2019).

However, this supplement concerns four P rundown sites, which were established as part of the Targeted P project (Sylvester-Bradley *et al*., 2016) and were monitored until harvest 2019. The final results from these sites post-date the above Work Package 3 report, so are described here.

2 Materials and methods

In brief, at each site half of the plots (*c*.0.5 ha except at Stetchworth where plots were 50 m x 24 m) were fertilised annually in order to maintain soil P at Index 2, whilst the other half received no P fertiliser inputs.

2.1 Site selection

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

Table 1. Rundown site locations, soil types and mean initial soil P levels (all Index 2) [standard deviation of mean in square brackets].

Site	Soil type	Initial soil sample	Initial soil P (mg/l)	Initial soil pH
Boxworth, South Cambridgeshire	Clay loam	26 Nov 2010	24.0 (2.86)	7.5
Modbury, Devon	Silty clay loam[1]	24 Sept 2010	20.7 (2.27)	7.3
King's Pyon, Herefordshire	Silty clay loam	3 Mar 2011	16.4 (1.18)	6.8
Stetchworth, East Cambridgeshire	Sandy loam	16 Feb 2012	19.4 (2.97)	8.1

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

2.2 Experimental treatments and assessments

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

Annual fertiliser P input requirements were estimated, based on RB209 recommendations, and broadcast as TSP, typically before autumn cultivations. Plot-specific crop yields and P concentrations were not measured from 2011 to 2016 so, to estimate the crop P offtakes (and hence fertiliser P requirements), average crop yields for each farm were multiplied by standard P concentrations from RB209 (Defra, 2010; AHDB, 2017).

To assess the progress towards the target soil P indices [i.e. with 'maintenance' plots all at P Index 2 and 'rundown' plots all at P Index 1], soil samples were taken from each plot after harvest, and soil P was analysed using Olsen's method (by NRM labs.).

For cereal and oilseed harvests in 2017, 2018 and 2019, harvest yield was estimated using five randomly placed 0.25 m^2 quadrats per plot, with the exception of Modbury in 2019 where yield data was taken from the farm's records (combine monitor). Above-ground crop was sampled, separated into grain and straw fractions, weighed (fresh weight) and dried (80°C for 24 hours) before being reweighed (dry weight). Samples were sent to the laboratory to measure P concentration in the straw and grain fractions. It was not appropriate to use the quadrat method for the sugar beet harvest (Stetchworth 2019) so, prior to harvest, the numbers of plants in pre-determined areas were counted, and then at harvest 20 beets and tops were randomly selected from each plot, weighed and dried as above. This allowed yields to be calculated on a per hectare basis.

Statistical analysis was undertaken with GenStat version 19 using a two-sample t test with treatment as the group factor. However, results should be interpreted with caution due to the small sample size. A *P* value of <0.05 was taken to indicate a significant difference between treatments.

Table 2. Crops grown in harvest years 2011 to 2019, and mean rates of P applied (NB: *not* P_2O_5) as TSP to the 'maintenance' plots at the four rundown Experiments. (NB: W, winter; Sp, spring; OSR, oilseed rape; Bn, Beans; Cer, cereal; By, barley; G, grass; Wt, wheat; Lin, linseed; SBt, sugar beet; Trit, Triticale).

Site	2011	2012	2013	2014	2015	2016	2017	2018	2019
S. Cambs.	W Cer	W Wt	W OSR	W Wt	W By	W Bn	W Wt	Sp By	W OSR
Devon	WOSR	W Wt	W Oat	W Wt	W OSR	W Wt	W Oat	W Wt	W OSR
Herefords.	SpLin	Lin	W Wt	W Wt	W OSR	W Wt	Trit	G Ley	G Ley
E. Cambs.	-	Sp Wt	Sp By	W By	S Bt	Sp Wt	Peas	W Wt	S Bt
					P applied, kg/ha				
S. Cambs.	26	26	33	26	26	17	26	22	22
Devon	22	28	33	39	22	28	24	28	22
Herefords.	39	13	48	39	22	28	20	35	NA
E. Cambs.	-	33	33	35	22	22	17	28	22

3 Results

3.1 Soil P

Annual soil P levels for 'maintenance' and 'rundown' (nil P applied) treatments are shown for each of the four 'rundown' sites in Figure 1. With four replicate measurements in each year at each site, the precision of soil P assessments was generally good (mean SE 1.65 mg/l) so that, beyond the first year or so, treatment effects were detected with increasing confidence.

Nil 'rundown' treatments at Boxworth, Modbury and Stetchworth that started in Index 2 (16-25 mg/l) all ran down significantly over the eight/nine years of the experiments, if not consistently from year to year; all three sites were at P Index 1 (10-15 mg/l) by 2019. At both the Boxworth and Modbury sites there was a reduction in soil P concentration of 10 mg/l between 2010 and 2019. For Stetchworth, there was a reduction of 8 mg/l between 2012 and 2019 (Table 3). On average, all three sites ran down by 1 mg/l/year, although as noted above, the pattern of rundown was not consistent. Overall, the rates of rundown were somewhat slower than the 9-year half-life found by Johnston *et al*. (2016) at sites managed through the last century by Rothamsted Research.

Table 3. Changes in soil P (mg/l) [P index] between the start and end of the rundown period for Maintenance (Mt) and Rundown (Rd) treatments at four sites.

	Boxworth, S Cambs		**Modbury, Devon**		**King's Pyon, Herefords**		**Stetchworth, E Cambs**	
P mg/l [Index]	Mt	Rd	Mt	Rd	Mt	Rd	Mt	Rd
Start	24 [2]		21 [2]		16 [2]		19 [2]	
End	19 [2]	14 [1]	17 [2]	11 [1]	43 [3]	31 [3]	26 [2]	12 [1]
Difference	-5	-10	-4	-10	+27	+15	+7	-8
Time period	Nov-10 to Oct-19		Sept-10 to Sept-19		Mar-11 to Sept-19		Mar-12 to Oct-19	

In contrast, at the Herefordshire site (which started closer to P Index 1), soil P with the nil treatment surprisingly tended to increase; after discussion with the farmer, nothing known about this site provides an obvious explanation of these increases, so further investigations continue.

Over the short term, year to year changes in soil P were largely similar for both treatments at each site and were generally larger than the confidence limits of the measurements, so it would appear that, although assessments were made by the same staff, with the same sampling technique, and using the same analytical laboratory at all sites for all years, there were other factors that caused annual perturbations in soil P levels, and sometimes these were major.

The maintenance treatments largely achieved their purpose at all sites, albeit that the pattern of annual changes was somewhat erratic, particularly at King's Pyon in the last two years (Figure 1). The 2018 result may have arisen from the fertiliser P applied in spring 2018 remaining available through to autumn due to the very dry summer of 2018 and the lack of topsoil disturbance due to the establishment of a herbage seed crop. However, a repeat measurement taken in spring 2019 showed that the soil P concentration had increased further, by 12 mg/l (rundown) to 15 mg/l (maintenance)! By the end of the monitoring period soil P at King's Pyon was 43 mg/l in the Maintenance plots and 31 mg/l in the Rundown plots, compared with *c.*16 mg/l in spring 2011.

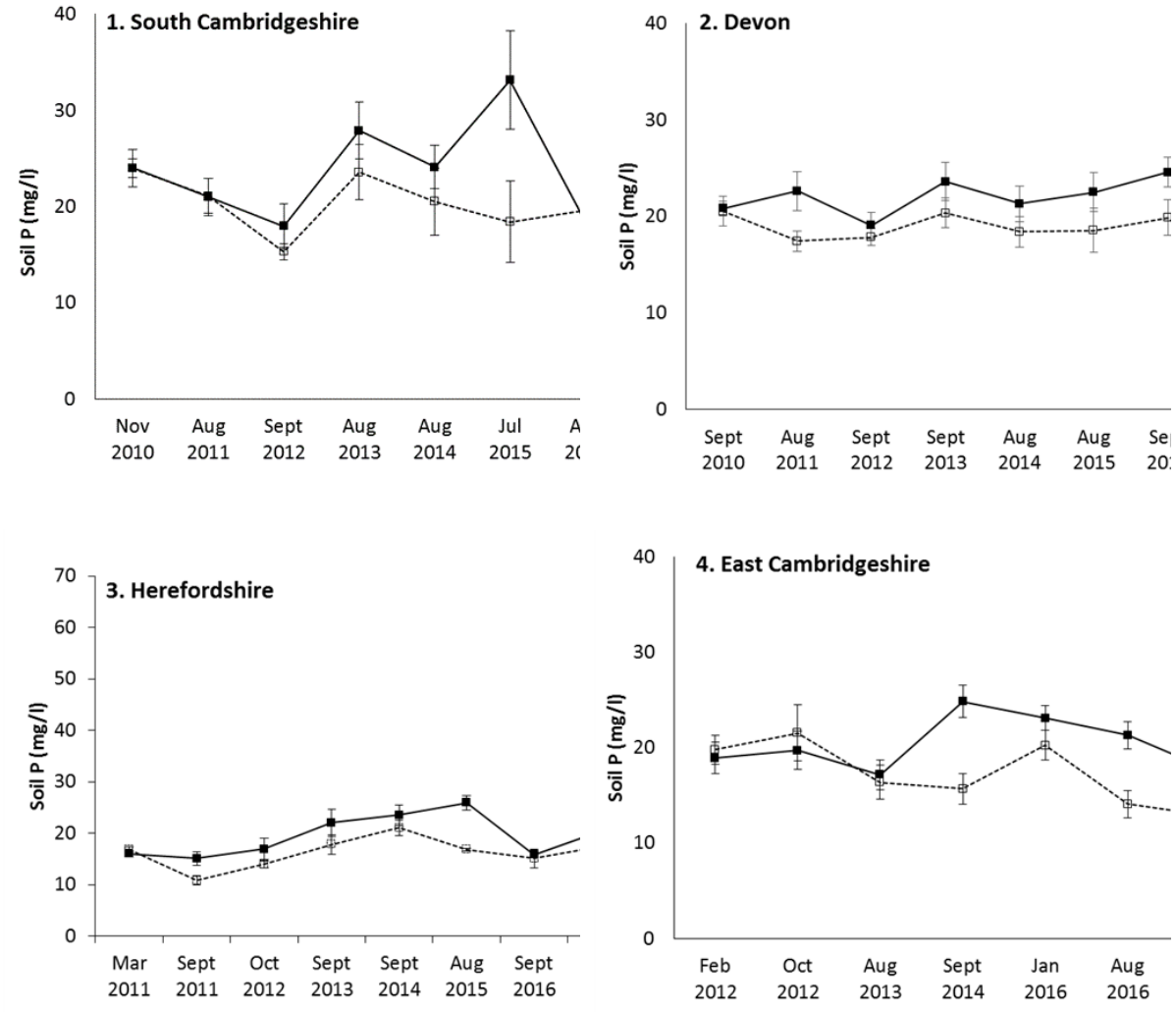

Figure 1. Annual levels of soil P (mg/l) at the four rundown sites for Maintenance (annual application of P; closed black symbols & full lines) and Rundown (nil P applied; open symbols & dotted lines) treatments.

Differences between treatments arose within the first year at the two western sites but developed more gradually at the eastern sites. Differences over the rundown period averaged 4.4 mg/l at Boxworth, 4.3 mg/l at Modbury, 7.7 mg/l at King's Pyon (or 3.8 mg/l if the results after September 2018 are omitted), and 5.2 mg/l at Stetchworth. During that time the rundown treatments were within P Index 1 for three years at Boxworth and Modbury, two years at King's Pyon and four years at Stetchworth; for sites other than Kings Pyon these were usually the most recent years. However, the inter-annual variation has been such that no site can be assumed to remain exactly within the narrow range of P Index 1 (10-15 mg/l) in future seasons. The minimum value recorded was 11 mg/l at Modbury in October 2017. Ignoring the King's Pyon site where soil P appears to be increasing, linear trend lines predict that rundown plots will reach the top of P Index 0 by 2023 at Stetchworth, 2024 at Modbury and 2025 at Boxworth.

3.2 Crop yield

Crop measurements commenced at three sites (other than King's Pyon) in 2017 when the decision was made to delay the start of multi-factor experimentation (which would have compared potentially efficient P management systems). Crop yields were less in the rundown treatments at Boxworth in 2017 and 2019, at Modbury in 2018 and 2019 and at Stetchworth in 2018 and 2019 (Table 4); the yield differences ranged from 0.34 to 2.0 t/ha. In comparison, there was no difference in crop yields between maintenance and rundown treatments at Modbury in 2017 or Boxworth in 2018.

The difference in crop yield was almost significant (P = 0.05) at Modbury in 2019; oilseed rape yield from the rundown treatment was 1.5 t/ha less than from the maintenance treatment. This was likely to be due to the very poor crop establishment in two of the rundown plots where soil P was at Index 0 (0-9 mg/l) (Plate 1).

There was a clear statistically significant relationship between soil P (mg/l) and oilseed rape yield at the Modbury site (Figure 2). The high R^2 suggests that soil P was a very important determinant of crop yield, explaining >90% of the variation in yield. When the relationship between soil P and crop yield was plotted individually for the two treatments the R^2 for the rundown treatment was >0.90, compared to about 0.60 for the maintenance treatment. The effect on yield seems to be greatest on the plots where soil P was Index 0 and early establishment was poor. However, at other sites, or in other seasons, there was no statistically significant relationship between soil P and crop yield.

Table 4. Crop yields (t/ha @ 85% dry matter) and yield differences (with confidence levels) for Maintenance (Mt; P applied to maintain soil at P Index 2) and Rundown (Rd; nil P applied) treatments at the four rundown sites in 2017, 2018 and 2019.

Year	Boxworth, S Cambs		Modbury, Devon		King's Pyon, Herefords		Stetchworth, E Cambs	
	Mt	Rd	Mt	Rd	Mt	Rd	Mt	Rd
2017	Winter wheat		Winter oats		Triticale		Peas	
Yield, t/ha	2.98	2.64	7.31	7.32	No yield data		No yield data	
[SD]	[0.55]	[0.28]	[0.95]	[0.77]				
Mt-Rd		-0.34		+0.01				
P value	*0.34*		*0.99*					
2018	Spring barley		Winter barley		Grass ley		Winter wheat	
Yield, t/ha	5.25	5.25	9.31	8.76	No yield data		7.73	6.85
[SD]	[0.86]	[0.62]	[0.51]	[0.59]			[1.29]	[0.58]
Mt-Rd		0.00		-0.55				-0.88
P value	*0.99*		*0.21*				*0.26*	
2019	Winter oilseed rape		Winter oilseed rape		Grass ley		Sugar beet	
Yield, t/ha	3.92	3.38	4.0	2.5	No yield data		96	94
[SD]	[0.77]	[0.86]	[0.13]	[0.97]			[7.4]	[6.3]
Mt-Rd		-0.57		-1.5				-2.0
P value	*0.39*		*0.05*				*0.74*	

Plate 1. Oilseed rape at Modbury, a) to d) autumn 2018 and e) April 2019

a) establishment: rundown plot.

b) establishment: maintenance plot

c) maintenance (far left) and rundown (far right)

d) rundown (far left) and maintenance (far right)

e) rundown (far left) and maintenance (far right)

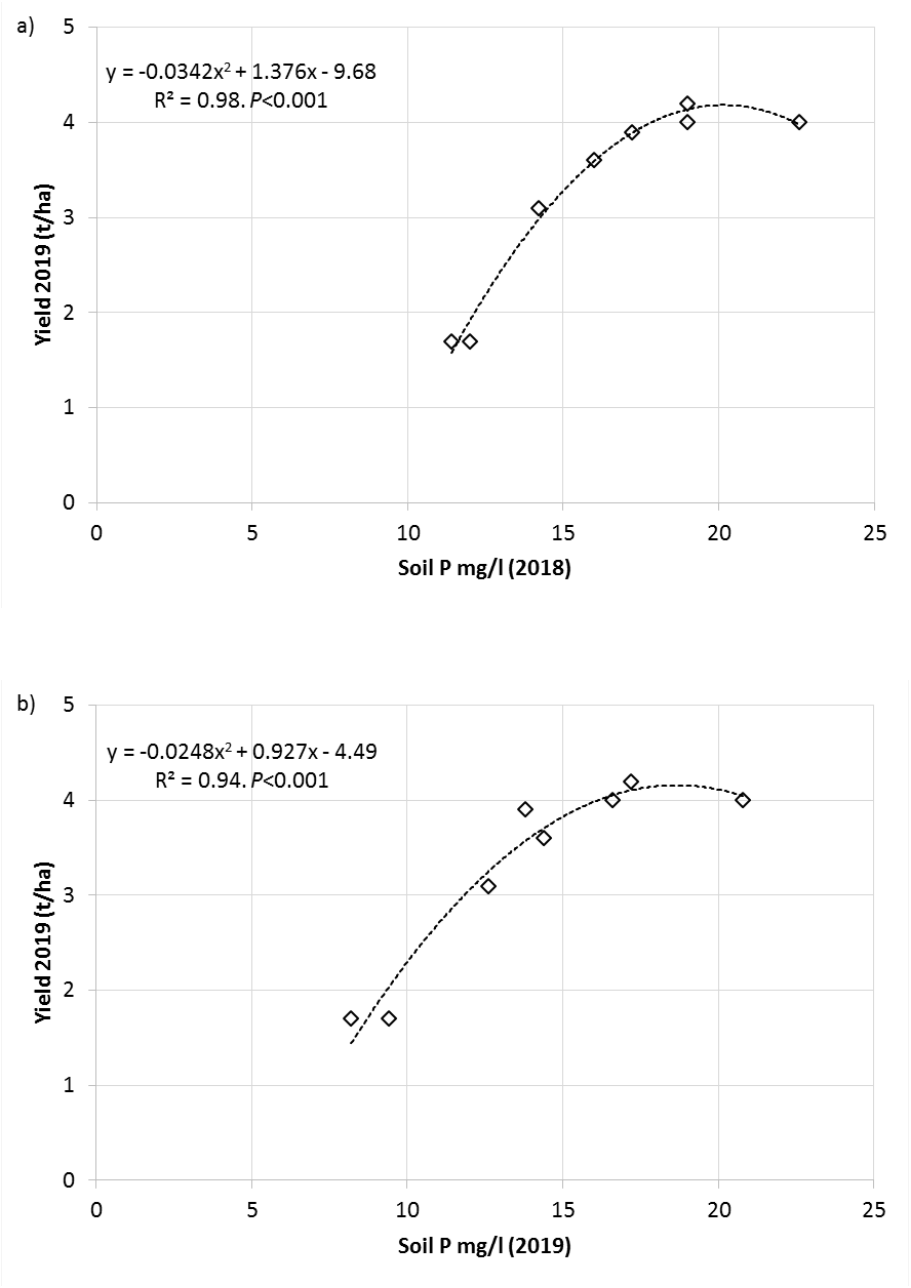

Figure 2. Relationship between soil P (mg/l) as measured in a) 2018 and b) 2019 and winter oilseed rape yield at Modbury in 2019.

3.3 Crop P concentration (grain and straw)

In 2017, grain P concentrations were closely similar in the maintenance and rundown treatments at both Modbury and Boxworth (Table 5). Similarly, in 2018, grain P concentrations were slightly lower in the rundown treatment at Modbury and Stetchworth. At Boxworth, spring barley grain P was greater from the rundown than the maintenance treatment. In the final year (2019) there were again small differences between P concentration in oilseed and sugar beet root. However, differences were generally within the confidence limits of these measurements so should be interpreted with caution.

Overall grain P values ranged between 0.28% and 0.41% and most were lower than the 0.40% P assumed as the average content of cereal grain in RB209 (equivalent to 7.8 kg P_2O_5 per tonne of grain at 85% dry matter).

Table 5. Grain P concentration (% dry matter) for Maintenance (Mt) and Rundown (Rd) treatments in 2017, 2018 and 2019 at the four rundown sites.

Year	Boxworth, S Cambs		Modbury, Devon		King's Pyon, Herefords	Stetchworth, E Cambs	
	Mt	Rd	Mt	Rd		Mt	Rd
2017	Winter wheat		Winter oats		Triticale	Peas	
Grain P (%), [SD]	0.341 [0.009]	0.340 [0.015]	0.362 [0.008]	0.361 [0.028]	No data	No data	
Mt-Rd		-0.001		-0.001			
P value	*0.87*		*0.93*				
2018	Spring barley		Winter barley		Grass ley	Winter wheat	
Grain P (%), [SD]	0.370 [0.036]	0.413 [0.046]	0.321 [0.028]	0.279 [0.035]	No data	0.323 [0.031]	0.305 [0.030]
Mt-Rd		+0.043		-0.048			-0.018
P value	*0.19*		*0.08*			*0.44*	
2019	Winter oilseed rape		Winter oilseed rape		Grass ley	Sugar beet roots	
Grain P (%), [SD]	0.780 [0.107]	0.733 [0.093]	No data		No data	0.082 [0.014]	0.053 [0.018]
Mt-Rd		-0.046					-0.029
P value	*0.54*					*0.05*	

At Boxworth, there was no significant relationship between soil P and crop P in any year. However, for Modbury, there was a significant relationship between soil P (mg/l) and winter barley grain P concentration (% dry matter) at harvest 2018 (Figure 3). There was no data for grain P concentration for the oilseed rape crop in 2019 as this site was harvested by farm combine.

For Stetchworth, there was a significant relationship between soil P (mg/l) and winter wheat grain P concentration in 2018 and between soil P (mg/l) and sugar beet root P concentration (% dry matter) in 2019 (Figure 4).

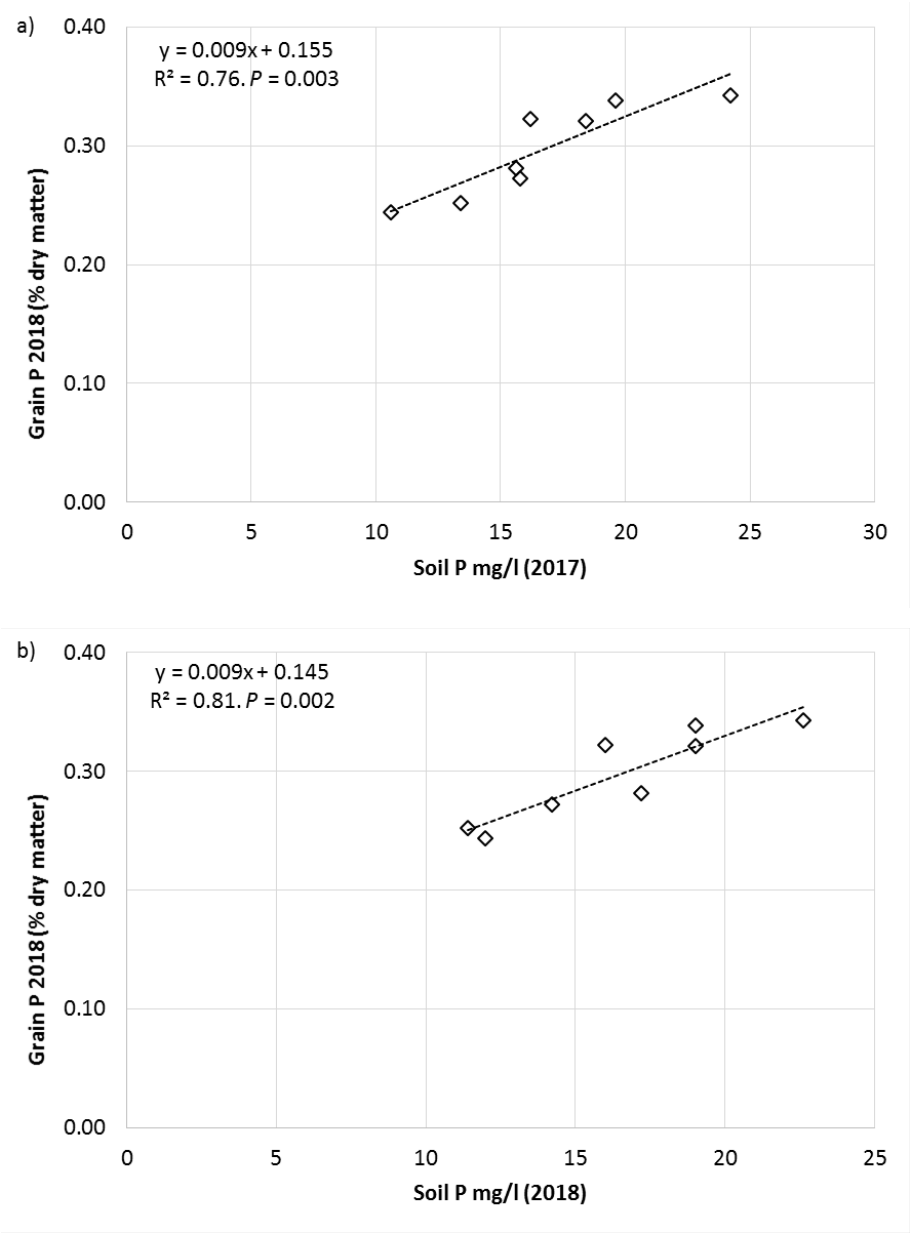

Figure 3. Relationship between soil P (mg/l) as measured in a) 2017 and b) 2018 and winter barley grain P concentration at Modbury in 2018.

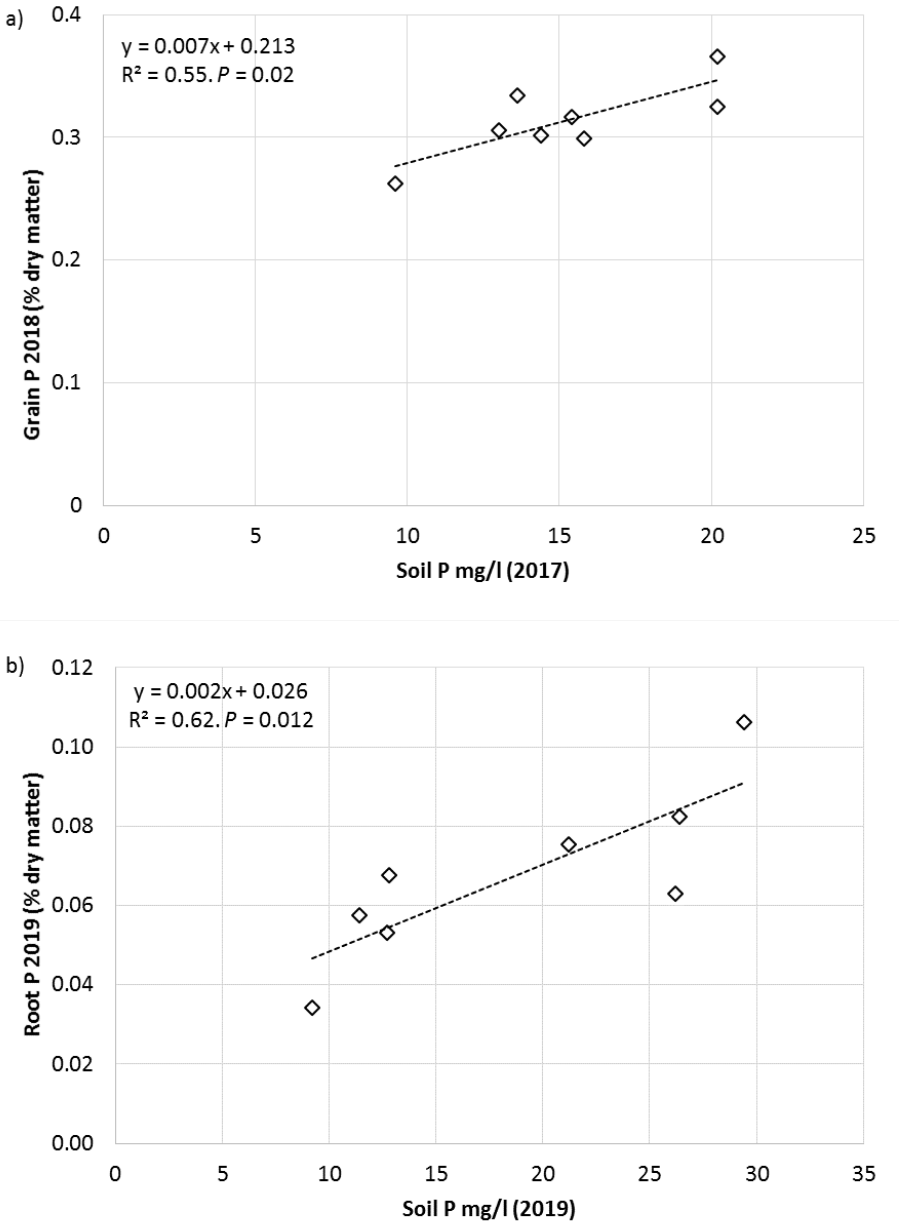

Figure 4. Stetchworth: a) relationship between soil P (mg/l) in 2017 and winter wheat grain P concentration at harvest 2018 and b) soil P (mg/l) in 2019 and sugar beet root P concentration at harvest 2019.

There was no difference in the straw P content (% dry matter) of the maintenance and rundown treatment for the winter wheat, winter oats and spring barley crops (Table 6). However, for the winter barley crop at Devon in 2018, straw P concentration was higher from the maintenance than from the rundown treatment (*P* = 0.04).

Likewise, there was no difference in the oilseed rape straw content or sugar beet top P concentration (% dry matter) between treatments in 2019 at Boxworth and Stetchworth, respectively (Table 6).

Only at Boxworth in 2017 was there a significant relationship between soil P (mg/l) and spring barley straw P content (Figure 5).

Table 6. Straw and sugar beet top P concentration (% dry matter) for Maintenance (Mt) and Rundown (Rd) treatments in 2017, 2018 and 2019 at the four rundown sites.

Year	**Boxworth, S Cambs**		**Modbury, Devon**		**King's Pyon, Herefords**	**Stetchworth, E Cambs**	
	Mt	Rd	Mt	Rd		Mt	Rd
2017	Winter wheat		Winter oats		Triticale	Peas	
Grain P (%), [SD]	0.042 [0.007]	0.044 [0.008]	0.100 [0.015]	0.072 [0.024]	No data	No data	
Mt-Rd		+0.003		-0.028			
P value	*0.62*		*0.10*				
2018	Spring barley		Winter barley		Grass ley	Winter wheat	
Grain P (%), [SD]	0.048 [0.010]	0.065 [0.019]	0.037 [0.003]	0.027 [0.006]	No data	0.067 [0.023]	0.049 [0.009]
Mt-Rd		+0.018		-0.009			-0.017
P value	*0.15*		*0.04*			*0.21*	
2019	Winter oilseed rape		Winter oilseed rape		Grass ley	Sugar beet tops	
Grain P (%), [SD]	0.134 [0.021]	0.131 [0.011]	No data		No data	0.168 [0.014]	0.152 [0.007]
Mt-Rd		-0.003					-0.016
P value	*0.89*					*0.10*	

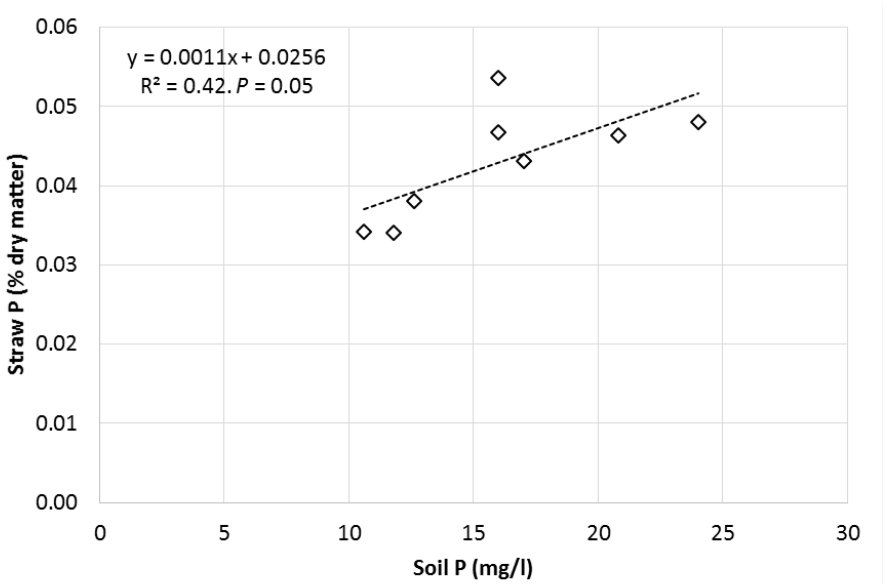

Figure 5. Relationship between soil P (mg/l) and spring barley straw P concentration at Boxworth in 2017.

There was no relationship between grain P (% dry matter) and crop yield for the winter or spring cereal crops in any year at any site. However, for the oilseed rape crop at Boxworth in 2019, there was a negative linear relationship between grain P and crop yield; for both maintenance and rundown treatments higher oilseed rape yields were associated with lower grain P concentrations (Figure 6). It was not possible to determine if the same relationship was noted for the oilseed rape crop at Modbury in 2019 as no grain P data was available. In contrast, at Stetchworth, root P concentration (% dry matter) typically increased as crop yield increased (Figure 6).

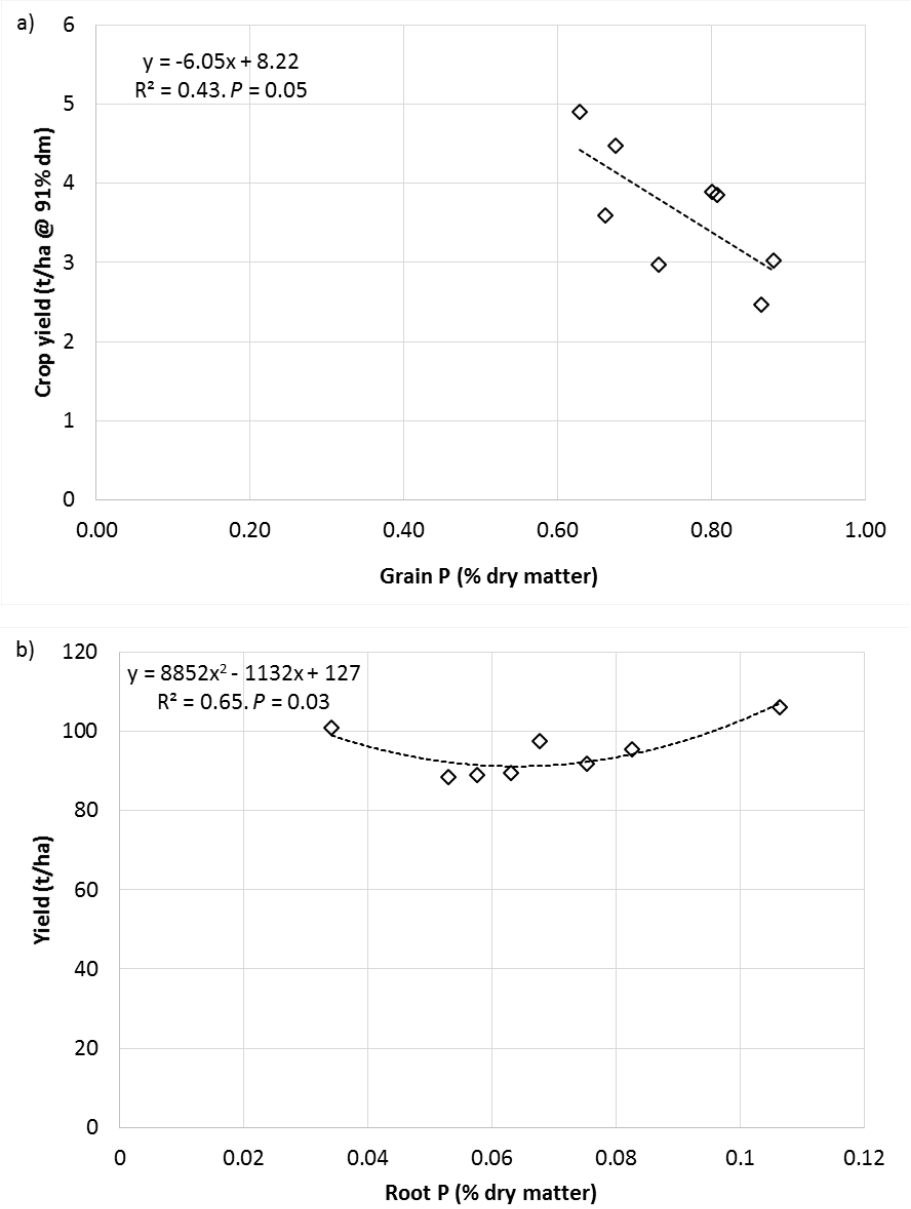

Figure 6. Relationship between a) grain P (% dry matter) and oilseed rape yield (t/ha @ 91% dry matter) at Boxworth in 2019 and b) between root P (% dry matter) and sugar beet yield (t/ha) at Stetchworth in 2019.

4 Conclusions

The rates of soil P rundown were slower than anticipated at all sites. These results show that the nine-year half-life that Johnston *et al*. (2016) used as an overall summary of the rundown rates in the Rothamsted experiments are not applicable for soil P management generally. It thus appears that a new approach should be advocated whereby land managers and their consultants strive to determine directly (by relating successive soil analyses to successive crop P removals) the rates at which soil P are changing on any particular block of land.

However, as was noted when results from these sites were considered previously (Sylvester-Bradley *et al.,* 2016), the significant annual variations in the soil P levels at all sites blurred any interpretation of soil P trends through time, and prompted questions about how appropriate current advice is about routine soil P determination.

Farmers are currently advised to collect one single sample per field (or part field if variation is known), to submit this for one single laboratory analysis, and to compare this result with a similar single result determined 3-5 years previously. The variability to be expected after following this advice must significantly exceed that seen in Figure 1 because the latter arose despite a much more assiduous approach: in particular four, not one, samples were taken, each sample represented only 2-4 ha rather than a whole field, and sampling was repeated annually rather than every four or so years.

With the experimental data showing such large perturbations, it is clear that significant additional factors were affecting the results, over-and-above variability due to sampling and analysis; probably concerning soil temperature and moisture conditions (Song *et al*., 2012), and probably also due to varying intervals since the most recent fertiliser application, variation in soil P sorption capacity (which is mapped in Scotland but not in the rest of the UK; SRUC, 2015), variation in mineralisation of P from soil organic matter (Saunders & Metson, 1971) and variation in soil bulk density, after drying and milling the sample (Drewry, 2013).

Once differences in soil P had developed between maintenance and rundown treatments at each site, crop yield measurements did show differences (Table 4) of up to 0.9 t/ha (cereals), 1.5 t/ha (oilseed rape) and 2.0 t/ha (sugar beet), whilst also showing differences in P concentrations of grain and straw biomass. Trials with apparent (although not statistically significant) reduced yields were also the trials in which grain P was less than 0.32% for the run-down treatment.

There were significant relationships between soil P (mg/l) and crop P concentrations at Stetchworth and Modbury but not at Boxworth. Similarly, there was only a significant relationship between soil P (mg/) and oilseed rape yield at Modbury in 2019.

As an outcome of this project extension, three of the four sites are now shown to be ready to test genotypes, products and practices with potential to improve the efficiency of crop P nutrition. The urgency of initiating such studies is high, given the very poor efficiency of P fertilisers revealed in earlier phases of this research programme on P nutrition.

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