Soil texture-adapted structure liming for efficient reduction of phosphorus leaching

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Background and Objectives

Phosphorus (P) impairment of surface waters remains a concern worldwide, and agriculture is one of the contributors (Sharpley et al., 2015). Swedish arable land amounts to 2.5 million hectares of which about 10 % has highly enriched soil P contents due to heavy fertilization in the 1970s and 1980s (Andersson, 1986). About 5 % (125 000 ha) can be classified as arable land with a high P leaching risk. According to recent estimates, 45 % of anthropogenic phosphorus (P) losses originate from agriculture (Övergödning och läckage av växtnäring - Jordbruksverket.se). Thus, finding mitigation measures that effectively reduce P leaching is a high-priority task (www.miljomal.se/). Although different measures have been taken to minimize P losses from arable fields during recent years, many questions about their efficiency remain. One of these is how structure liming, which affects soil aggregation by cation exchange, lime carbonation, and pozzolanic reactions (Bell, 1996) will affect losses of particulate P over time. Berglund (1971) found that $Ca(OH)_2$ significantly improved the structure of arable clay soils. Recently, Svanbäck et al. (2014) and Ulén & Etana (2014) investigated the benefit of $Ca(OH)_2$ to mitigate P leaching in two Swedish soils. Blomquist (2021) investigated the effects of structure lime (mixture of $Ca(OH)_2$ and $CaCO_3$) on soil aggregate stability in different parts of Sweden and found that there was a significant relationship between aggregate stability and the rate of lime applied. This project investigated 1) phosphorus leaching in a field trial, and 2) the amount of $Ca(OH)_2$ required to significantly reduce soil particle leaching in soils with different clay content. The objectives of this project were:

1. To quantify the effect of slaked lime on phosphorus losses from arable clay soil;
2. To match the amount of slaked lime to the soil clay content for efficient reduction of phosphorus leaching.

The hypothesis we tested was:
Significant reduction of phosphorus leaching from arable land could be achieved by matching the amount of $Ca(OH)_2$ to the clay content of the soil.

1. Materials and methods

1.1 Field trial

A field trial has been underway since 2019 on a soil with a clay mineral composition typical for east-central Sweden. The field trial is located about 15 km south of Uppsala at Krusenberg (59°43′0″ N; 17°41′21″E). The trial was established in 2010 on a clay loam soil (30 % clay) to study the effect of grassed buffer strips on phosphorus leaching. The structure liming project was started after the termination of the earlier project. The design consists of 12 separately drained plots. Each of the plots is drained at the center by laying a drainage pipe at 0.9 m depth. The internal flow between the plots is protected by vertically inserted plastic sheets from 0.25 m to 0.90 m depths. Drainage water is led to an automated measuring station, where flow-proportional subsamples are taken (Larsbo et al., 2016).

Experimental design

The experimental field has 12 separately drained plots, and the plot area is 72 m^2 (6 m X 12 m). Two adjacent plots will make up a block, totally six blocks. One plot was amended with $Ca(OH)_2$ and the other used as a control (no amendment). Totally, we have six replications of each treatment. In early August 2019, the site was cleared off grass and cultivated to a depth of 15 cm. Later, $Ca(OH)_2$ was applied at a rate of 5.0 Mg ha^{-1} and mixed thoroughly within the cultivated depth using a chisel plough. In Sweden, the common rate of structure lime (80-85 % $CaCO_3$ +15-20 % $Ca(OH)_2$, is 8 Mg ha^{-1}. We used a greater dose $Ca(OH)_2$ than that because earlier measurements showed high particulate phosphorus leaching from this field. During the experimental years, winter wheat, peas, and Barley were grown on the field.

Sampling and analyses of drainage water

In this field trial, we measured phosphorus losses only in drainage samples since surface runoff was too little as the soil was highly permeable. Flow proportional drainage water was sampled in an automated measuring station. Chemical analyses were carried out by an accredited water laboratory at the Department of Water & Environment, SLU. The samples were analyzed for dissolved orthophosphate (ISO15923 – 1:2013), total phosphorus (SS – EN ISO 6878:2005), total organic carbon (SS - EN 1484), turbidity (SS - EN ISO 7027: 1929) and pH (SS – EN ISO 10523-2012).

1.2 Laboratory test: rate of $Ca(OH)_2$ needed for amending soils with different clay contents

To broaden the results of the field experiment, we tested the effect of different rate of $Ca(OH)_2$ on soils collected in the topsoils of nine sites (Table 2) as follows:

Table 1. $Ca(OH)_2$ on nine soils with different clay content

Site	Clay content (%)	Rate of $Ca(OH)_2$, Mg/ha
Kleva, Skåne	11	0; 2; 3
Daggan, Skåne	16	0; 2; 3; 5
Ulleråker 1, Uppland	20	0; 2; 3; 5
Lilla Böslid, Halland	30	0; 2; 3; 5; 8
Hammarby alé	26	0; 2; 3; 5; 8
Krusenberg, Uppland	34	0; 2; 3; 5; 8
Ulleråker 2	36	0; 2; 3; 5; 8
Förslöv, Skåne	51	0; 3; 5; 8; 11
Långtora, Uppland	64	0; 3; 5; 8; 11

Fig.1. Incorporation of slacked lime after spreading.

Table 2. Textural composition of the soils used for the laboratory test and turbidity in leachates

Site	clay	Silt	Sand	OM	Turb 1*	Turb 2*
Kleva	11	35	54	2.0	428	334
Daggan	16	37	47	2.1	135	101
Ulleråker 1	20	35	45	4.0	1504	1495
Hammarby alé	26	60	14	3.7	634	599
Lilla Böslid	31	46	23	1.1	1232	1225
Krusenberg	34	37	29	1.4	766	745
Ulleråker 2	36	27	37	2.4	748	736
Förslev	51	40	15	4.0	186	159
Långtora	64	34	2	7.8	1297	1281

* Turb 1- turbidity measured immediately after shaking sample; Turb 2 – turbidity measured after sedimentation according Stock´s law.

Soil samples were collected when the soil water content was less than field capacity, stored in a cold room and the clods were carefully broken manually into smaller ones and sieved to collect 1-8 mm aggregates. The amount of $Ca(OH)_2$ to be applied to one kg soil was determined by considering dry bulk density of each site in 20 cm soil depth. Each treatment was replicated four times and the treated soils were incubated for at least six months. Then, the incubated samples were carefully packed into mini-lysimeters (15 cm in height & 20 cm in diameter). The samples in the mini-lysimeters were exposed to rain simulation (10-12 mm/h) to collect percolating water (Etana et al., 2009). Rain simulation was first applied for ten minutes to homogenously wet the samples. Then, the samples were kept covered for 24 h, and rain simulation continued for 16 hrs while percolated water was collected in plastic jars. Then the samples were shaken to homogenize, and 250 mL was taken to measure turbidity (Czyz & Dexter 2015) as an estimator of the soil particle concentration in the leachates.

1.3 Statistics

For the field experiment, t-test was used to compare the data from the amended plots and control plots. For the laboratory tests, we used multiple regression analysis using lime and clay as regressor and turbidity as a response. The result of the statistical analyses is given in appendix 1.

2. Results and Discussion

2.1 Results of the field trial

Fig. 2 shows total phosphorus and dissolved reactive phosphorus in drainage water. We obtained sufficient samples from the drainage pipes on ten occasions during the experimental years. On average, leaching of total phosphorus (Tot-P) and dissolved reactive phosphorus (DRP) was decreased by 75 % and 25 %, respectively. Although the difference between the amended and control plots has not been significant on several occasions, the trend that liming gave lower phosphorus losses has been constant (Fig. 3). The decrease of DRP by liming might be due to phosphorus fixation as a result of rise in soil pH (Penn & Camberato, 2019; Norberg & Aronsson, 2022). The soil pH was increased from 7 to 8 as measured two months after liming but it was dropped to the original value in spring 2020. In general, pH was greater in leachates than in the soil (appendix 1) and the difference between limed and control plots was not statistically significant. Crop yield was lower by 3 % in limed plots in 2020 but no significant difference was measured in later years. Turbidity, which is a measure of soil particle concentration in leachates, is given in Fig. 4. On average, liming reduced soil losses by 55 % and the difference between total soil loss and clay loss was very low indicating that leaching through drainage pipes contained mainly fine soil particles. Improving soil aggregation and minimizing soil disturbance is therefore important to protect phosphorus losses to surface wasters. Fig. 5 shows the relationship between total phosphorus and turbidity ($R^2 = 0.72$) indicating that turbidity can be used as a surrogate method to estimate phosphorus losses in clay soils (Spackman Jones, 2011). In this trial, leaching occurred mainly outside the vegetation period so arable fields should be kept undisturbed during this time.

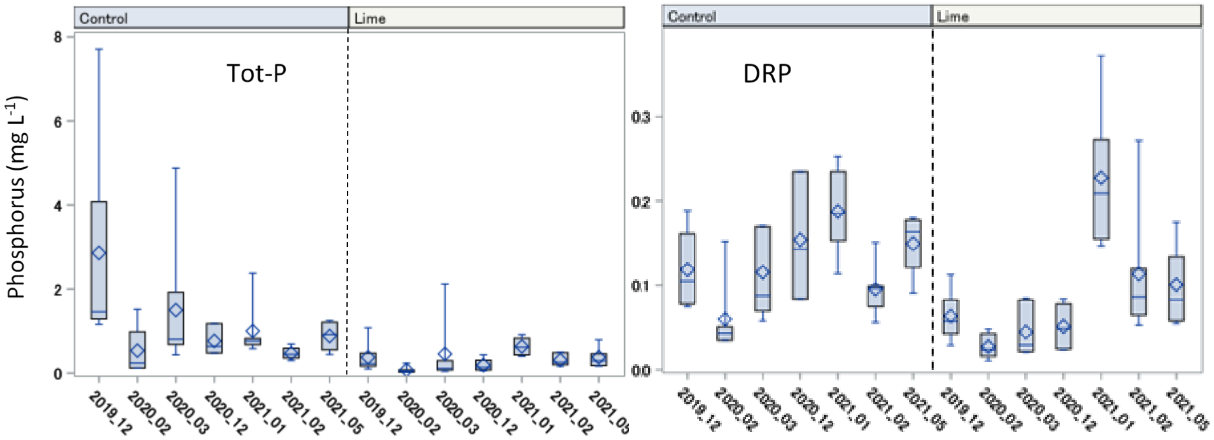

Fig. 2. Total phosphorus (left) and dissolved reactive phosphorus (right) in limed and control plots.

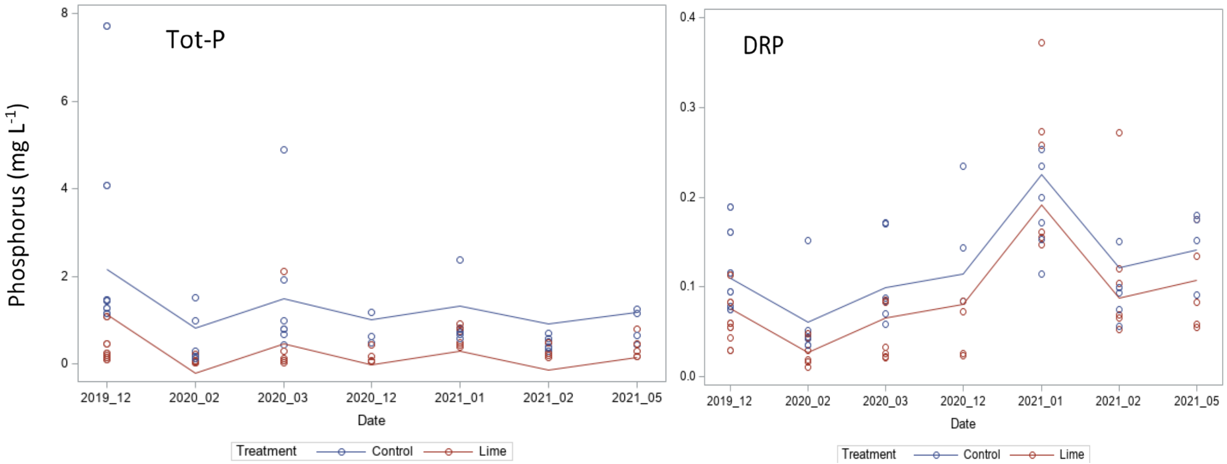

Fig. 3. Trends of phosphorus leaching during the experimental years.

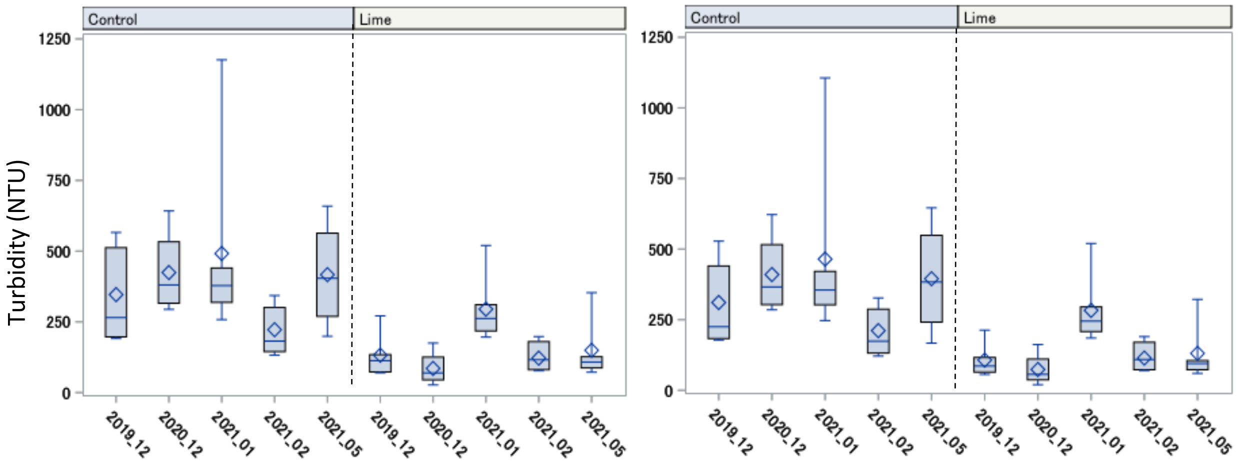

Fig. 4. Total turbidity (left) and clay turbidity (right) in limed and control plots. Total turbidity was measured immediately after shaking the samples, and clay turbidity was measured after sedimentation according to Stock´s law.

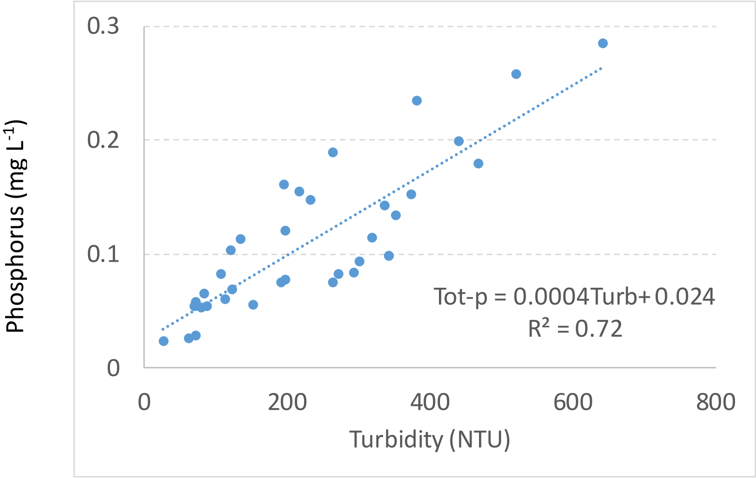

Fig. 5. Phosphorus in leachates as a function of turbidity.

2.2. Laboratory test - rate of $Ca(OH)_2$ needed to amend soils with different clay contents

Fig. 6 shows turbidity index of nine soils as amended with different clay contents. Here, turbidity index (TI) is defined as the ratio of turbidity of amended samples to the turbidity of the control sample, which is given in Table 2. TI of the control sample is 1 and that of amended samples is less than 1 if soil aggregate was improved by liming. As we hypothesized, the required of $Ca(OH)_2$ to reduce soil losses with leaching water increased with the clay content of the soil. However, the required amount was not directly proportional to the clay content of the soil. In addition to the clay content, other factors such as management legacy, soil water content at the time of incorporation, and soil pulverization level during mixing may have significant effects. Blomquist (2021) reported that initial pH, soil organic content, and type of clay minerals have a significant influence on the structure liming effects. Our laboratory test showed that up to 2 Mg ha^{-1} $Ca(OH)_2$ significantly reduced particle losses light clay soils. However, in soil samples from Daggan ((clay content =16 %), the difference in turbidy of the control and limed samples was small. The samples from this site were taken in a second-year grass lay, which improved soil aggregation. Thus, the difference in soil loss between the control and limed samples diminished. Application of 2 Mgha^{-1} reduced soil particle losses in medium clay soils by 35-55 %. The corresponding reduction by 3 Mgha^{-1} was 60-70 %. This rate reduced soil particle losses in Långtora samples (clay content = 64 %) by approximately 50 % and increasing the application rate to 5 Mgha^{-1} almost stopped particle leaching. Our result is in line with that of Blomquist (2021), who found a clear dose-response effect. A rate greater than 5 Mg ha^{-1} $Ca(OH)_2$ did not result in a significant reduction. In general, structure liming is recommended in soils with greater than 15 % clay but in Kleva (clay =11 %), 2 Mg ha^{-1} $Ca(OH)_2$ significantly reduced soil particle leaching. In this laboratory test, we carefully prepared small soil aggregates (≤ 8 mm in diameter) and mixed them with lime when the soil water content was less than field capacity. Although the mixing in the field was in much bigger soil clods, the results we obtained for Krusenberg (clay content =34 %) in the laboratory test and field trial were quite similar. The common application rate of structure lime is 5-8 Mg ha^{-1}, which corresponds to 1-1.5 Mg ha^{-1} $Ca(OH)_2$. The current recommended application rate should be to achieve a high leaching reduction in medium and heavy clay soils. It is wise to apply more lime to a leaching-prone than to amend the whole arable field.

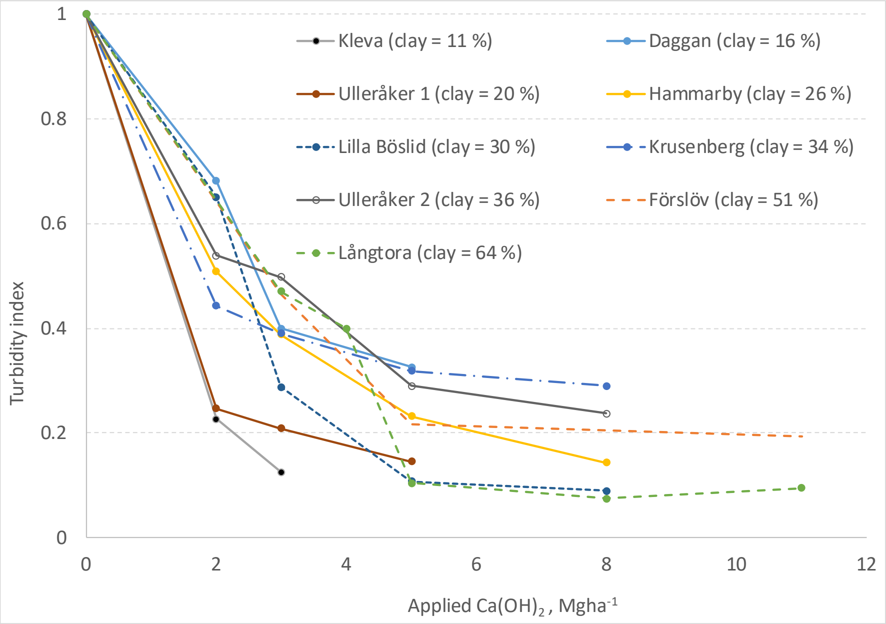

Fig. 6. Turbidity of nine soils amended with different amount of Ca(OH)$_2$.

3. Conclusion

1. Our field trial showed that amendment of Swedish clay soils with Ca(OH)$_2$ is effective in reducing soil and phosphorus losses to surface waters.
2. The laboratory test showed that approximately 2 Mg ha^{-1} Ca(OH)$_2$ is required to significantly reduce particle losses in light clay soils. For medium and heavy clay soils 3 Mg ha^{-1} Ca(OH)$_2$ or more is required. This amount is much greater than the common dose in practice. It is wise to apply a sufficient dose to a leaching-prone area than to apply an inadequate amount to the whole field.

4. References

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Appendix 1. Results of statistical analyses. The methods used were General Linear Model and means comparison applying Tukey's studentized range test

Date	Treatment	Tot-P	DRP	Nitrate-N	Tot-N	TOC	Turb 1	Turb 2	pH
Dec 2019	Control	2.90	0.12	16.1	18.7	38.2	346	310	7.5
	Limed	0.39	0.07	10.8	15.6	8.61	132	107	7.5
	Pr>F	0.003	0.001	0.001	0.007	0.003	0.03	0.03	ns
Feb 2020	Control	0.54	0.06	12.0	13.1	8.53			8.2
	Limed	0.08	0.03	11.1	13.3	3.70			8.0
	Pr>F	ns	ns	ns	ns	ns			ns
Mar 2020	Control	1.50	0.12	11.6	13.9	20.0			8.0
	Limed	0.46	0.4	10.8	13.3	8.68			7.9
	Pr>F	ns	0.04	ns	ns	ns			ns
Dec 2020	Control	0.77	0.15	6.37	8.13	13.4	424	410	7.6
	Limed	0.19	0.05	10.5	11.7	6.75	85.0	74.1	7.7
	Pr>F	0.04	ns	ns	ns	0.04	0.007	0.006	ns
Jan 2021	Control	1.00	0.19	3.40	5.19	15.8	464	421	7.4
	Limed	0.64	0.23	4.37	5.81	12.9	295	284	7.5
	Pr>F	ns	ns	ns	ns	ns	ns	ns	ns
Feb 2021	Control	0.47	0.11	3.99	4.44	9.27	222	211	7.6
	Limed	0.31	0.09	5.13	5.7	7.35	122	114	7.6
	Pr>F	ns	ns	ns	ns	ns	0.002	0.002	ns
May 2021	Control	0.88	0.15	0.86	1.64	14.2	416	395	7.9
	Limed	0.38	0.10	1.22	2.06	9.96	149	131	7.9
	Pr>F	ns	ns	ns	ns	ns	ns	ns	ns
Mean	Contol	1.43	0.12	9.66	11.1	20.4	350	349	7.7
	Limed	0.36	0.09	7.70	10.3	8.34	157	143	7.7
	Pr>F	0.001	0.01	ns	ns	0.001	0.001	0.001	ns

ns =statistically not significant;

Tot-P = Total phosphorus; DRP = Dissolved reactive phosphorus; TOC = total organic carbon; Nitrate-N = mineral nitrogen; Tot-N = sum of organic and mineral nitrogen; Turb 1= Turbididity as measured without sedimentation; Turb 2 (clay turbidity) = Turbidity as measured after sedimentation of particles > clay size according to Stock´s law.