Phosphorus leaching from clay soils can be counteracted by structure liming

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Abstract Two field experiments with drained plots on clay soils (60 and 25 % clay) demonstrated a significant reduction in leaching of total phosphorus after application of structure lime. Aggregate stability, was significantly improved. Phosphorus leaching in particulate form was significantly reduced following structure liming at the site with a very high clay content. Sites representing low (50 mg kg^{-1}) and high (140 mg kg^{-1}) levels of phosphorus extractable with acid ammonium lactate in topsoil displayed differing effects on leaching of dissolved reactive phosphorus. This form of phosphorus was only significantly reduced compared with the control at one site with high topsoil P status and relatively high (17-18%) degree of phosphorus saturation in the subsoil. Laboratory experiments with simulated rain events applied to topsoil lysimeters from the same site also demonstrated a significant reduction in leaching of dissolved reactive phosphorus. These findings indicate that structure liming is an appropriate leaching mitigation measure on soils with both a high clay content and high soil phosphorus status.

Key words: *Aggregate stability, drainage water, mitigation method, nutrients, turbidity*

Introduction

Phosphorus (P) and nitrogen (N) are both nutrients which have the potential to seriously increase eutrophication of surface waters if available in high concentrations in the water and with proportionally high contribution of P (low N:P ratio) (Smith & Schindler, 2009). In Swedish clay soil areas, P leaching either in particulate (PP) or dissolved reactive (DRP) form is a major environmental problem for water quality (Ulén et al., 2007). Structure liming is officially recommended as a measure to improve clay soil structure, in order to reduce P leaching (SBA, 2013). This amendment is applied either in the form of quicklime (calcium oxide, CaO), or hydrated (slaked) lime ($Ca(OH)_2$), the latter being more common. When these forms of lime are mixed with a clay soil, several reactions take place at soil aggregate level and an immediate improvement in soil stability, porosity and aggregate strength has been reported (Choquette et al., 1987). The reactions include cation exchange, flocculation and agglomeration, together with slower cementing and the virtually irreversible pozzolanic reaction (Kavak & Baykal, 2012). In addition, complex binding of amorphous P occurs (Zhu & Alva, 1994), as well as precipitation to ß-tricalcium phosphate at higher pH (Gray & Schwab, 1993). Liming may stabilise clay soils by moderating swelling and shrinking processes. These are known to form cracks, which apart from enhancing fast macropore flow redistribute larger macroaggregates to smaller sizes (Grant & Dexter, 1990). Limited swelling is partly due to the suppressive effect of Ca^{2+} ions in the diffuse double layer of clay particles and the limited shrinkage is partly due to more uniform spatial arrangement of particles or structural entities in limed soil (Ledin, 1981). The neutral salt gypsum ($CaSO_4$) has a corresponding stabilising effect and aggregation may follow from the compressed diffuse double layer and increased rate of P adsorption (e.g. Uusitalo et al., 2012). This compression is a result of increased electrolytic concentrations, while the corresponding process after adding lime mainly is a result of dehydration and increased pH. Carefully mixing $Ca(OH)_2$ into soils with a high clay content can result in an effective pozzolanic (cementing) reaction, forming aluminium-silicate hydroxides, silicate hydroxides and/or aluminate hydroxides (Almukhtar et al., 2012). These reactions take place since clay soils have a high sum of silicon and aluminium oxides (He et al., 1995). The cementing effect has the potential to increase the resistance to dissolution of soil aggregates in water and thus reduce P leaching. The resistance is commonly analysed by the aggregate stability test and a gentle method demonstrating disruptive forces close to the field phenomenon is most appropriate (Oades & Waters, 1991). For soils with a high concentration of available P any reduced P leaching may also be the result of decreased P concentration in water caused by the above-mentioned P complex formation and increased adsorption of orthophosphates and phosphate ions. These P forms are included in the analytical method dissolved reactive P (DRP) (e.g. Haygarth & Sharpley, 2000).

Only two field experiments on the effect of structure liming on P leaching from Swedish clay soils have been carried out to date. The effects of drain backfilling with burnt shell-ash from Estonia when draining clay soils is currently being studied in Lithuania (Šaulys & Bastienė, 2007) and is to our knowledge the only ongoing long-term experiment monitoring drainage water quality. The aim of the present paper was to investigate any mitigating effect of structure liming on phosphorus losses from two agricultural clay soils with similar mineralogy but different clay and soil P status. Any effect on nitrogen leaching was simultaneously monitored. The following hypotheses were tested: After structure liming, (i) leaching losses of particulate phosphorus (PP) are significantly reduced; (ii) leaching losses of dissolved reactive P (DRP) are significantly reduced; and (iii) dissolution of soil aggregates by water disruption is significantly reduced.

Materials and methods

Field experiments with drained plots

The two field experiments with drained plots (Figure 1) were carried out in eastern Sweden, 20-30 km southwest of Stockholm city. Both sites have clay soil (Table 2) dominated by the 2:1 mineral illite. The Bornsjön experimental field, with a soil with high clay content (57-61% clay), is situated 20 km from the coast of the Baltic Sea, while the Wiad site is situated near the coast of the Baltic Sea and with a topsoil clay content which is significantly lower (22-29%). The experimental setup comprised 28 drained plots at Bornsjön and eight drained plots at Wiad. Number of replicates was four for each treatment, including structure liming, at both sites. The acid ammonium lactate-extractable P (P-AL) content in topsoil, determined according to Egnér et al. (1960), is 30-43 mg P-AL kg soil^{-1} at Bornsjön and more than three-fold higher (110-170 mg P-AL kg soil^{-1}) at Wiad. Due to this and to a high content of aluminium (Al) in Bornsjön soil, the degree of P saturation (DPS-AL), determined according to Ulén (2006), is very low at Bornsjön but quite high at Wiad (Table 2). In both field experiments, the soil was amended with structure lime, at Bornsjön in the form of burnt lime (CaO) and at Wiad in the form of a commercially available product with active lime in slaked form ($Ca(OH)_2$) (Table 1). Total amount applied, recalculated to active CaO, was 5 t ha^{-1} at Bornsjön and 2 t ha^{-1} at Wiad. At both sites, application took place under dry conditions in September (2007 at Bornsjön and 2011 at Wiad) and the structure lime was immediately and carefully cultivated into the topsoil in several directions with a good cultivator machine. The crop sequence after structure liming was spring barley, spring barley, oats, pea and spring barley at Bornsjön and spring barley and oats 2011/2013 after liming at Wiad. In the monitoring period 2006-2009 before liming at Wiad 2006-2007, grass ley was grown and ploughed under, followed by winter wheat.

At Bornsjön, water was sampled flow-proportionally in six agrohydrological years (1 July-30 June). A composite sample from each plot was stored for at most one week in an underground chamber (10-15^{o}C) before being sent to the laboratory for analysis. At Wiad, water flow was measured with tilting vessels and water samples were manually collected weekly when drainage occurred in two agrohydrological years. The samples were sent immediately to the Water Laboratory at the Department of Soil and Environment, Swedish University of Agricultural Sciences.

Experiments on leaching from topsoil (0-20 cm)

Twelve topsoil lysimeters, 20 cm in diameter and 20 cm high (plastic tubes with sharp iron rims) were extracted from Bornsjön unfertilised fallow, between the experimental plots (Figure 1), using a tractor-powered hydraulic double-action piston in October 2010. The monoliths were extracted under moist soil conditions, in order for the samples to be as undisturbed as possible. The soil monoliths were then trimmed by hand and stored under cold conditions (+4°C) until the start of the rain simulation experiments, which was within 3 months of sampling. The base of the monoliths was prepared and a special base cap fitted to each lysimeter. In the laboratory, eight lysimeters were amended with the same amount of structure lime as in the field experiment, with a theoretical dose of 5 t ha^{-1} as CaO, but using both pure burnt lime (4 lysimeters) and pure slaked lime (4 lysimeters) (Table 3). The lime was mixed into the soil, which was then reconsolidated for six months after the disturbance through repeated gentle wetting of the soil, followed by drying. Artificial rain events were applied to Bornsjön soil using a laboratory rain chamber, with a rain intensity of 8-10 mm h^{-1} and a distance to the soil surface of 1.5 m (Svanbäck et al., 2013) (Table 3). Three artificial rain events were applied for 3 hours per event, with 1-2 days drying between events. Since the soil had frequent macropores, no problems with ponding occurred and all water discharged rapidly through the soil. A total leached volume of 50-64 mm was discharged, equal to the theoretical pore volume of the Bornsjön soil. Corresponding experiments at this site on application of pesticides and bromide have demonstrated breakthrough curves equal to less than 25% of the theoretical pore volume, thus indicating preferential flow (Larsbo et al., 2013).

An undisturbed soil monolith of similar size was sampled from each of the eight experimental plots at Wiad (Figure 1) (4 structure-limed and 4 without lime) by pressing plastic tubes with sharp iron rims into the topsoil. Sampling took place on 17 October 2013, slightly more than two years after structure liming, which at that site had been followed by conventional tillage and cultivation of cereal crops. In the laboratory the soil monoliths were then similarly trimmed by hand, the base was prepared and a special base cap was fitted to each lysimeter. Simulated rainfall was applied using equipment described by Liu et al. (2012), applying a rain intensity of 32 mm $hour^{-1}$. After 2 or 2.5 hours leaching, a water volume corresponding to 77-90 mm discharge was collected. The procedure was repeated 3 times, with one day in between, with the soil under lid. Total drainage amount was nearly twice the theoretical pore volume of the Wiad soil. There were generally no problems with water ponding for the lysimeters from this site, with the water effectively discharging through the soil columns.

Soil aggregate tests

At the Bornsjön site, aggregates (mean 8-11 mm diameter) corresponding to in total 120 g field-moist soil per plot were collected on 27 August 2010, three years after structure liming. This large aggregates were chosen since they are more friable, weaker and have lower tensile strength than smaller aggregates (Utomo & Dexter, 1981). Consequently they can act as more sensitive indicators of aggregate strength than smaller aggregates. Each of 16 replicate samples from each treatment (4 per plot) was placed in a plastic cylinder (100 mm high, 102 mm in diameter and with 0.6 mm mesh at the bottom) and manually immersed three times in a beaker with 300 mL synthetic rainwater. The solute was then transferred to a 250-mL plastic bottle, which was shaken with a slow oscillating movement (90 revolutions min^{-1}) for 10 minutes. Content of soil particles in solution was then determined by turbidimeter (2100N Hach-Lange company, Düsseldorf, Germany) (Cryz et al., 2002). Large particles and fine aggregates larger than the claysize (<0.2 μm) were then allowed to settle for 4.5 hours (Sheldrick & Wang, 1933) and the content of dispersed clay still in solution was determined. The supernatant water was analysed for particulate P (PP) and dissolved reactive P (DRP).

Two years after structure liming (October 2013), topsoil samples (0-20 cm) from each of the eight plots (both limed and controls) at Wiad were collected and gently transported to the laboratory. Soil aggregates (8-11 mm, in total 120 g field-moist soil per plot) and dispersed clay content were measured after corresponding pre-treatment as for Bornsjön.

Water analysis

For all samples of drain water and leachate, pH was measured on the following day, DRP within two days and total P (TP) and total nitrogen (TN) within 4 days, after storage at +4^{o}C. TotP was analysed as soluble molybdate-reactive P after acid oxidation with $K_2S_2O_8$ (ECS, 1996), while DRP was analysed after pre-filtration using filters with pore diameter 0.2 μm (Schleicher & Schüll GmbH, Dassel, Germany) with the same colorimetric determination (ECS, 1996). Particulate P was estimated as the difference between TP before and after filtration of the water with the same filters. TN was analysed with a carbon nitrogen (CN) analyser (Shimadzu, GmBH, Duisburg, Germany).

Statistics

Coefficient of variance (CV) was used to reflect differences in discharge and leaching between different plots. To analyse differences in leaching between the different treatments in the field experiments, a general mixed model (SAS software Version 9.2) was used. To account for the time series structure of the data, correlations between measurements over time were modelled with a spatial power covariance structure (Littell et al., 2006). Factors for the spatial variations were used as covariates at Bornsjön, where they showed a distinct spatial pattern (Svanbäck et al., 2014). A significance level of α=0.05 was applied, including the p value associated with the F statistics of a given effect (p_r>F). Comparisons between lysimeters from the same site, which were all treated in the same simulated rain events, were estimated using basic two-sample test statistics as used in the aggregate studies.

Results

Field experiments

The narrow drain spacing (8 m) at Bornsjön resulted in high discharge (mean 500 mm yr^{-1}). At Wiad, discharge of water was low (mean 140 mm yr^{-1}), but the variation in discharge between different plots was somewhat larger (CV = 30%) than at Bornsjön (CV = 25%). Apart from less intensive tile drainage, the main reason for the low discharge at Wiad is probably the topography and location of the plots, in a gentle slope close to the bank of a stream recipient. Water may leach to the groundwater and thus bypass the tile drains before reaching the stream. Consequently, TP leaching from the Bornsjön control plots (mean 0.97 kg ha^{-1} yr^{-1}) was significantly higher than at Wiad (0.30 kg ha^{-1} yr^{-1}).

The TP leaching losses at Bornsjön (mean 1.0 kg ha^{-1} yr^{-1}) were significantly (p_r>F<0.002) lower from structure-limed plots than from the non-limed control in the six monitoring years. This was also the case for PP leaching, which was 83% of TP leaching. The PP leaching (mean 0.8 kg PP ha^{-1} yr^{-1}), which demonstrated similar large variance (CV = 75), was significantly reduced following structure liming at this site (p_r>F<0.002). In contrast, PP leaching losses were not significantly lower after liming at Wiad, when statistically evaluated with the model and taking the spatial variation in the three previous monitoring years into account. In that pre-period of three agrohydrological years (2006/2009), P leaching was similar to that in the control plots in 2011-2013. Leaching of DRP was on average 0.15 kg ha^{-1} yr^{-1} and comprised a much lower proportion of TP leaching in the drain water at Bornsjön than at Wiad (45%). In addition, the CV value for DRP leaching was low (20%) between plots at Bornsjön (Svanbäck et al., 2014) and did not change after structure liming. Leaching of DRP was 55% of TP leaching, with a mean value of 0.11 kg ha^{-1} yr^{-1} (CV = 70%), at Wiad and was significantly (p_r>F<0.002) lower from plots with structure liming than from the control plots in the two years monitored (Table 4).

The results were thus contrasting for P forms at the two sites. Only P leaching in PP form at Bornsjön and in DRP form at Wiad were significantly reduced following structure liming (Table IV). Simultaneously, there was a significantly lower P-AL content in the topsoil at Bornsjön (38-44 mg kg^{-1} soil) compared with Wiad (120-140 mg kg^{-1} soil). At Bornsjön, the pH in the topsoil showed no significant differences between structure-limed plots before (6.3 ± 0.1) and two or four years after liming (6.5 ± 0.3 both occasions). Moreover, there was no significant difference in topsoil pH measured before (7.2 ± 0.5) and after (7.3 ± 0.5) liming at Wiad at six months or two years after liming. The pH in drain water was similarly stable and with no significant differences between structure-limed and unlimed plots (Table IV).

Nitrogen leaching was nearly 30 kg ha^{-1} yr^{-1} at Bornsjön, but quite low from the fallow plots (6 kg TN ha^{-1} yr^{-1}). Nitrogen leaching was moderate (12-14 kg TN ha^{-1} yr^{-1}) at Wiad after cereals in the experimental period and lower in the pre-period, when ley was grown (Table IV). The leaching observed after cereals was of the same magnitude as is commonly found on the Swedish east coast (e.g. Kyllmar et al., 2006). The TN/TP ratio in drain water was mostly high, except for the fallow at Bornsjön (9:1) (Table 4).

Simulated rainfall events in the laboratory

For Bornsjön topsoil to which structure lime had been added in the laboratory, the differences in topsoil P-AL and DPS-AL between structure-limed and unlimed plots were non-significant after treatments. However, following application of simulated rain, there was a significant reduction in PP leaching (Table 5), as also observed in the field experiments. The DRP concentration was only estimated by difference between TP and PP**,** since the analysis was disturbed by high pH. Moreover, only small amounts of DRP were measured before liming and the amounts were only marginally lower (0.01-0.02 kg ha^{-1}) and not significantly different from those in lysimeters amended with structure lime.

There was no significant difference in topsoil P-AL and topsoil DPS-AL between structure-limed and unlimed plots at Wiad (Table V). However, application of simulated rainfall to these lysimeters resulted in a significant reduction in leaching of TP. Similarly to the field studies (Table 4), for the lysimeters from Wiad the P reduction was statistically significant for DRP, but not for PP

Aggregate stability tests

The large-sized soil aggregates (8-11 mm) from Bornsjön showed more resistance to dissolution in water after structure liming (Figure 1a), irrespective of whether the soil had been conventionally ploughed (control) or only shallow tilled (an additional treatment given in Figure 1a). The large-sized soil aggregates from the field plots at Wiad amended with structure lime similarly displayed significantly greater resistance to dissolution in water than aggregates from plots with no such amendment. This was apparent both before and after the clay particles were allowed to settle (Figure 1b). After settling, the supernatant with dispersed clay colloids from Wiad demonstrated significantly lower P concentrations in both PP and DRP form after structure liming and also significantly lower turbidity values than the supernatant from Bornsjön (Table 4).

Discussion

The two field experiments represented sites with high (Bornsjön) and rather moderate (Wiad) TP losses compared with the Swedish average of 0.4 kg TP (and 0.2 kg DRP ha^{-1} yr^{-1}) (Ulén et al., 2007). At Bornsjön, where the soil has a high clay content, most losses took place in PP form while DRP losses were moderate. This is similar to findings for drained Finnish soils with a high clay content (Uusitalo et al., 2001). At Wiad the moderate leaching losses of PP and DRP via tile drains is a consequence of the low water discharge, while flow-weighted mean concentration was quite high (0.2 mg TP L^{-1}). The two sites compared also represented soils with very high (Bornsjön) and moderate (Wiad) topsoil clay content, but only the Bornsjön soil demonstrated significant effects of structure liming in reducing PP leaching. In addition, the two sites represented soil with a low (Bornsjön) and a high (Wiad) level of AL-extractable P and displayed contrasting effects on DRP leaching after structure liming. Leaching of DRP was only significantly lower for structure-limed soil compared with the control for the Wiad site, with its high topsoil P status and relatively high (17-18%) DPS-AL value in the entire subsoil down to the tile drains. One explanation for this could be formation of Ca-P complexes or Ca-precipitates at Wiad owing to a presumed high concentration of DRP in the soil water solution and the high pH after liming. Such types of reactions have been indicated to take place in a clay soil with a history of pig manure addition (Ulén & Snäll, 2007).

There are concerns that a high pH can suppress P availability and reduce plant uptake of P, especially in coarse-textured soils (e.g. Murphy & Stevens, 2010). However, pH in the field experiments with structure liming seemed to have equilibrated with the clay in the soil, since there were no significant differences in soil pH between structure-limed and unlimed plots at Bornsjön 2 years after liming and at Wiad 0.5 years after liming. Furthermore, quite similar pH was observed in the drainage water from the limed plots compared with the unlimed plots at both sites (Table 4), as well as in leachate water from Wiad (Table 5). A general increase in yield on limed plots has been reported at Bornsjön, especially in the first year after liming (Svanbäck et al., 2014). This was probably an indirect effect, through improved soil structure, but the crop (barley) still had a high P content (0.3% of dry weight), which was similar to the P content in barley crops from non-limed soils. The yields of spring barley and oats at Wiad showed no significant differences in either year after liming compared with the control. Recent tests on seeding of winter wheat three days after structural liming showed good results in the field near the Bornsjön experimental area (data not shown).

Gypsum application causes compression of the electronic double layer and clay colloids flocculate as lime, but as a result of the increased Ca^{2+} concentration and electric conductivity (Haynes & Naidau, 1998), and not the increased pH. Any reduction in P by precipitation should be minor using this neutral salt. However the cementing effect may be limited in time and significant effects on P leaching have been reported to end after 2.5 years (Uusitalo et al., 2012). Relatively short-term effects for this and other amendments such as water treatment residuals and coal combustion slag have also been demonstrated in laboratory experiments with simulated rain (O'Connor et al., 2005).

Results obtained in lysimeter studies with concentrated simulated rainfall events in the laboratory should be viewed with caution. They may be regarded more as prolonged water extraction, which dissolves high amounts of DRP in the water-saturated soil. In all lysimeter experiments, water flow is also forced into a straighter vertical direction than would occur in the field and horizontal transport of PP, which typically occurs in field conditions, is prevented. Topsoil studies may also give less realistic results due to the critical role of the subsoil (e.g. Sinaj et al., 2002). At Wiad, leaching of DRP may also occur from the subsoil with its relatively high 18% DPS-AL value (Table 2). However, the DRP/TP ratio in leachate from the Wiad lysimeter was high (75-80%) and the reduction in DRP was significant, as found with drainage water from the experimental plots.

After application of the lime in the present field experiments, there was visible mixing with the soil, most probably facilitated by subsequent tillage, harrowing and growing crops in the present field experiments. This also illustrates the importance of soil microorganisms and plant roots in the formation and stabilisation of soil aggregates (Oades, 1993). The settled clay particles from Wiad soils might contain more P than the colloids in suspension, since the P concentration was lowered even more than the turbidity (Table 6). The settled material might include biofilms, root exudates, organic macromolecules and other traces of biological glue in a corresponding way to water sediment deposits (e.g. Droppo, 2001; Williams et al., 2008). There is an urgent need for comparable field and laboratory investigations for a better mechanistic understanding of the formation and dissolution of soil aggregates.

Due to the necessity to reduce the P load and N load in the Baltic Sea area simultaneously, actions on arable land should focus on soil structure improvements rather than converting arable land to fallow (Svanbäck et al., 2014). In drain water from structure-limed plots at Bornsjön and Wiad, the N/P ratio was 60-110 but only 9 in the water from the fallow plots (Table 4). The latter is close to the level which can promote growth of N-fixing algae in e.g. the brackish water of Stockholm archipelago (Boesch et al., 2006). However, at Wiad the TN/TP ratio in the drain water was higher (20:1) after growing grass, and under such conditions the presence of N-fixing blue-green algae in receiving water is less plausible.

Conclusions

Dissolution of large macro-aggregates in water was significantly reduced after liming of two soils with a high and very high clay content, respectively. In view of the generally high PP losses from the Bornsjön soil, it could be concluded that at this site efforts to combat eutrophication of the nearby Baltic Sea should concentrate on mitigation of P losses, including P in particulate form (PP). Structure liming was demonstrated to reduce PP losses for at least six years at this site. Results from Wiad highlight the importance of simultaneously reducing leaching of P in dissolved reactive (DRP) form from soils with a high risk of DRP leaching, which was shown to be achieved by structure liming. However, more field studies are needed to clarify the effect of structure liming on P leaching as a function of available soil P content alone, and in combination with different soil clay contents. Such studies should be of a long-term nature, since lime distribution into the soil and soil aggregate formation by biological activities take time.

Acknowledgements

Thanks are expressed to Hans Tallberg for hosting the experiment and taking water samples, and to Stefan Ekberg, Annelie Mejbert, Ana Maria Mingot Soranio and Nargish Parvage for analytical work. Financial support was provided by the Swedish Farmers’ Foundation for Agricultural Research (SLF).

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Table 1. Experimental set-up in the Swedish field experiments with structure liming, including number of agrohydrological years with monitoring before and after treatment. Each treatment was represented by four replicate plots. At Bornsjön there was a stabilisation year after drainage

	Bornsjön[a]	Wiad[b]
Plot size (m)	24x20	55x60
Tile drain spacing (m)	8	14
Lime amendment	CaO	$Ca(OH)_2$
Time of application	26 September 2007	13 September 2011
Number of replicates	4	4
Load equivalent to CaO (t ha^{-1})	5	2
Control	No lime, no P fertiliser	No lime, no P fertiliser
Pre-period	2006/2007	No lime and P fertiliser
Monitoring before treatment	1 year (2006/2007)	3 years (2006/2009)
Monitoring after treatment	6 years (2007/2013)	2 years (2011/2013)

[a] Site description and results in Svanbäck et al. (2014)
[b] Site description in Gustafson & Torstensson (1988)..

Table 2. Soil texture and soil phosphorus (P) characteristics of the field plot experiments at Wiad and Bornsjön, including degree of P saturation in acid lactate extract (DPS-AL)

	Bornsjön			Wiad		
Parameters	0-23	23-60	60-90	0-23	23-60	60-90
pH (H_2O)	6.3	6.6	7.0	7.1	-	-
Clay (%)	59	61	61	26	37	53
Silt (%)	40	38	39	43	39	36
Sand (%)	1	1	0	32	24	12
Organic matter (%)	3.9	1.1	0	2.0	1.2	0
P-AL (mg kg soil^{-1})	49	24	16	143	92	93
Al-AL (mmol kg soil^{-1})	16	13	14	6	9	9
Fe-AL (mmol kg soil^{-1})	6.1	5.3	7.5	6	8	8
DPS-AL (mole-based %)	7	4	2	36	17	18

Table 3. Experimental set-up in laboratory experiments with simulated rain events. Each treatment was represented by four replicate topsoil from each of the two Swedish field sites

	Bornsjön	Wiad
Lysimeter sampling year	2010[a]	2013[b]
Amendment	CaO and $Ca(OH)_2$	$Ca(OH)_2$
Load expressed as CaO (t ha^{-1})	5	2
Application + incorporation into topsoil	To lysimeters in laboratory	Before, in the field

[a] In untreated fallow. After mixing in the amendments, the soil was reconsolidated for 6 months.
[b] Two years after application in the field, towards the end of the field leaching study

Table 4. Mean annual discharge, water pH and leaching losses of total P (TotP), particulate P (PP), and dissolved reactive P (DRP), total percentage of DRP/P total nitrogen (TN) and TN/TP ratio in the experimental plot experiments (4 replicates). Treatments were: at Bornsjön structure liming (CaO), a control (without liming and P fertilising) and unfertilised fallow (Fallow); at Wiad structure liming ($Ca(OH)_2$), a control (without liming) and a pre-period partly with fallow. All treatments without fallow were conventionally ploughed.

	Bornsjön[a]			Wiad		
Period	2007/2013			2011/2013		2007/2009
Treatments	CaO	Control	Fallow	$Ca(OH)_2$	Control	Pre-period
Discharge (mm yr^{-1})	505	546	460	137	142	140
pH in water	7.1	6.8	7.1	7.1	7.0	-
TP (kg ha^{-1} yr^{-1})	0.59**	0.97	0.77	0.13**	0.30	0.29
PP (kg ha^{-1} yr^{-1})	0.46**	0.82	0.60	0.07	0.14	0.14
DRP (kg ha^{-1} yr^{-1})	0.13	0.15	0.17	0.08**	0.15	0.11
DRP/TP (%)	20	15	20	50	50	40
TN (kg ha^{-1} yr^{-1})	30	29	6**	14	12	5
Ratio TN/TP	60	40	9	110	40	20

[a] For more details, see Svanbäck et al. (2014).

**Significantly lower leaching losses from 4 limed lysimeters compared with 4 control ($p_r > F < 0.002$).

Table 5. Mean topsoil lysimeter characteristics, discharge and leaching losses of total P (TP), particulate P (PP) and dissolved reactive P (DRP) after simulated rainfall in the laboratory

	Bornsjön laboratory lysimeters[a]			Wiad laboratory lysimeters	
Treatments	CaO	$Ca(OH)_2$	Control	$Ca(OH)_2$	Control
Soil characteristics					
Soil pH	9.5	8.8	5.9	7.5	6.5
P-AL (mg kg soil^{-1})	38	41	44	120	140
Al-AL (mmol kg soil^{-1})	16	17	15	7	6
Fe-AL (mmol kg soil^{-1})	6.6	6.8	4.8	6	7
DPS-AL (mole-based %)	6	9	5	30	37
Lysimeter leaching					
Discharge (mm)	68	68	66	175	179
Water pH	8.5	8.4	7.1	7.3	7.0
TP (kg ha^{-1})	0.03**	0.04**	0.15	0.11**	0.13
PP (kg ha^{-1})	0.02**	0.03**	0.13	0.03	0.03
DRP (kg ha^{-1})	0.01[a]	0.01[b]	0.02	0.08**	0.10
DRP/PP (%)	25	25	10	75	80

**Significantly ($p<0.05$) lower leaching compared with unlimed control.

[a] For more details, see Ulén et al. (2012).

[b] Estimated values, since high pH disturbed DRP analysis.

Table 6. Mean concentrations of turbidity (nephelometric turbidity units, NTU), total P (TP), particulate P (PP) and dissolved reactive P (DRP), with standard deviation (SD), after sedimentation of dispersed particles of larger (8-11 mm) aggregates in tests on samples from Wiad and the ratio between the two treatments

Treatment	Turbidity (NTU)		TP (mg L^{-1})		PP (mg L^{-1})		DRP (mg L^{-1})	
	Mean	SD	Mean	SD	Mean	SD	Mean	SD
Structure-limed	780**	120	0.24**	0.11	0.18**	0.10	0.05**	0.01
Control	1300	260	0.60	0.07	0.48	0.05	0.10	0.02
Ratio	0.6		0.4		0.4		0.5	

** Significantly lower concentrations from limed plots ($p<0.05$) compared with unlimed soil.

FIGURE CAPTIONS

Figure 1. Map of Sweden and the coastal area south of Stockholm where the two experimental fields are situated. Sampling sites of topsoil lysimeters are indicated (dots) relative to the experimental plots (squares) to the right.

Figure 2a) Relative turbidity after settling of dispersed particles in samples taken from Bornsjön in autumn 2010. Control (=100, not structure-limed) compared with structure-limed plot (SL). SL and control were conventionally ploughed but at Bornsjön relative turbidity after shallow tillage with a cultivator is included for comparison (diagram based on Ulén et al., 2012). 2b) Relative turbidity after settling of dispersed particles in samples taken from Wiad in October 2011.