Uptake, mobilisation, and fixation of phosphorus in long-term agricultural field experiments with phosphorus fertiliser and liming: Final report, project No. H1133140

Upptag och fastläggning av fosfor i långliggande kalk- och fosforförsök: kalkning som produktions- och miljöåtgärd: Slutrapport, projekt nr H1133140

Magnus Simonsson, Swedish University of Agricultural Sciences (SLU), Dep. of Soil and Environment, P.O. Box 7014, S-750 07, Uppsala, Sweden. E-mail: magnus.simonsson@slu.se
Thomas Kätterer, Swedish University of Agricultural Sciences (SLU), Dep. of Ecology, P.O. Box 7044, S-750 07 Uppsala, Sweden.
Gunnar Börjesson, Swedish University of Agricultural Sciences (SLU), Dep. of Soil and Environment, P.O. Box 7014, S-750 07, Uppsala, Sweden.

Background

Leaching of phosphorus (P) to surface water from the Swedish agricultural land must be reduced to rescind the eutrophication problems that occur in many of our lakes and the Baltic Sea (Miljörådet, 2009). Since a few years, the administrative boards of several Swedish counties grant subsidies for structure liming to prevent leaching of P bound to eroding soil particles. Because P is at the same time an essential nutrient for crops, the question arises how the liming affects long-term P availability for the crops. What is the risk of a conflict between the environmental goals and an effective use of the finite P resource?

Although P solubility has long been known to vary with the soil pH (Gardner and Kelley, 1940), the expected effects of liming on the availability of soil P depend on soil type and the pH of the soil prior to liming (Haynes, 1982). Because water extracts of agricultural soils are commonly in disequilibrium with known P-bearing mineral phases, it is generally believed that adsorption to oxide surfaces, rather than mineral solubility of discrete P minerals, controls the solubility of P in soils (Murrmann and Peech, 1969; Devau et al., 2009, 2011; Weng et al., 2011; Gustafsson et al., 2012). Apparently in conflict with the common experience, which postulates that liming to slightly acidic or neutral pH enhances P availiability in soils (e.g., Havlin et al., 1999), recent studies have reported minimum P solubility in the pH range 5–7 (Devau et al., 2011; Gustafsson et al., 2012). Also simultaneous sorption of P and Ca was observed in laboratory experiments by Agbenin et al. (1996) to the extent that the author concluded that liming might hamper the availability of P in the particular soils. The modelling of Weng et al. (2011) suggested that suppressed P solubility might be explained by co-sorption of P and Ca onto Fe oxide surfaces under conditions with high concentrations of Ca^{2+} ions in the soil solution. Also, if large amounts of exchangeable Al is present in the soil, this may precipitate as Al hydroxide and temporarily immobilise P by adsorption onto the newly formed hydroxide surfaces (Haynes, 1982). Short-term additions of P, acid or base in the laboratory apparently fail to imitate the retention and mobilisation of P taking place at a decennial time scale in the field. For instance, Gustafsson et al. (2012) found that phosphate or arsenate added in the laboratory was reactive on a short term (6 days), whereas the majority of P added as fertiliser during several decades in the field was unavailable to rapid equilibration in the laboratory. Recent studies have been conducted using XANES spectroscopy to reveal the forms of P present in the soil. Khatiwada (2012) showed that fertiliser applications resulted in P forms that varied depending on the time of incubation (5 weeks–6 months); finally, a mixture of sorption species and precipitates with Ca or Fe were formed in the tested mildly acidic soil (pH ≈ 6). Eriksson et al. (2015) concluded that sorption to Al-bearing oxides predominated the P added by fertilisation during several decennia, even in a calcareous soil. It remains that the long-term effects of P fertiliser and liming must be assessed using soil materials that have undergone the different management practices under field conditions during extended periods of time.

Liming of acidic soil is since long considered to increase the microbial activity and enhance mineralisation of phosphorus (Ghani and Aleem, 1942). Several studies have demonstrated the importance of enzyme activity for mineralisation rate, such as acid and alkaline phosphatases (Tarafdar and Jungk, 1987; McLatchey and Reddy, 1998; Chen et al., 2002). Because P mineralisation potentially involves a wide variety of enzymes, each having its particular optimum pH, the net effect of a change in pH is difficult to predict. However, Halstead et al. (1963), measuring P mineralisation rates in acidic soils from eastern Canada, found a positive effect of liming on the mineralisation of organic P. Trasar-Cepeda et al. (1991) performed a similar study, by adjusting the pH of Andisol to a range of values (5.5–6.5) using $Ca(OH)_2$; although P mineralisation rates were not significantly correlated with the phosphatase activity, the turnover of organic phosphorus significantly increased in soils receiving the highest dose of $Ca(OH)_2$. It may therefore be hypothesised that liming could be expected to deplete the stocks of organic P in a soil.

The present investigation evaluated availability of P in a number of Swedish long-term field experiments with varying application rates of lime and P fertiliser. A combination of archive data evaluation and laboratory experiments with soils from these experiments was used to cast light on the following questions:

1. How did liming affect the P uptake by the crops?
2. How did it affect the solubility of the P added by fertiliser applications?
3. What was the effect of liming on the stocks of soil organic matter and, specifically, on soil organic P?

Materials and methods

The report is based on two sets of Swedish field experiments: The so-called ‘permanent liming trials’ (experimental plan ID R3-1002) were represented by one experiment at Röbäcksdalen in north Sweden and one experiment at Västra Eknö in east central Sweden (Table 1). The ‘long-term liming and phosphorus trials’ (experimental plan ID R3-1001) are situated at the experimental station Lanna in southwest Sweden; the two relevant experiments are henceforth referred to as ‘Lanna-1936’ and ‘Lanna-1941’.

The site at Röbäcksdalen is situated 10 m above sea level on a fluvial plain, 1 km from the river Umeälven. The bedrock in the area is dominated by metamorphic greywacke and argillite (SGU, 1989). The experimental area is situated on a clayey–silty sediment, which settled in a post-glacial marine environment and contains gyttja and iron sulphide. The soil profile, however, is mainly located in an overlying coarser sediment of fluvial silt and sand deposited by the river during the Holocene land uplift (Eklund, 1991). Also Västra Eknö is situated 10 m above sea level in a plain with postglacial clay; the soil texture at the experimental site is silty clay. The bedrock in the area is dominated by Precambrian gneiss, gneiss–granite and schist (Magnusson, 1975). The experiments at Röbäckdalen and Västra Eknö were started in 1962 with an unlimed control and two application rates of limestone powder (Table 2; Simán, 1985). A basic application at the start of the experiment was followed by maintenance liming at 4-yr intervals. Lime treatments are combined with P- and K treatments based on off-take calculations: half, full or double replacement (P added as superphosphate). The treatments were run, in turn, within two crop residue management systems: residues left in the field (‘A’) or removed upon harvest (‘B’). Farmyard manure was not applied in the experiments. The replication (number of blocks) is threefold at Röbäcksdalen, twofold at Västra Eknö. The crop rotation at both experiments is a non-fixed sequence of cereals (60–70% of the years) and ley (12–24%), occasionally interspersed with oil seed, legumes etc.

The experimental station at Lanna is situated at 75 m altitude on a vast plain with marine glacial clay overlain by postglacial silty clay loam, approximately 30 cm thick (Johansson, 1944). The glacial clay is often calcareous, and may contain appreciable amounts of ‘phosphoric acid’ (0.1–0.2%; Munthe, 1903), at Lanna identified as apatite by Eriksson et al. (in prep). The postglacial sediment was deposited on top of the glacial clay as discussed by Johansson (1944). The relevant experiments at Lanna (plan ID R3-1001) were started in 1936 and 1941, respectively, as four-block experiments ($n = 4$) with applications of slaked lime (Lanna-1936) or quicklime (Lanna-1941) corresponding to 6 ton ha^{-1} CaO in half of the plots, whereas the remaining plots were left unlimed (Ohlsson, 1979). Liming levels were combined with phosphorus treatments, in this report restricted to the unfertilised control and annual applications of superphosphate (17.5 kg ha^{-1} yr^{-1} P). In the 1970’s, quicklime (6 ton ha^{-1} CaO) was applied on two blocks of each experiment (1977 in Lanna-1936, 1974 in Lanna-1941), resulting in a halved replication rate ($n = 2$) and four liming levels. The latter will be referred to as ‘No/No’ for a treatment without application of lime, ‘Yes/No’ for a treatment that received lime in the beginning of the experiment, but did not in the 1970’s etc; a single ‘No’ or ‘Yes’ refers to a treatment before the second liming occasion in the 1970’s (Table 2). Applications of N and K followed the general practices of the experimental station, and previous applications of farmyard manure (20 ton ha^{-1} once per 6 yr) was arrested in the late 1950’s, when the crop rotation became a non-fixed sequence dominated by cereals interspersed with occasional fallows and oil seed crops (Ohlsson, 1979).

Table 1. Site locations, texture and approximate initial (or earliest available data; see footnote) soil chemistry of the field experiments. The last numbers of the experiment code (e.g. ‘1962’) indicate the year when the experiment started. Västra Eknö was discontinued in 2011; the other experiments are still running (as by 2016).

Plan ID	Alias for this paper (experiment code)	Coordinates	Soil texture	pH (H_2O)	CEC_{pH7} ($cmol_c$ kg^{-1})	P-AL (mg kg^{-1})[1]
R3-1002	Röbäcksdalen (AC-2-1962)	63.8086°N 20.2459°E	Silt loam[2]	5.0[3]	11[3]	48[3]
″	Västra Eknö (U-3-1962)	59.4378°N 15.9939°E	Silty clay[2]	5.2[3]	20[3]	30[3]
R3-1001	Lanna-1936 (R-29-1936)	58.3485°N 13.1276°E	Topsoil of silty clay loam on subsoil of clay (from approx. 30 cm)[4]	6.0[5]	19[6]	–[7]
″	Lanna-1941 (R-27-1941)	58.3448°N 13.1174°E		5.9[5]	20[6]	–[7]

[1] Phosphorus extracted by 0.1 M ammonium lactate + 0.4 acetic acid, pH 3.75 (Egnér et al., 1960). [2] Texture based on unpublished data from 1986 of G. Simán. [3] Simán (1985). [4] Texture of the adjacent field ‘Skifte I’ (Johansson, 1944). [5] Control plots in 1971 (Lanna-1936) and 1969 (Lanna-1941). [6] Control plots in 1983 (Lanna-1936) and 1985 (Lanna-1941). [7] Initial values unavailable at Lanna; present range: 18–50 mg kg^{-1} (Lanna-1936) and 17–30 (Lanna-1941).

Table 2. Summary of treatments selected for the present study.

Plan ID	Experiments	Liming levels	Applications until 2012 (ton CaO ha^{-1})	Liming agent	P fertiliser levels	
R3-1002	Röbäcksdalen	I. No lime	0	Limestone powder, all occasions in both experiments	1	Half replacement
		II. 70% BS[1]	6.4		2	Full ”
		III. 100% BS[2]	14		3	Double ”
”	Västra Eknö	I. No lime	0			
		II. 70% BS[1]	7.4–9.1			
		III. 100% BS[2]	36			
R3-1001	Lanna-1936,	No/No	0	Quicklime (CaO), except for slaked lime at start of Lanna-1936	No P	No P fertiliser
”	Lanna-1941	Yes/No	6		Super-P	17.5 kg ha^{-1} yr^{-1} P as superphosphate[3]
		No/Yes[4]	6			
		Yes/Yes	12			

[1] Liming to 70 % base saturation. [2] Liming to 100 % base saturation. [3] Only treatments receiving no or annual applications of superphosphate were considered in this report. [4] Second liming occasion in 1977 (Lanna-1936) and 1974 (Lanna-1941).

The database of the field experiments at Lanna contained plot-wise data on harvest yields since the start of experiments until 2010, and treatment-wise P concentrations in harvested crops 1968–1972, 1995–2009, allowing analysis of P-uptake for a limited period mainly after the second liming occasion. In the R3-1002 experiments, plot-wise harvest yields were available 1987–2005 at Röbäcksdalen and 1971–2007 at Västra Eknö. Concentrations of P in harvested crops were available treatment-wise for the same years, allowing calculation of the P balance during this time. However, only the treatments with incorporation of harvest residues were considered, because no weighing of harvest residues had been performed in the treatments with removal of these materials. Before statistical treatment of harvest yields, normalisation was performed, so that the value 100 represented the overall average of each crop within each experiment. Analyses of variance was then performed within each plan ID (each comprising two experiments at the same time) and using block identity (e.g., 2×2 individual blocks for the two experiments with plan ID R3-1001), liming levels and P fertiliser levels as factors. Individual years were somewhat crudely treated as independent observations. For the off-take of P (kg ha^{-1} yr^{-1} of P), only annual means for each treatment and experiment were available, and the ANOVAs were performed on the absolute values using experiment ID, crop type, liming levels and P fertiliser levels as factors.

Soil sampling was performed in the autumn 2012 in the still active experiments (Lanna-1936, Lanna-1941 and Röbäcksdalen), after harvest but before ploughing or application of any fertiliser or lime. Soil pH(H_2O) was measured with a combined glass electrode (5 ml soil + 25 ml deionised water, reaction overnight). Soil Olsen-P was extracted using the conventional procedures (Olsen et al., 1954; Pierzynski, 2000). Soil P was also extracted according to the ‘AL’ and ‘HCl’ procedures of Egnér et al. (1960). Extraction with 0.2 M ammonium oxalate / oxalic acid pH 3.0 was performed according to van Reeuwijk (1993), followed by measurement of aluminium (‘Al_{ox}’), Fe (‘Fe_{ox}’), P (‘P_{ox}’) and Si (‘Si_{ox}’). Soil organic carbon and nitrogen were measured by dry combustion (Leco TruMac CN). Soil organic P was estimated using the procedure of Saunders & Williams (1955), by extracting 2 g soil with 100 ml 0.1 M H_2SO_4, with and without preceding ignition of the soil at 550°C. The extra P extracted after ignition is used as an estimate of organic P in the soil.

P solubility as a function of pH was assessed in batch equilibrations with soil and additions of acid or base. The procedure mainly followed Gustafsson et al. (2012): 2 g air-dried fine earth and 30 ml of solution containing background electrolyte (0.01 M $NaNO_3$) with additions of acid (up to 5 mM

HNO_3) or base (up to 2 mM NaOH) were introduced in 50 ml polypropylene centrifuge tubes, and allowed to react during 7 d at ambient temperature (20–23°C; reciprocating horizontal shaker, 130 min^{-1}). At the end of this time, the solutions were centrifuged, filtered (0.2 µm), and pH, P, Al, Ca and Fe concentrations were measured. Long-term effects of lime applications ware studied using plot-wise samples from 2012 (Röbäcksdalen and Lanna-1936). In addition, short-term effects of liming were assessed using treatment-wise archive samples from the four experiments in the years 1968–1984; from each experiment, two points in time were selected as close before and after a liming operation as available.

Results and discussion

Harvest and P off-take

Analyses of variance showed that liming increased both harvest and P off-take in the experiments at Röbäcksdalen and Västra Eknö (Table 3). At Röbäcksdalen also the concentration of P in the harvest increased due the liming, whereas no such effect was observed at Västra Eknö, meaning that the reasons for the increased P off-take differed between sites. Also at Lanna, harvest yields were enhanced by the liming, whereas there was no systematic effect on P concentrations and no effect on the uptake of P. The effects on harvest yields, as by the late 1970's, were described in detail by Ohlsson (1979). Although our results indicate no deterioration in the off-take of P because of liming, the data are somewhat ambiguous as to how readily the P was taken up by the crop.

P solubility in batch equilibration experiments

The variability in dissolved P was much greater in from Röbäcksdalen than in the silty clay Lanna-1936, both between the steps of an individual suite of batch equilibrations (normally eight steps per soil sample), between the different treatments with lime in the field and between block (plots) receiving the same treatment in the field (Figure 1; cf. Östlund, 2013). It therefore appears that the silty clay of Lanna exerted a stronger buffering of the P solubility than did the silt loam at Röbäcksdalen. Similarly to previous studies, additions of acid mobilised dissolved P in the latter soil (cf. Murrmann and Peech, 1969; Gustafsson et al., 2012). However, for a given pH, the limed treatments had similar or higher P solubility than the unlimed ones. Furthermore, Figure 1 b shows synergistic effects of liming and P fertiliser applications, with the largest effects of P fertiliser applications occurring where lime also was applied.

The experiments with archive samples, from samplings before and after liming operations, revealed no adverse effect of liming on P solubility (Figure 2). The solubility pattern in the 2012 samples from Röbäcksdalen (Figure 1) was established already in the samples from the 1980's (Figure 2); the relevant treatments at this site had been limed once in 1978 after the start of the experiment in 1962. Figure 2 b suggests a small positive effect of liming the previously unlimed soil at Lanna ('No' liming was split into 'No/No' and 'No/Yes' between the 'early' and 'late' samplings; Table 2). Additional titrations on soils from Västra Eknö and Lanna-1941 (not shown here) indicate that positive effects of liming occurred in some samples, although they were smaller than the long-term effects of Figure 1. The results suggest that rather than drastically improving the availability of P already present in the soil, the liming tended to mitigate the fixation of applied fertiliser P into unavailable forms. Possible mechanisms are discussed in Simonsson et al. (in prep.).

Table 3. Summary of treatments selected for the present study. Normalised harvest yields shown as averages over one treatment level at a time (e.g., for 'I. No lime', 88 is an average over three P fertiliser levels receiving no lime). Values that do not have one or more letters ('a, b' etc.) in common are significantly different (P < 5 %) according to analysis of variance (ANOVA) and Tukey-adjusted pair-wise comparisons.

Plan ID	Factor	Treatment	Normalised harvest yield	P off-take (kg ha^{-1} yr^{-1})
R3-1002[1]	Liming	I. No lime	88^{b}	8.8^{c}
		II. 70% BS	105^{b}	10.5^{b}
		III. 100% BS	105^{a}	11.4^{a}
	P fertiliser	1. Half replac	71^{c}	7.2^{c}
		2. Full replac	95^{b}	9.9^{b}
		3. Double replac	131^{a}	13.7^{a}
R3-1001[2]	Liming	No/No	87^{c}	15.1
		Yes/No	94^{b}	"
		No/Yes	99^{ab}	"
		Yes/Yes	100^{a}	"
	P fertiliser	No P	88^{b}	13^{b}
		Super-P	102^{a}	17^{a}

[1] Data 1987–2005 (Röbäcksdalen), 1985–2007 (Västra Eknö). 2 Data 1977–2010 (Lanna-1936), 1974–2010 (Lanna-1941).

Extractable P forms

Trends in P-AL solution were qualitatively in agreement with the P solubility trends described above (example data in Figure 3). The half, full and double replacement of P ('1', '2', '3' in Figure 3) resulted in progressively higher P-AL values, and liming had a positive effect on P-AL at Röbäcksdalen. P-HCl varied slightly (up to 20 %) with P-fertiliser application rates, but was not significantly changed by liming (not shown). Overall, differences in P-balance between the treatments at Röbäcksdalen (–120 to +680 kg ha^{-1} during 1962–2012) were only partly recovered as differences in P-HCl at 0–20 cm depth (range 1 800–2 200 kg ha^{-1}, assuming a density of 1 300 kg m^{-3}). By contrast, the ratio of P-AL/P-HCl indicated elevated extractability of soil P due to liming at this site. P_{ox} was intermediate, both regarding extracted quantity and sensitivity to P and lime applications (not shown).

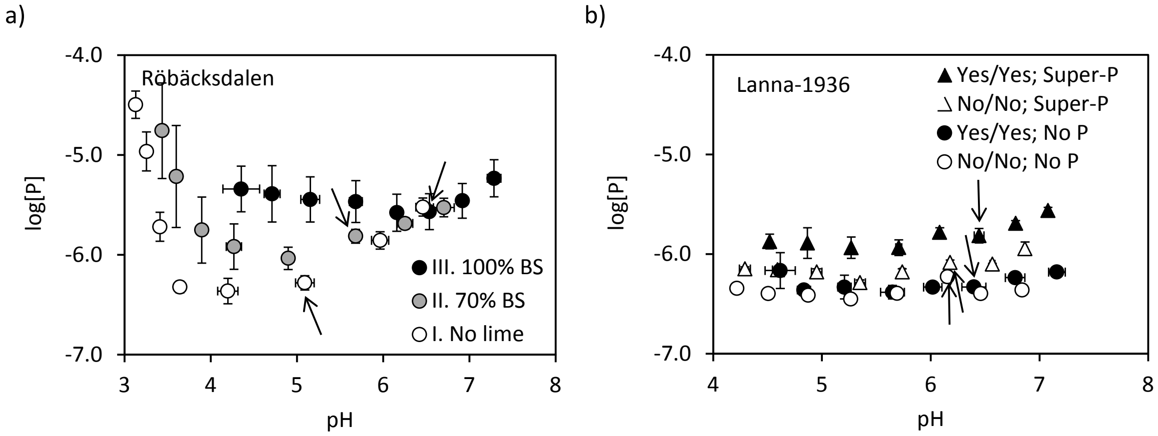

Figure 1. Long-term effects of liming on the solubility of P, expressed as the log_{10} dissolved P concentration (mol l^{-1}), in batch equilibrations with additions of acid (HNO_3), base (NaOH), or neither, to topsoil samples (0–20 cm) from 2012. Arrows indicate samples, where neither acid nor base was added in the laboratory. At Röbäcksdalen (a) three levels of lime applications were tested, with treatment mean (symbols) and standard error (bars) for soil from three plots. At Lanna-1936 (b), two levels of lime applications combined with two levels of P fertiliser were tested; mean and standard error over two plots.

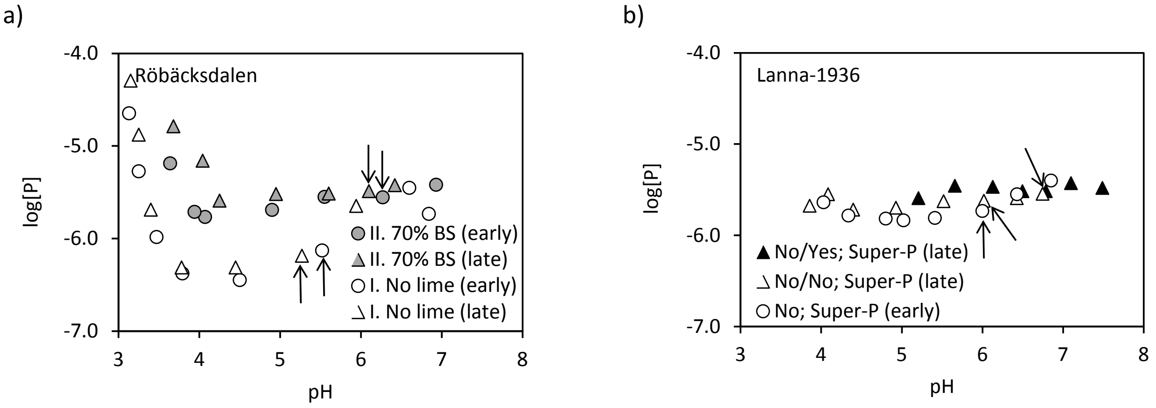

Figure 2. Short-term effects of liming on the solubility of P; $\log_{10}$ dissolved P concentration (mol l^{-1}). 'Early' and 'late' sampling occasions refer to 1980 and 1984 at Röbäcksdalen (a), 1977 and 1980 at Lanna-1936 (b). Liming was undertaken 1982 at Röbäcksdalen and 1977 (after the sampling) at Lanna-1936. Arrows indicate which samples that received neither acid or base in the laboratory.

Olsen-P showed a contrasting behaviour. The Olsen solution has been advocated for P testing, because it extracts a labile P fraction that is plant available at the time scale relevant for a growing season (e.g., Fardeau et al., 1988). Particularly, its use is recommended in naturally calcareous soils (Jordan-Meille et al., 2012). However, literature data indicate that liming may suppress Olsen-P; the reason for this 'artefact' was discussed by Sorn-srivichai et al. (1984) and by Curtin and Syers (2001). With liming and P fertiliser treated as separate factors, ANOVA for the results of Röbäcksdalen indicated a significant negative effect of liming on Olsen-P ($P < 0.001$), despite the enhanced P solubility according to the batch equilibrations. Although this pattern was not observed at Lanna, it can be concluded that Olsen-P may incorrectly reflect temporal trends in P availability after liming under some circumstances.

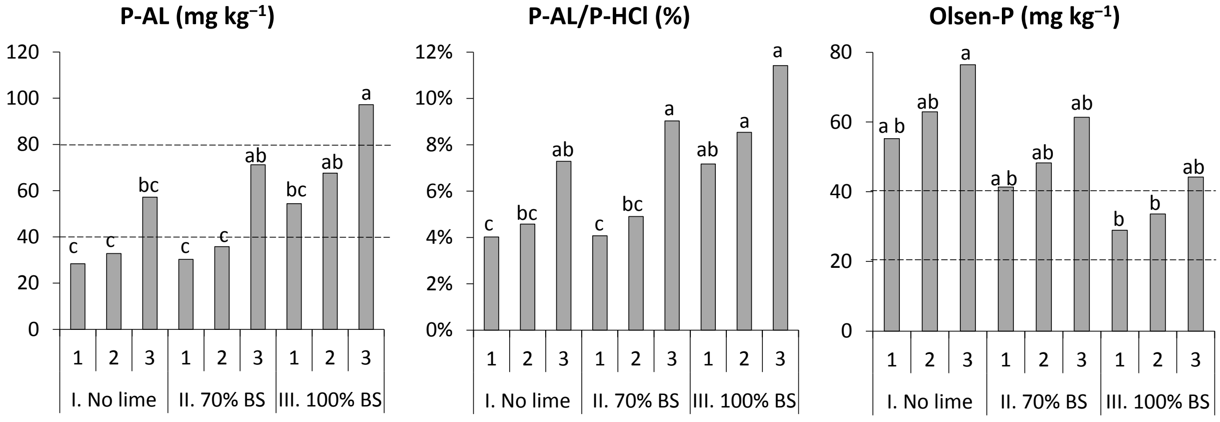

Figure 3. Soil chemistry of topsoil (0–20 cm) samples from 2012 at Röbäcksdalen: Olsen-P, P-AL and the ratio of P-AL/P-HCl. Dashed horizontal lines indicate upper and lower limits of the 'medium' range for Olsen-P according to Danish extension standards, and for P-AL ('class III') according to Swedish standards (Jordan-Meille et al., 2012). Values that do not have one or more letters ('a', 'b' etc.) in common are significantly different (P < 5 %) according to analysis of variance (ANOVA) and Tukey-adjusted pair-wise comparisons (general linear model with the three blocks and nine overall treatments used as factors; the P-AL/P-HCl ratio was analysed after log transformation, the other variables untransformed).

Effects on organic P

In none of the investigated experiments did liming result in a lower content of organic carbon (C), nitrogen (N) or P in the soil (Table 4). A small reduction in organic carbon and C/N ratio resulted from the removal of harvest residues at Röbäcksdalen. Liming, too, yielded a slightly reduced C/N ratio, indicating a stimulated mineralisation of organic matter. Unexpected is, therefore, an increase in the stock of organic P in limed treatments at this site. Converted to surface-related quantities, the range in organic P was of the order of 630–690 kg ha^{-1} (20 cm, 1 300 kg m^{-3}); i.e., the liming to 100 % base saturation yielded an additional 60 kg ha^{-1} of organic P compared to the unlimed control. This is slightly more than, but of the same order of magnitude as, the extra input of organic P with harvest residues in the limed treatment, as estimated by Sigtryggsson (2015; 0.5 kg ha^{-1} yr^{-1} P, or 25 kg ha^{-1} over the 50 yr that the experiment was run until the soil sampling in 2012). Because P fertiliser was added using a replacement strategy at Röbäcksdalen, Sigtryggsson (2015) suggested that the extra P fertiliser, supplied to compensate for the higher harvest yields in limed treatments, might to some extent inhibit the mineralisation of organic P, allowing a build-up of the pool in the soil. Mineralisation of organic P is controlled by the demand for phosphate, and the phosphatase activity may decrease if phosphate is added to the system (Nannipieri et al., 1978; Nakas et al., 1987).

Table 4. Organic carbon, nitrogen and phosphorus, and their ratios, in the topsoil (0–20 cm) samples from 2012. As in Table 3, treatment means were calculated over one treatment level at a time, and superscripts 'a' and 'b' relate to ANOVA and pairwise comparisons calculated as for the harvest. For the ratios (C/N and C/P), values were log transformed before the analysis; shown are treatment means back-transformed.

Plan ID	Experiment	Factor	Treatment	Org C	Org N	Org P	C/N	C/P
				(% dry weight)		(mg kg^{-1})	(weight ratio)	
R3-1002	Röbäcksdalen	Harvest residues	Incorp	1.9^{a}	0.14	250	13.7^{a}	73
			Removed	1.8^{b}	″	″	13.4^{b}	″
		Liming	I. No lime	1.8	0.14	230^{b}	13.7^{a}	78^{a}
			II. 70% BS	″	″	260^{a}	13.6^{ab}	73^{ab}
			III. 100% BS	″	″	270^{a}	13.3^{b}	69^{b}
		P fertiliser	1. Half replac	1.8	0.14	250	13.5	73
			2. Full replac	″	″	″	″	″
			3. Double replac	″	″	″	″	″
R3-1001	Lanna-1936, Lanna-1941	Liming	No/No	1.8	0.16	260	11.5	70
			Yes/No	″	″	″	″	″
			No/Yes	″	″	″	″	″
			Yes/Yes	″	″	″	″	″
		P fertiliser	No P	1.8	0.16	260	11.5	70
			Super-P	″	″	″	″	″

At Lanna, no treatment effects were observed in the soil organic C, N or P (Table 4). With the higher harvest yield in limed treatments (Table 3), a stimulated decomposition of harvest residues is apparently required to explain the absence of a response in soil organic C. In absolute terms, the greater harvest yield in the 'Yes/Yes' treatment, compared to 'No/No' (Table 3), implies an excess of 20 ton ha^{-1} of C harvested from the former treatment, as summed up over the approximately 70 yr of the experiments. Assuming a similar extra input to the soil of roots and harvest residues (Bolinder et al., 2007) due to the liming, results in an an excess C input corresponding to approximately 0.8 % of the topsoil mass. However, the mean error of the ANOVA for soil organic C at Lanna was 0.12 % C. After decomposition of most of the extra C, it is questionable whether a stationary content of soil organic C can be interpreted as a stimulated decomposition of harvest residues. It remains, however, that the liming did not affect the soil organic pools to any observable extent at Lanna.

Conclusions

Based on the results, the following conclusions can be drawn:

1. Liming enhanced harvest yields and partly also the uptake of P by the crops.
2. No evidence was found of any depressed P solubility as a result of liming, neither on the short (2–10 yr) or long (decennial) term.
3. Liming frequently resulted in higher extractability of P with the 'AL method'. The AL-method thereby appeared to qualitatively reflect the enhanced P solubility due to liming found in the solubility study (Point 2). By contrast, liming tended to depress Olsen-extractable P. The latter extractant, alone, may therefore lead to erroneous conclusions regarding temporal trends in P availability after liming.
4. Although liming enhanced crop production and might stimulate mineralisation of organic matter, no evidence was found for any long-term depletion of organic P in the soil due to liming.
5. The data of the present study indicate no need to increase P fertiliser application rates immediately after a liming operation, to compensate for any enhanced fixation of the added P.

Publications

The following BSc reports with results from the projects are available on the internet, both are written in Swedish with an English abstract; in addition a manuscript is being prepared for submission to a scientific journal:

1. Östlund, A. 2013. Effect of liming on phosphorus solubility – a batch leaching experiment based on two Swedish long-term field experiments. *Examensarbeten, Institutionen för mark och miljö, 2013:17*; available at: http://stud.epsilon.slu.se/5993/.
2. Sigtryggsson, C. 2015. Effects of liming on phosphorus mineralization – organic phosphorus in the permanent field trial at Röbäcksdalen (R3-1002). *Examensarbeten, Institutionen för mark och miljö, SLU, 2015:09*; available at: http://stud.epsilon.slu.se/8502/
3. Simonsson, M., Östlund, A., Renfjäll, L., Sigtryggsson, C., Kätterer, T. and Börjesson, G. in prep. Solubility and turnover of phosphorus as affected by liming – results from Swedish long-term experiments. *Manuscript for submission to, e.g., Soil Use and Management*.

Communication

Beside the mentioned publications, the results have so far been communicated orally as follows:

1. "*Kalkningskemi – effekter på fosfortillgänglighet*" ("The chemistry of liming – effects on the availability of phosphorus"). Oral presentation at the 'HIR' conference in Linköping, 5 October 2015.
2. "Liming and P availability". Oral presentation at the seminar "Estimation of soil phosphorus availability to crops – How can we improve fertilization?" organised by *Markkarteringsrådet, Greppa Näringen*, SLU and *Uppsala Vattencentrum* in Uppsala 18 February 2016.

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