

## RESEARCH ARTICLE

Soil Use  
and Management

WILEY

# Long-term effects of lime and phosphorus application on soil extractable (Olsen) phosphorus differ between two arable UK soils

J. E. Holland<sup>1</sup> | R. White<sup>2</sup> | S. M. Haefele<sup>3</sup> | K. W. T. Goulding<sup>3</sup> | S. P. McGrath<sup>3</sup> | M. J. Glendining<sup>4</sup>

<sup>1</sup>Agri-Food and Biosciences Institute, Belfast, UK

<sup>2</sup>Applied Research and Statistics, Rothamsted Research, Harpenden, UK

<sup>3</sup>Sustainable Soils and Crops, Rothamsted Research, Harpenden, UK

<sup>4</sup>Intelligent Data Ecosystems, Rothamsted Research, Harpenden, UK

## Correspondence

J. E. Holland, Agri-Food and Biosciences Institute, Belfast, UK.  
Email: [jonathan.holland@afbini.gov.uk](mailto:jonathan.holland@afbini.gov.uk)

## Funding information

Biotechnology and Biological Sciences Research Council; Lawes Agricultural trust

## Abstract

Liming induces several positive effects on soil processes, although the specific nature of these impacts is variable for some soil properties such as extractable soil phosphorus. The aim of this study was to analyse the long-term effect of liming on soil extractable phosphorus (Olsen P) concentrations, together with the corresponding effects on soil pH and P uptake by different crops. The soil and crop data were collected from two long-term experiment sites at Rothamsted Research with contrasting soil texture (Rothamsted and Woburn). Liming had significant effects on Olsen P on a silty loam soil at Rothamsted and a sandy loam soil at Woburn. At both sites where no P was applied the highest Olsen P value was in the lime control treatment (no lime) which was significantly greater than all of the liming treatments. Between 1968 and 1994 temporal changes in Olsen P were not affected by liming. The P removal in the grain showed significant differences in responses between crop species which indicates differences in the availability of P to a specific plant and the efficiency of P used by each crop accordingly. The contrasting results in this study indicate that liming can lead to differences in soil P availability, because of its effect on soil pH; also this effect can be partly explained by the differences in soil texture at each site. The amount of plant available P cannot be determined from Olsen P data only, and the P removal in grain should be taken into account in order to thoroughly evaluate P status of arable crops.

## KEYWORDS

critical concentrations, liming, soil available phosphorus, soil extraction methods, soil pH

## 1 | INTRODUCTION

Liming is a common management strategy for ameliorating soil acidity but that also causes many long-term effects on soils, crops and biodiversity (Holland

et al., 2018). The main impact of liming soils is an increase in pH, although the type and application rate of liming material controls the rate and nature of the changes observed (Goulding et al., 1989). For example, there are simultaneous biological and chemical changes,

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both of which can influence the availability of soil nutrients (Bolan et al., 2003; Goulding, 2016): arbuscular mycorrhizal (AM) fungi have specific pH optima, and thus there are pH-dependent limits such as an upper soil pH value at which root colonization by AM fungi is limited (Clark, 1997; Wang et al., 1993). Furthermore, liming increases the Ca in the soil solution which can influence the availability of nutrients (e.g. B, Cu, Fe, Mn, Mo and Zn) in the soil which has implications for plant uptake (White & Holland, 2018). Because liming impacts several soil chemical processes (including organic P mineralization, K adsorption, S immobilization and trace element adsorption), there is scope for this common soil management practice to be better understood (Holland et al., 2018).

Recently, there have been conflicting reports on the optimum soil pH for the uptake of phosphorus (P) by crop plants. Several studies have approached this question with different tests of soil extractable P, and there has been strong focus on the chemical processes, such as the adsorption–desorption study of P Barrow (2017) which suggested that the optimum pH for P uptake was below neutral (i.e. between 4 and 6). In contrast, the ‘classic’ view states that there are two optima at pH 4.5 and 6.5 (Penn & Camberato, 2019). The literature is inconsistent regarding the impacts of liming on soil P (either extractable or soluble P); examples of contrasting liming responses include: an increasing effect (Haynes, 1982; Murphy, 2007; Naidu et al., 1987), a decreasing effect (Azeez et al., 2020; Curtin & Syers, 2001) and no effect (Viade et al., 2011). The evaluation of liming effects should not be done too soon after lime has been applied. The differences between the above studies can be partly explained by the length of time since lime was applied.

In contrast, for crop response, there is strong evidence that liming increases P availability to plants: a positive yield response was associated with improved P availability to several different crop types on the long-term liming experiment at both the Rothamsted and Woburn sites (Holland et al., 2019). Similar findings have been reported for other long-term liming experiments in Denmark (Azeez et al., 2020), Germany (von Tucher et al., 2018) and Sweden (Börjesson & Kirchmann, 2022). These conflicting results present a challenge in reconciling the differences in the responses to liming observed in soil extractable P in contrast to those for crop yields or crop P uptake. Indeed, previous predictions of general plant nutrient availability using soil pH have been shown to be overly simplistic and misleading (Hartemink & Barrow, 2023). There remain, therefore, complex questions regarding the relationship between soil pH and nutrient availability, not just for P. A better understanding is needed of soil nutrient availability and how changes in soil pH influence both soil nutrient cycling and plant uptake and efficiency of utilization.

Barrow and Hartemink (2023) argue that the interaction of soil effects and the rate of plant uptake determine nutrient availability. Compared with other soil properties the soil pH effect is dominant because it influences the solubility, mobility and adsorption of P in the soil (Hartemink & Barrow, 2023). Owing to the dynamic nature of these soil processes it is important not to rely on short-term results. Consequently, there is great value in the evaluation of liming effects from a long-term experiment to fully understand the implications for crop production and soil fertility (Johnston & Poulton, 2018).

The main aim of this paper was to evaluate the long-term impact of liming and its interaction with soil properties on Olsen P and P removal in grain. To achieve this, we used data from the Long-Term Liming Experiment at Rothamsted and Woburn and set the following objectives: (i) to evaluate the effects of liming and P treatments on soil pH and Olsen P; (ii) to investigate the temporal changes in Olsen P and (iii) to examine effects of liming on P removal in grain.

## 2 | MATERIALS AND METHODS

### 2.1 | Experimental site description and experimental design

The Long-Term Liming (LTL) Experiment ran at two sites of Rothamsted Research (the Rothamsted and Woburn farms) in the UK between 1962 and 1996. The crops during this period are typical of UK arable production systems and included spring crops: barley, beans, oats, oilseed rape, linseed, potatoes and lupins. The winter crops were lupins, oilseed rape, triticale and wheat. Selected soil properties for the Rothamsted and Woburn sites are given in Table S1. Further information on the sites was provided by Holland et al. (2019). The sites are only 30 km apart, so climatic differences are small: the mean annual precipitation (1962–1996) was 693 mm at Rothamsted and 638 mm at Woburn. More importantly, differences over the growing season (April–July) were minimal, with precipitation being 210 mm at Rothamsted and 208 mm at Woburn.

A factorial experimental design was used at each site with two randomized blocks of 16 plots split into two sub-plots in some years (each main plot was 6 × 18 m; ca. 0.01 ha). Four rates of lime with and without fertilizer P and K (4 × 2 × 2 factorial), with two replicates, gave a total of 32 main plots. Nitrogen (N) fertilizer was applied to all plots at a rate appropriate to the crop and site. The applied N rate varied significantly year to year; e.g. from no N applied for spring beans up to 271 kg N ha<sup>-1</sup> for winter oilseed rape. The N rate for each year is available for Rothamsted (Glendining, 2020a) and Woburn (Glendining, 2020b).

The sub-plots tested Mg, Mn or S in various years. During the first period (1962–1980) various Mg and K treatments were tested, but from 1981 onwards all plots received basal applications of Mg and K (100 kg Mg ha<sup>-1</sup> and 120 kg K ha<sup>-1</sup>, respectively) starting in 1981. The sub-plot treatments and K main plot treatments are not considered here. Four rates (main plot treatments) of liming were applied as ground chalk (CaCO<sub>3</sub>): control (zero lime), low (L), medium (M) and high (H) rates of lime. The experimental design is described in more detail for Rothamsted by Glendining (2020a) and Woburn by Glendining (2020b). Over the 35 years of the experiment the total amounts of lime added were 15 and 9 for the L treatment, 24.5 and 25.5 for the M treatment and 52.5 and 45. t CaCO<sub>3</sub> ha<sup>-1</sup> for the H treatment for Rothamsted and Woburn, respectively. Lime was applied on similar dates at each site, and there were six to seven separate applications between 1962 and 1996. The years when lime was applied were 1962 (twice), 1963 (Rothamsted only), 1978, 1981, 1982 and 1986 (Table S2). There were only small differences between the experimental sites at Rothamsted and Woburn in the lime application rates and the dates of lime applications so it was considered acceptable to compare these sites. The lime requirement was determined by the methods of Woodruff (1948) and Shoemaker et al. (1961).

P was applied (at the whole plot level) as triple superphosphate (Table S3). The applications of P are described in two different application periods. In Period 1 (1962–1980) the zero P treatments were nil and K (16 plots) and the +P treatments were P and PK (16 plots). In Period 2 (1981–1996) the zero P treatment was nil (8 plots), and the +P treatments were P1, P2 and P3 (24 plots) (Table S3). We simplified the subsequent data analysis of temporal changes to assess the effect of P at two levels: control (zero P) and + P (all plots where P was added in either Period 1 or 2).

## 2.2 | Soil chemical analysis

Soil samples were collected in the autumn/winter after the harvest. Soil was not sampled every year, and extractable (Olsen) P and pH were not always measured. Olsen P was the selected soil extraction method as it is the most common method used in the UK (AHDB, 2017). Nine years of soil data are considered here for Rothamsted (1968, 1972, 1973, 1974, 1981, 1982, 1986, 1989 and 1994) and 7 years for Woburn (1972, 1973, 1974, 1981, 1986, 1989 and 1994), when both Olsen P and soil pH were measured in all plots. Data from soil sampled in 1982 at Woburn was excluded from the analysis, as the Olsen P results were unreliable. Soil was sampled from the surface to 23 cm, which was the depth of ploughing. Soil pH was measured in 1:2.5

soil:water suspensions using a standard electrode and pH meter. Soil extractable P was determined according to Olsen's method (Olsen, 1954). Soil samples (5 g) were air-dried and sieved to ≤2 mm for analysis. Olsen P was extracted using a 100 mL 0.5 M NaHCO<sub>3</sub> solution at pH 8.5 (stored at 20°C). The samples were shaken for 30 min on an orbital shaker (130 rpm, 20°C) and filtered through Whatman 42 filter papers with activated charcoal (0.1 g) added. Detection was undertaken with a continuous flow analyser and the extractable (Olsen) P concentration expressed in mg kg<sup>-1</sup>. The soil pH and Olsen P data are available for Rothamsted (Glendining et al., 2023) and Woburn (Glendining et al., 2024).

## 2.3 | P removal in grain

The P removal in the grain of three arable cereal crops (kg P ha<sup>-1</sup>) was calculated for spring barley (variety—Porthos, 1978), spring oat (variety—Peniarth, 1981) and winter wheat (variety—Genesis, 1995). The yield of each treatment was multiplied by the P concentration (%) in the grain to determine the P removal in grain (kg P ha<sup>-1</sup>). Sub-samples of grains from each plot were ground to powder <0.5 mm, using a Retsch 400 ultracentrifugal mill (Retsch GmbH, Germany). The milled samples were digested with a solution of 1% H<sub>2</sub>O<sub>2</sub> and 68% HNO<sub>3</sub>, and the P concentration was determined by inductively coupled plasma mass spectrometry (ICP-OES). The grain concentration of P and other minerals is available for Rothamsted (Jordan-Meille et al., 2021a) and Woburn (Jordan-Meille et al., 2021b).

## 2.4 | Data analysis

For each site, analysis of variance (ANOVA) was used to test for main (e.g. lime and the addition of P) treatment factor effects and interactions with the following dependent variables: Olsen P, soil pH and P removal in grain. The Olsen P data were examined using a simple test for skewness and were not found to be normally distributed. The suitability of natural log transformation was assessed by residual diagnostic plots (i.e. a histogram of the residuals, a 'residuals versus fitted values' plot, and a plot of the sorted residuals versus normal scores). In the ANOVA, time was considered as a categorical variable. The temporal changes in Olsen P were evaluated on a natural log scale using a restricted maximum likelihood (REML) approach for sampling years from 1968 to 1994, different combinations of dependent variables and treatment factors were tested together and then selected or removed to give a parsimonious model. Using REML allowed regression analysis

with time as a continuous variable with the main factors (lime and the addition of P) modelled as fixed effects (and their interactions). The model selected was one that had the fewest parameters consistent with having a statistically significant reduction in the log-likelihood compared with the log-likelihood nearest nested model. Time (i.e. year) was treated as a variable in order to examine the change in Olsen P separately for each site as a rate over time. Autocorrelation of the residuals was evaluated by comparing models that included a temporal correlation auto-regressive 1 (AR1) structure, using likelihood ratio tests (Teste et al., 2021; Zuur et al., 2009). There was no consistent evidence of autocorrelation in the Olsen P data (i.e. for same plots over different years). The data showing the changes in time were plotted on the natural log scale which enabled linear slopes to be estimated which are easier for the reader to interpret. All analyses were done in GenStat for Windows (VSN International, 2022).

### 3 | RESULTS

#### 3.1 | Soil pH and Olsen P

There were highly significant liming effects on soil pH for both soil types (based on data from all the measurement years), but no P treatment effects on soil pH for either soil type (Table 1). A significant lime  $\times$  P treatment interaction effect on soil pH was only detected in the sandy loam soil at Woburn. There were significant liming effects on Olsen P in both soil types. Again, highly significant P treatment effects were detected for Olsen P in both soil types, but a significant treatment interaction effect between lime and P addition was only detected for the silty clay loam (Rothamsted) in Olsen P. The overall mean Olsen P ( $\text{mg kg}^{-1}$ ) concentration and the corresponding soil pH are given for all the years which were analysed for each soil type in Figure 1. The liming effect was greater for the sandy loam soil than for the more highly buffered silty clay loam soil.

Temporal analysis of Olsen P concentrations was conducted at each site (soil type) (Figure 2). For each soil type there were highly significant P treatment effects and lime treatment effects, but the latter were complex. The rate of

change in Olsen P was the same for all the liming treatments. The slope in the silty clay loam soil was significantly different from zero, but not significantly different between the liming or P treatments, but the treatments did affect the intercepts (Table 2). In comparison, in the sandy loam soil there were significant P effects on the slope, but not for the liming treatment, and the intercepts were significantly different between each combination of liming and P treatments. The Olsen P concentrations were greater in the sandy loam soil than the silty clay loam, and over time the decrease in Olsen P was slightly greater in the sandy loam soil (Figure 2).

#### 3.2 | P removal in grain

P removal in grain was tested for significant treatment effects (Table 3). However, there were only 3 years with sufficient data to calculate P removal in grain and in each year. A highly significant liming effect on the P removal in grain was found for barley and wheat crops, but no effect was detected in oat. At both sites there was a highly significant P effect detected but no liming  $\times$  P interactions. P removal in grain ( $\text{kg P ha}^{-1}$ ) for each liming treatment is given for each soil type for the three different crops in selected years in Figure 3. The P removed in the grain was significantly lower for the lime control treatment compared with the lime (L, M and H) treatments for the barley and wheat crops.

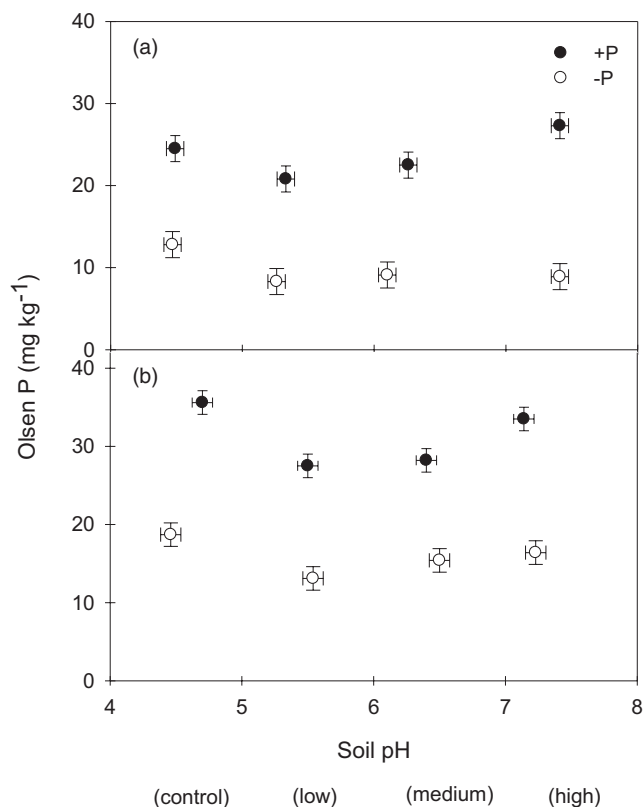
### 4 | DISCUSSION

#### 4.1 | The effects of liming on Olsen P

The liming effect on both soil types (Table 1) is in agreement with previous research with contrasting responses on the effects of liming on soil P availability (Azeez et al., 2020; Murphy, 2007; Viade et al., 2011). After 74 years liming had decreased Olsen P values in a sandy arable soil in Denmark (Azeez et al., 2020), and an incubation experiment with New Zealand soils with contrasting P status showed that liming mostly decreased Olsen P values, although in some soils they increased

Soil type	Dependent variable	Lime	Phosphate	Lime $\times$ phosphate
Silty clay loam	pH	<0.001	0.088	0.335
Sandy loam soil	pH	<0.001	0.971	<0.001
Silty clay loam	Ext. P	<0.001	<0.001	0.015
Sandy loam soil	Ext. P	<0.001	<0.001	0.181

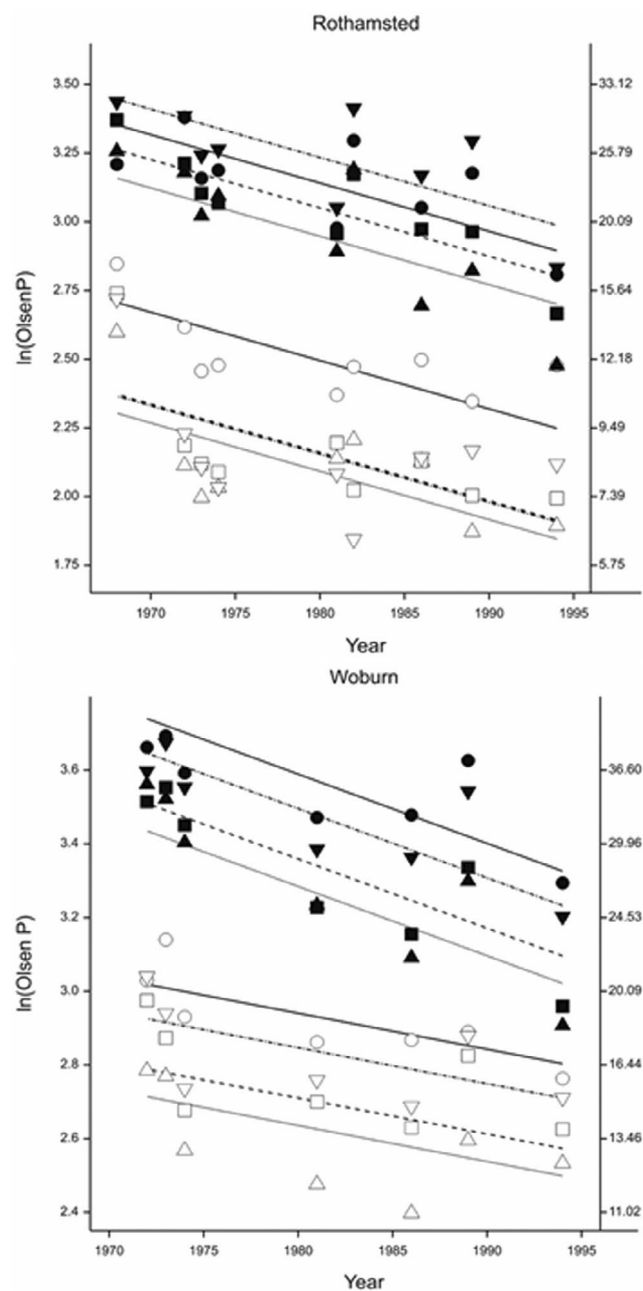
**TABLE 1** The significance level (*p* value) for the effects of lime and phosphate (P) treatments and their interaction on soil pH and Olsen P for a silty clay loam soil (Rothamsted) and sandy loam soil (Woburn) for all years of the experiment from 1968 to 1994.



**FIGURE 1** Soil pH and Olsen P ( $\text{mg kg}^{-1}$ ) for four liming rates (control, low, medium and high) with ( $\bullet$  +P) and without ( $\circ$  -P) P addition for a silty clay loam soil (Rothamsted) and a sandy loam soil (Woburn) for all years (1968–1994); the vertical error bars represent the standard error of difference of means (SED) for lime  $\times$  P treatment for Olsen P and the horizontal error bars represent the SED for lime  $\times$  P treatment for soil pH.

(Curtin & Syers, 2001). Murphy (2007) reported that liming increased Olsen P values in the upper top soil (with a sandy loam texture), but they decreased at greater soil depths. Viade et al. (2011) observed no significant effect of liming on Olsen P and, overall, a thorough review by Haynes (1982) found that liming can either increase, decrease or have no effect on Olsen P.

The nature of the different responses to liming between the soils in the LTL Experiment (Figures 1 and 2) is likely partially because of soil texture, which influences adsorption–desorption reactions in the sandy loam at Woburn and the silty clay loam at Rothamsted (Table S2). In general terms, the adsorption properties and the soil pH buffering capacity differ between these two soils; the sandy loam is able to adsorb less P than the silty clay loam soil. Evaluation of soil P reactions in for Rothamsted and Woburn soils by Blake et al. (2003) illustrated the importance of clay content in determining available sites for P sorption with lighter (less clay content) textured soils behaving differently from heavier textured soils. The sandy loam soil has less P buffer



**FIGURE 2** Temporal changes in Olsen P ( $\text{mg kg}^{-1}$ ) for four liming treatments (control  $\circ$  and  $\bullet$ , low  $\Delta$  and  $\blacktriangle$ , medium  $\square$  and  $\blacksquare$ , high  $\nabla$  and  $\blacktriangledown$ ) for a silty clay loam soil (Rothamsted) and a sandy loam soil (Woburn) for selected years between 1968 and 1994; filled symbols are the + P treatment and empty symbols are -P (P control); the fitted linear regression lines correspond to the lime and phosphorus treatments; the regression lines represent the following liming treatments: Solid = control, dotted = low, dashed = medium and dot-dashed = high; the left-hand x-axis is on the natural log scale, and the right-hand x-axis is on the natural scale.

capacity than the silty clay loam soil, and this affected the concentration of the Olsen P which was measured (Figure 1). Confirming the critical importance of clay content on P availability, Gustafsson et al. (2012) found

**TABLE 2** The regression coefficients (intercept and slope) and their standard errors for the modelled concentration ( $\text{mg kg}^{-1}$ ) of Olsen P between selected years from 1968 to 1994, the t-slope and t probability for a silty clay loam soil<sup>a</sup> (Rothamsted) and sandy loam soil<sup>b</sup> (Woburn).

Soil	Treatment (lime; -/+P)	Intercept	s.e.	Slope	s.e.	T slope	t. pr
Silty clay loam	Nil/-P	2.497	0.068	-0.0176	0.0048	-3.67	0.008
Silty clay loam	Nil/+P	3.143	0.068	-0.0176	0.0048	-3.67	0.008
Silty clay loam	Low/-P	2.094	0.068	-0.0176	0.0048	-3.67	0.008
Silty clay loam	Low/+P	2.949	0.068	-0.0176	0.0048	-3.67	0.008
Silty clay loam	Medium/-P	2.163	0.068	-0.0176	0.0048	-3.67	0.008
Silty clay loam	Medium/+P	3.052	0.068	-0.0176	0.0048	-3.67	0.008
Silty clay loam	High/-P	2.157	0.068	-0.0176	0.0048	-3.67	0.008
Silty clay loam	High/+P	3.236	0.068	-0.0176	0.0048	-3.67	0.008
Sandy loam	Nil/-P	2.928	0.0419	-0.00978	0.005585	-1.75	0.104
Sandy loam	Nil/+P	3.565	0.0419	-0.0188	0.005585	-3.37	0.005
Sandy loam	Low/-P	2.623	0.0419	-0.00978	0.005585	-1.75	0.104
Sandy loam	Low/+P	3.260	0.0419	-0.0188	0.005585	-3.37	0.005
Sandy loam	Medium/-P	2.698	0.0419	-0.00978	0.005585	-1.75	0.104
Sandy loam	Medium/+P	3.335	0.0419	-0.0188	0.005585	-3.37	0.005
Sandy loam	High/-P	2.835	0.0419	-0.00978	0.005585	-1.75	0.104
Sandy loam	High/+P	3.472	0.0419	-0.0188	0.005585	-3.37	0.005

<sup>a</sup>For the silty clay loam the F statistics were:  $F(1, 7.2) = 13.44$ ,  $pr = 0.008$  (Year);  $F(8, 114.5) = 663.69$ ,  $pr < 0.001$  (Lime  $\times$  Phosphorus).

<sup>b</sup>For the sandy loam the F statistics were:  $F(3, 196.1) = 21.18$ ,  $p < .001$  (Lime);  $F(2, 12.4) = 3256.95$ ,  $p < .001$  (Phosphorus);  $F(2, 12.8) = 7.06$ ,  $p = .009$  (Year  $\times$  Phosphorus).

**TABLE 3** The significance level ( $p$  value) for the effects of lime and phosphate (P) treatments on P removal in grain ( $\text{kg P ha}^{-1}$ ) for three different crop types (in selected years): Barley (1978), oat (1981) and wheat (1995).

Crop	Lime	Phosphate	Lime $\times$ phosphate
Barley	<0.001	<0.001	0.469
Oats	0.06	<0.001	0.33
Wheat	<0.001	<0.001	0.667

that soils containing 20% clay had a minimum P availability between pH 6 and 7, but there was no pH minimum in soils containing <10% clay. The Olsen P values in this study differed with soil texture, in agreement with the analysis of 55 European long-term field experiments which found higher critical values for sandy soils compared with loam soils (Steinfurth et al., 2022).

Soil pH has been described as the master variable determining soil chemical processes (Penn & Camberato, 2019). However, Hartemink and Barrow (2023) recently warned of the significant complexity associated with soil pH—plant nutrient relationships, stating that soil pH cannot be used to estimate plant nutrient availability. In agreement with this, we observed the greatest Olsen P values in the control and high lime treatments which had very

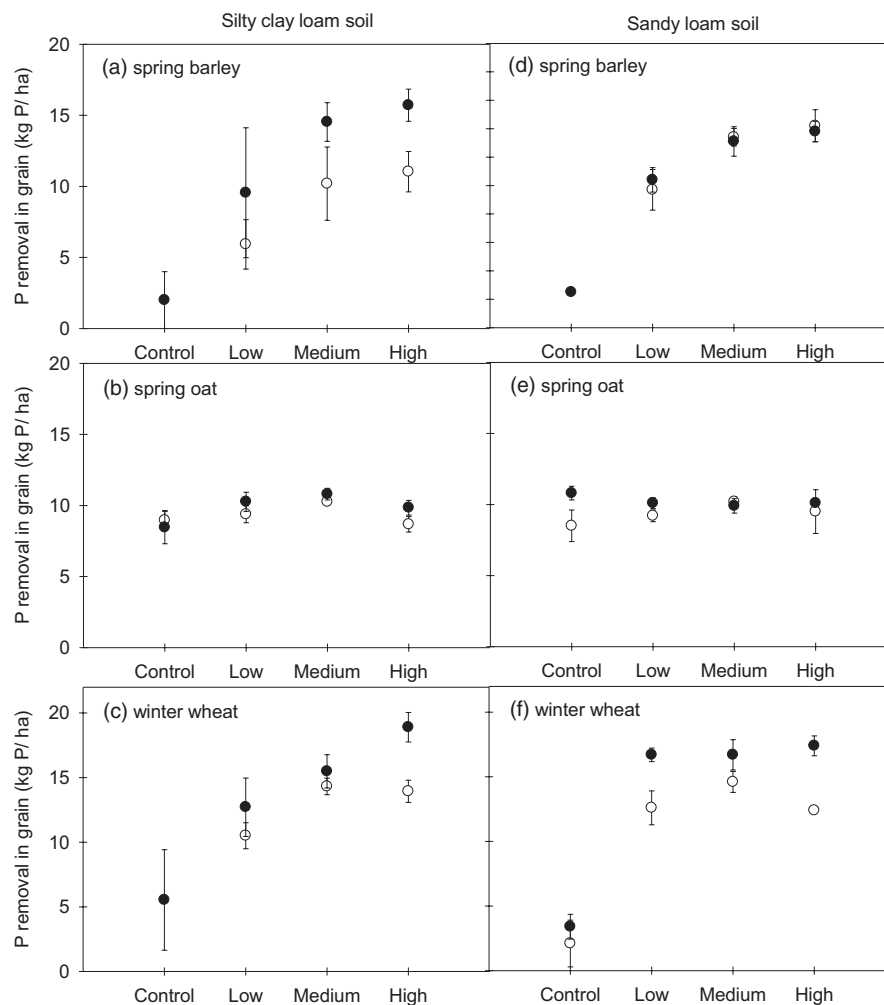
different soil pH values (Figure 1). Our results for soil pH vs. Olsen P follow an approximate U-shaped relationship, as previously described by Barrow (2017) and Barrow and Hartemink (2023): lowest Olsen P values were observed in the low and medium lime treatments, corresponding with a soil pH between 5 and 6.

## 4.2 | Effect of the soil P extraction method

Previous studies have suggested that the Olsen P method induces the precipitation of Ca phosphate, introducing an artefact (Curtin & Syers, 2001; Sorn-Srivichai et al., 1984). These criticisms raise concerns about the validity of Olsen P values using the Olsen method in general and perhaps even more when there is added Ca such as when liming is a treatment. We found higher Olsen P in the high lime treatment on the sandy loam soil (see Figure 1) evidence that the bicarbonate extracting solution does not always decrease the concentration of Olsen P. Furthermore, given the large Olsen P values observed in the control treatment (Figure 1) which received no lime, there must be some doubt as to whether there is an artefact from the Olsen method.

However, the method of determining Olsen soil P is critical and should be selected based on the soil pH. A previous study of other soils at Rothamsted found that P

**FIGURE 3** P removal in grain ( $\text{kg P ha}^{-1}$ ) of spring barley (a, d) in 1978, spring oat (b, e) in 1981 and winter wheat (c, f) in 1995 at four liming rates (control, low, medium and high) with ( $\bullet$  +P) and without ( $\circ$  -P) P addition on a silty clay loam soil (Rothamsted) and sandy loam soil (Woburn); bars represent the standard error of the mean.



extracted with 10mM  $\text{CaCl}_2$  decreased at both low and high soil pH values (Ortas & Rowell, 2000). A very different result to that which we observed, indicating great sensitivity of extraction methods to soil pH.

### 4.3 | Temporal effects on Olsen P after liming

The time to equilibrium is important when evaluating liming effects. The slow dissolution of  $\text{CaCO}_3$  means that there is often uncertainty in the relative supply of Ca to the soil solution, which strongly influences adsorption-desorption reactions. Twenty years after lime was applied in 1972, the effect of this initial application of lime on Olsen P decreased in both soils (Figure 2). The Long-Term Liming experiment made repeated applications of lime to try and maintain distinct, pre-determined soil pH values in order to study pH effects (Table 1). It is important to distinguish between this and a one-off application of lime. The temporal changes in Olsen P (Figure 2) must be considered in this context and the long-term liming effects on Olsen P. Short-term liming effects have been used (Bouray et al., 2022) to

evaluate specific soil process changes. Our results confirm the importance of long-term experiments to understand liming-induced changes to soils. Indeed, the effects of liming on improving P use efficiency can persist for more than four decades (Tiecher et al., 2023).

### 4.4 | Effect of liming on P removal in grain

The fertilizer recommendations for England and Wales are based on the Olsen-P soil test, and currently the recommendation for Index 2 is a critical range of values of 16–25  $\text{mg L}^{-1}$  (which can be converted to 12–19  $\text{mg kg}^{-1}$  as these are units used in this study) for the optimization of crop yields (AHDB, 2017). In the UK the Index 2 is an advised target range for adequate soil Olsen-P (AHDB, 2017). Where no P was applied, we found that the three liming treatments (Low, Medium and High) had an Olsen P concentration <12  $\text{mg kg}^{-1}$  for the silty clay loam soil (Rothamsted); in contrast the sandy loam soil (Woburn) was within the range of critical concentrations for Index 2 (Figures 1 and 2). All the P treated samples on both soil types were >19  $\text{mg kg}^{-1}$ .

Therefore, according to the recommendations for UK arable soils there should be no P deficiency impact on yield and little difference in the P removal in grain between the liming treatments. However, P removal in grain ( $\text{kg P ha}^{-1}$ ) was significantly less ( $p < .05$ ) in the control (no lime) treatment compared with the +P treatments for the barley and wheat crops in 1978 and 1995, respectively, while for oat there was no liming effect on P removed in the grain (Figure 3). The differences in P removal in grain between crops suggest distinct plant responses to P availability owing to liming. In this study there is some evidence that oat performs better than barley and wheat at low soil pH, and this difference may be because of a superior P uptake ability of oat. Evaluation of liming effects on yield between crops from this long-term experiment (Holland et al., 2019; Jordan-Meille et al., 2021) confirms the importance of considering a range of critical soil P concentrations and caution against using a single value. The incorporation in this study of the P removed in the grain of each crop moves towards a better understanding of the effects of pH on nutrient availability as it incorporates crop growth. A complete crop P balance would require the P removed in the straw to be measured. Figure 2 only shows the P removed in the grain and does not fully account for total crop uptake. Thus, Barrow and Hartemink (2023) emphasize the importance of evaluating both the soil and crop growth in order to fully understand nutrient acquisition by the crop caused by the effects of changes in soil pH. Future research on nutrient availability should evaluate both soil and plant effects to thoroughly determine the effects of liming on crop management.

## 5 | CONCLUSION

The Long-Term Liming experiment at Rothamsted and Woburn continues to provide insights into significance of soil-crop nutrient relationships that have implications for agronomy. Soil texture, and clay content in particular, is one of the explanatory factors which influenced the effect of liming on Olsen P. The sandy loam soil at Woburn had a greater response to liming than the more highly buffered silty clay loam soil at Rothamsted. The temporal changes in Olsen P observed are a response to repeated lime applications. Differences in P removal in grain between crops indicate that the evaluation of nutrient availability to crops as a result of liming using only soil data is insufficient: crop growth and nutrient acquisition data are also necessary for an effective understanding.

## ACKNOWLEDGEMENTS

We thank the Lawes Agricultural Trust and Rothamsted Research for information and data from the e-RA database. The Rothamsted Long-Term Experiments National

Bioscience Research Infrastructure (RLTE-NBRI) is supported by the UK BBSRC (Biotechnology and Biological Sciences Research Council, BBS/E/RH/23NB0007, 2017–2023) and the Lawes Agricultural Trust. Dr Sarah Perryman provided support with collation of the archived data. Dr Mark K. Conyers of Wagga, Wagga, New South Wales, Australia, provided insightful comments and suggestions which assisted with evaluating the results.

## DATA AVAILABILITY STATEMENT

The data that support the findings of this study are openly available in e-RA at <https://www.era.rothamsted.ac.uk/>.

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## SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

**How to cite this article:** Holland, J. E., White, R., Haefele, S. M., Goulding, K. W. T., McGrath, S. P., & Glendining, M. J. (2024). Long-term effects of lime and phosphorus application on soil extractable (Olsen) phosphorus differ between two arable UK soils. *Soil Use and Management*, 40, e13160. <https://doi.org/10.1111/sum.13160>