

Soil characteristics and tillage can predict the effect of 'structure lime' on soil aggregate stability

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ABSTRACT

Context. In Sweden, mixtures of 80–85% ground limestone and 15–20% slaked lime (hereafter, 'structure lime') are used in subsidised environmental schemes to improve aggregate stability and mitigate phosphorus losses on clay soils. **Aims.** This study investigated different rates of structure lime application and soil variables on aggregate stability on clay soils, and whether soil properties can predict aggregate stability following structure liming. **Methods.** Increasing application rates of 0–16 t ha⁻¹ of structure lime (SL0, SL4, SL8 and SL16) were tested in 30 field trials in Sweden. Soil aggregates (2–5 mm) were collected 1 year after liming and subjected to two rainfall events in a rain simulator. **Key results.** Leachate turbidity after the second simulated rainfall event decreased significantly (13% and 20%, respectively, in SL8 and SL16) compared with SL0, indicating improved aggregate stability. There was a near-significant interaction ($P = 0.056$) between treatment and trial. Grouping by initial pH_(H₂O) (range 6.2–8.3), clay content (10–61%), soil organic matter content (SOM, 2.2–7.1) and clay mineralogy (SmV index, 0.2–3.8) revealed different effects on turbidity. Discriminant analysis of soil characteristics and four tillage variables correctly classified the outcome for 27 of the 30 trial sites. **Conclusions.** Results show that structure liming can improve aggregate stability 1 year after liming, and can thereby prevent particulate P losses from soils with high clay and SOM content, low SmV index and low initial pH. The discriminant analysis also showed the importance of tillage for the outcome of structure liming. **Implications.** Clay soil characteristics such as SOM and pH significantly affected aggregate stability after structure liming.

Keywords: aggregate stability, clay content, clay mineralogy, pH, phosphorus losses, SOM, structure lime, turbidity.

Introduction

Acidification of soils is a process with both natural and human-made causes (Filipek 2011). Liming is a well-established global practice to counteract acidification and ameliorate acidic soils (Frank *et al.* 2019). Moreover, liming indirectly affects crop growth through the bioavailability of plant nutrients (Goulding 2016) and in the long-term, can increase crop yield (Haynes and Naidu 1998). In long-term liming trials at Rothamsted and Woburn in the UK, yields of most crops, with the exception of oats and potatoes, responded positively to the higher pH achieved by liming in the pH range 4.4–8.0 (Holland *et al.* 2019). Similarly, a recent survey of long-term field trials combined with an intensive soil monitoring programme in Sweden revealed that, among manageable yield variables studied, pH had the greatest potential to positively affect crop yield, even at values >6.5 (pH_(H₂O)), indicating a need for revision of the Swedish pH recommendations (Kirchmann *et al.* 2020).

Liming also affects soil physical conditions in clay soils (Holland *et al.* 2018) with different soil physical changes reported in the literature. Agricultural lime (CaCO₃) has been found to decrease bulk density and increase pore continuity (Frank *et al.* 2020), and has also been found to decrease soil penetration resistance and increase hydraulic conductivity (Kirkham *et al.* 2007). However, Frank *et al.* (2019) found that soil physical improvements, such as increased plant-available water capacity, recorded 6 months after liming were absent

12 months after liming, when the soil structure collapsed after soil tillage by ploughing and chiselling.

Application of CaO or Ca(OH)_2 either in pure form or in mixtures with CaCO_3 can be a way to achieve more long-lasting benefits. At 18°C , the water solubility of Ca(OH)_2 is approximately 130-fold higher than that of CaCO_3 (Blomquist et al. 2018). Therefore, use of Ca(OH)_2 can be expected to speed up cation exchange compared with using only CaCO_3 for liming. With increasing concentrations of Ca ions in the soil matrix, the water film surrounding clay minerals can shrink sharply, to only one-tenth of the original size; i.e. down to $0.001\ \mu\text{m}$ (Assarson 1977). The resulting particle agglomeration when clay mixed with lime becomes granular is easily observed (Choquette et al. 1987).

Cation exchange is a reversible process and besides more rapid cation exchange, the use of CaO or Ca(OH)_2 also leads to other strengthening processes through carbonation and pozzolanic reactions (Eades and Grim 1960). In soil, CaO will react with pore water forming Ca(OH)_2 accompanied by the release of heat in an exothermic reaction (Beetham 2015). In carbonation, lime in the form of Ca(OH)_2 reacts with carbon dioxide from the air, producing CaCO_3 (Witt 2002). This was also detected by Ledin (1981) using scanning electron microscopy (SEM) as cutans on microaggregates 8 years after liming a field with CaO . Pozzolanic activity is considered to be the main process ensuring good soil-lime stabilisation (Choquette et al. 1987) and involve dissolution of the silicate tetrahedra and aluminate octahedra of clay minerals in the highly alkaline environments ($\text{pH} > 12$) created when CaO and/or Ca(OH)_2 is applied (Åhnberg 2006; Al-Mukhtar et al. 2010). The pozzolanic reactions can result in a more permeable microstructure (Al-Mukhtar et al. 2012) but also improved soil strength (Kavak and Baykal 2012). Non-carbonated lime as binders are widely used for improvement of engineering properties of clay fills, as described by Beetham et al. (2015) for example, has also been tested for stabilisation of backfill in earth graves (Zimmermann et al. 2016, 2019) and drainage trench backfill (Šaulys and Bastienė 2006). Use of CaO and/or Ca(OH)_2 is much less common in agriculture, despite beneficial effects on physical properties of agricultural soils induced by pure CaO and Ca(OH)_2 , compared with pure CaCO_3 , being documented 40–50 years ago (Berglund 1971; Bohne and Hartge 1984). More recent studies confirm differences in aggregate stabilisation capacity between pure CaO and CaCO_3 (Keiblinger et al. 2016).

There is now increasing interest in liming using products containing CaO and/or Ca(OH)_2 in Swedish agriculture, as one of the side-effects can be a lower risk of particulate phosphorus (PP) losses from clay soils due to expected increase in aggregate stability. In Sweden, commercially available mixtures of 80–85% ground limestone and 15–20% slaked lime (hereafter, ‘structure lime’) are used to mitigate phosphorus loss and improve aggregate stability. Agriculture is the largest single source of P losses to the seas surrounding

Sweden, accounting for 45% of total anthropogenic net P loads (Hansson et al. 2019). In neighbouring waters such as the Baltic Sea, P is the growth-limiting nutrient for algal growth, so P inputs must be reduced to alleviate eutrophication (Boesch et al. 2006). Losses of P from soils are a function of soil texture and crops grown, as well as precipitation and discharge dynamics. On clay soils, particulate P (PP) is both released and transported to a greater extent than in the more coarse-textured soils (Johnsson et al. 2019) since P is bound to clay particles that are transported by preferential flow (Bergström et al. 2015). Both surface and sub-surface transport are episodic (Johnsson et al. 2019), but P losses can possibly be reduced by structure liming, through improved soil structure stability (Blomquist et al. 2018) and chemical precipitation of Ca–P compounds limiting the solubility of phosphate ions (Aronsson et al. 2019).

In a laboratory experiment, Lee et al. (2011) compared Ca(OH)_2 with CaCO_3 and $\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$ and found Ca(OH)_2 to be the most effective in converting water-soluble P into lesser soluble forms. Similarly, in a field experiment on a clay soil (top soil clay content 26%, $\text{pH}_{(\text{H}_2\text{O})}$ 7.1) containing high levels of plant-available P, application of Ca(OH)_2 reduced dissolved reactive phosphorus (DRP) levels in discharge from individually drained plots (Ulén and Etana 2014). In another field experiment on a soil with a high clay content (top soil clay content 60%, $\text{pH}_{(\text{H}_2\text{O})}$ 6.3), total P (tot-P) and PP concentrations in drainage water were found to be significantly reduced following application of pure CaO (Svanbäck et al. 2014). However, Eslamian et al. (2018) found that total dissolved phosphorus (TDP) concentrations were reduced with the addition of only two out of four CaO -containing liming products tested, whereas tot-P was significantly increased with all four products. These contrasting results indicate that the expected decrease in the risk of P losses due to structure liming does not always materialise.

In Sweden, use of pure CaO and/or Ca(OH)_2 in agriculture is very limited, but since 2010, approximately 65 000 ha of clay soils have been structure limed with commercial mixed products containing ~15–20% slaked lime and ~80–85% ground limestone. Application of these mixes of structure lime is a recommended measure in the water management plan for Sweden (VISS 2020) and is subsidised in national environmental schemes with the general aim of mitigating P losses. Despite growing use of mixed structure lime products in Sweden, there are few studies investigating their effectiveness, as pointed out by Greipsland et al. (2014).

As mixed structure lime products are relatively untested in a research context, the aim of this study was to answer a few important questions within practical structure liming and to bridge a knowledge gap. In the study, aggregate stability was used as a proxy for risk of P losses. Specific objectives were to: (1) determine whether structure liming increases aggregate stability, measured approximately 1 year after application, on clay soils; (2) determine whether the optimal structure liming

rate is greater at higher clay content; (3) investigate whether other initial soil variables, apart from clay content, determine the effect on aggregate stability; and (4) assess whether it is possible to use a set of soil properties to predict which clay soils will react to structure liming with increased aggregate stability.

Materials and methods

Study area, trial sites and experimental design

In 30 field trials, structure lime was spread and incorporated in autumn 2014, 2016 and 2017. Of these 30 trials, 28 were situated in the southern-most county of Sweden (Scania), within an area bounded by the corner points at 56.19°N, 12.71°E (trial site Lönkhult); at 56.07°N, 14.06°E (trial site Skottlandshus); at 55.50°N, 13.76°E (trial site Krageholm) and at 55.62°N, 13.33°E (trial site Svinarp). The remaining two trials were situated further north in the regions of Östergötland at 58.52°N, 16.50°E (trial site Bjärstad) and Uppsala at 59.55°N, 16.97°E (trial site Brunnsholm). Field trials, denomination, date of spreading, clay mineralogy characterisation (SmV index) and tillage before and after spreading the structure lime to a normal depth of 5–15 cm are summarised in Supplementary Table S1, together with the crop grown in the first year after structure liming. The trials had a randomised block design with three (occasionally four) replicates, and included four treatments with different application rates of structure lime. The standard application rate in Sweden is approximately 8 t ha⁻¹ of a mixed liming product. The treatments in all trials were:

- SL0. Control – no structure lime
- SL4. 0.5 × standard application rate = 4 t ha⁻¹ structure lime
- SL8. 1 × standard application rate = 8 t ha⁻¹ structure lime
- SL16. 2 × standard application rate = 16 t ha⁻¹ structure lime

In the first year (2014), the structure lime product used was marketed under the name Nordkalk Aktiv Struktur, later changed to Nordkalk Fostop Struktur. The product was a mixture of approximately 80–85% ground limestone (CaCO₃) and 15–20% slaked lime (Ca(OH)₂) with a water content of 15–25%. The chemical composition is shown in Table S2.

The 16 trials in the first year were situated at four different sites. At each site, four trials were established, with the aim of covering successively increasing clay content under similar trial conditions. The eight trials in 2016 followed the basic idea from 2014; i.e. to cover different clay contents at the same site but with only two trials per site, one with a low clay content (LC) and the other with a high clay content (HC). The four trials in 2017 followed a similar design to 2016 in having two soils at the same site, but selection was made after low soil organic matter (SOM) content (LO) and

high SOM content (HO), instead of clay content. Only four trials were possible to carry out in 2017 due to wet conditions preventing structure lime from being spread properly. All 28 trials listed above were situated in Scania, but two additional trials were performed further north in Sweden in autumn 2017. All trials were sampled plot-wise before liming in August–September of each year, to characterise the texture and nutritional status of the soils (Table S3). The SOM content varied between 2.2% and 7.1% in the field trials and plant-available calcium (Ca-AL) content varied between 950 and 11 450 mg kg⁻¹. Data on pH_(H₂O) and clay content for the 30 trials are depicted in Fig. 1, to show the range in soil properties at the trials. No soil classification according to the FAO initiated World Reference Base for Soil Resources (WRB) was done at the 30 trials. However, such soil classification surveys have been conducted for neighbouring Swedish long-term fertility experiments in the past (Kirchmann *et al.* 1996; Carlgren and Mattsson 2001). Therefore, all 28 trials in the county of Scania can as an approximation be classified as Haplic Phaeozems or Eutric Cambisols, and the northern-most trial at Brunnsholm as a Gleyic Cambisol. Approximately 1 year after liming, the trials were re-sampled plotwise to explore the short-term effect of structure liming.

Clay mineralogy determination

One topsoil sample (0–20 cm) per trial or trial site, consisting of a pooled sample of equal numbers of sub-samples from all plots in the trial, was examined with X-ray diffraction analysis to determine the mineralogy in the clay fraction. To demonstrate this semi-quantitatively, the intensity (=surface) of the three most pronounced clay mineralogy reflections in the X-ray curves at 14, 10 and 7 Å was measured. The percentage contribution from each of these three reflection curves was then used

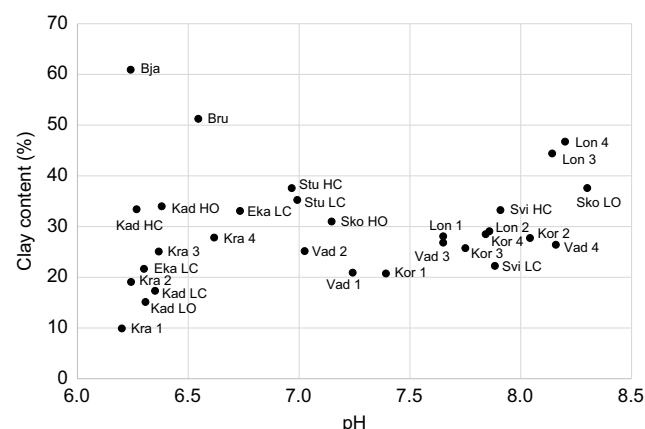


Fig. 1. Plot of initial pH_(H₂O) and clay content in the 30 trials. The trials had no liming requirement according to pH recommendations in Sweden, which for the trial soils, were in the range 6.2–6.5 (with sugar-beets + 0.5 pH unit). For detailed site information, see Table S1.

to calculate a SmV index as: $(\text{intensity } 14 \text{ \AA} / (\text{intensity } 10 \text{ \AA} + \text{intensity } 7 \text{ \AA}))$. The SmV index gives an estimate of the relationship between swelling and non-swelling clay minerals. It also indicates the relative proportions of clay minerals with high (smectite and vermiculite, intensity 14 Å) and low (illite, chlorite, kaoline, intensity 10 Å + intensity 7 Å) cation exchange capacity (CEC). A soil with a high proportion of swelling clay minerals is thus, characterised by high SmV index. The SmV index varied between 0.4 and 3.8 at the trial sites (Table S1).

Aggregate stability, sampling and measurements

Sampling of the soil for aggregate stability measurements was performed in the first year after liming in five trials in the spring shortly after drilling of a spring crop, and in the remaining 25 trials in the autumn after harvesting a cereal crop, approximately 1 year after spreading and incorporation of the structure lime (Table S1). The sampling was performed after shallow spring tillage or after shallow tillage down to approximately 6–8 cm in the autumn. The loose soil was sieved into three different size classes (average aggregate diameter >5 mm, 2–5 mm and <2 mm). The fraction of aggregates with diameter 2–5 mm was collected and stored dry and aerated until the aggregates were transported to the Swedish University of Agricultural Sciences in Uppsala.

Aggregates (average diameter 2–5 mm) were air dried to equalise differences in water content and then subjected to two simulated rainfall events 24 h apart, with an intensity of 32–39 mm h⁻¹ in both events. The simulated rainfall event lasted for 1 h, and the irrigation boom moved back and forth continuously without stopping at the ends during irrigation, so the aggregates were subjected to simulated rain for 5 min in the 1-h period. The leachate was collected after each rainfall event and turbidity and electrical conductivity (EC) were determined (turbidity A1/A2 and EC A1/A2). The muddy water was shaken for 10 min and then allowed to sediment for 4.5 h. After sedimentation, a supernatant sample was taken at a depth of 5.6 cm and the turbidity measured with a turbidimeter (Hach TL 2360 Turbidimeter, Hach, Loveland, Co.). The turbidity in the supernatant provides an estimate of the concentration of clay in the leachate (Etana *et al.* 2009) and is thereby a proxy for aggregate stability and risk of particulate P (PP) losses (Puustinen *et al.* 2005; Ulén *et al.* 2012). EC rises with liming and gives an indication of soluble calcium in the soil solution. Only turbidity and EC data from the second simulated rainfall event (turbidity A2 and EC A2) are reported here.

Statistical analyses

Values of turbidity and EC (from aggregate stability measurements after the second rainfall event) were log transformed before statistical analysis to meet the requirement of normally and homoscedastic residuals. The log-transformed

variables were analysed by analysis of variance (ANOVA) (General Linear Model in Minitab 18, Minitab Inc.), and the mean values were back-transformed to be calculated and presented as relative numbers.

In ANOVA, trial, treatment and the interaction between trial and treatment were used as fixed factors, and block nested in trial as a random factor in a hierarchical model. Pairwise comparisons of treatment averages were made according to Tukey's test. Unless otherwise stated, the significance level used in the calculations was $P < 0.05$.

Discriminant analysis was performed using the programme R (package lda) with two groups (significant or non-significant effect on turbidity A2 for the single trial). The variables used for classification were four soil variables and four variables that reflected the conditions at liming and incorporation. The purpose of the discriminant analysis was to test whether it was possible to classify the effect of structure liming on the soil using these variables.

Results

Aggregate stability

The aggregate stability (measured as turbidity A2) of aggregates 2–5 mm, sampled approximately 1 year after liming, and EC (EC A2) are shown in Fig. 2. After the second simulated rainfall event, there were statistically significant differences in turbidity between the treatments ($P < 0.001$). In treatments SL8 and SL16, turbidity decreased significantly by 13% and 20%, respectively, while in treatment SL4, there was a non-significant decrease of 10%. Treatments SL4 and SL8 did not differ significantly, and nor did treatments SL8 and SL16, but the difference between treatments SL4 and SL16 was statistically significant. However, there was a near-significant interaction between treatment and trial ($P = 0.056$). This means that the 30 different trials tended to react differently to the treatment with structure lime, making the results in Fig. 2 only generalisable with a great deal of caution. EC (EC A2) was also significantly affected by the treatments ($P < 0.001$). However, for EC A2, there was again a significant interaction ($P = 0.002$) between treatment and trial. This means that the EC was altered to different degrees by liming in the different soils in the 30 trials.

Aggregate stability – subdivision by initial pH, clay content, SOM content and SmV index

Based on the nearly significant interaction between treatment and trial for turbidity A2 ($P = 0.056$), the trials were divided into different groups. Fig. 3a–d shows the trials divided into different classes with respect to initial pH, clay content, SOM content and SmV index. In each pH group, there were 10 trials (Fig. 3a). The group with a starting pH below 6.5 before liming (mean initial pH 6.3) showed significant

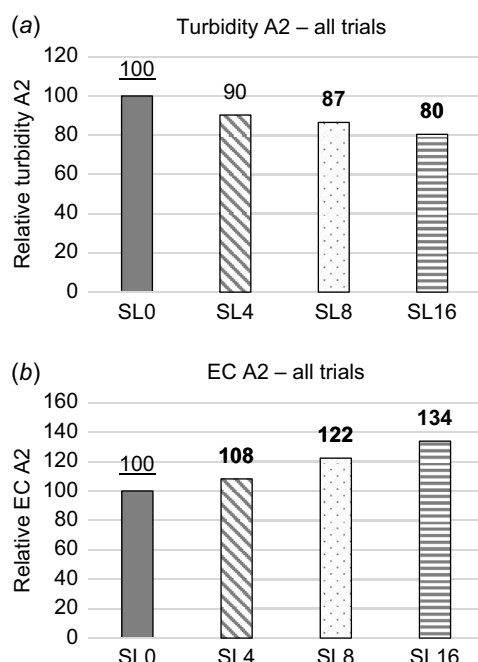


Fig. 2. (a) Relative turbidity and (b) relative electrical conductivity (EC) after a second simulated rainfall event on 2–5 mm aggregates of tilled soil collected 1 year after structure liming. Results for 30 trials with increasing application rates of structure lime. Treatment SL0 = 100. Values in bold indicate a significant difference from treatment SL0. Treatment SL0 = control; treatments SL4, SL8 and SL16 = 4, 8 and 16 t ha⁻¹ structure lime, respectively.

differences between treatments ($P < 0.001$), but no interaction ($P = 0.113$) between treatment and trial. In this group, treatment SL16 differed significantly from treatment SL0, with turbidity decreasing by 22% compared with SL0. The group with initial pH within the range 6.6–7.7 before liming (mean initial pH 7.1) also showed significant differences between treatments ($P = 0.011$), but no significant interaction ($P = 0.153$) between treatment and trial. In the pairwise comparison, there were significant differences between treatments SL8 and SL16 compared with treatment SL0, with decreases in turbidity of 18% and 19%, respectively, relative to SL0. In the group with initial pH > 7.8 (mean initial pH 8.0), there were no significant differences between treatments ($P = 0.237$).

Classification by clay content (Fig. 3b) was made on the basis of the functional groups used in Sweden: light clay soils (LC, 15–25% clay content), medium clay soils (MC, 25–40% clay content) and heavy clay soils (HC, 40–60% clay content). This classification did not divide the 30 trials into equally sized groups but provided the advantage of making results compatible with a general conceptual framework used in the Swedish farming community when referring to different soil types. The group of light clay (LC) soils consisted of 10 trials in which nine trials were true

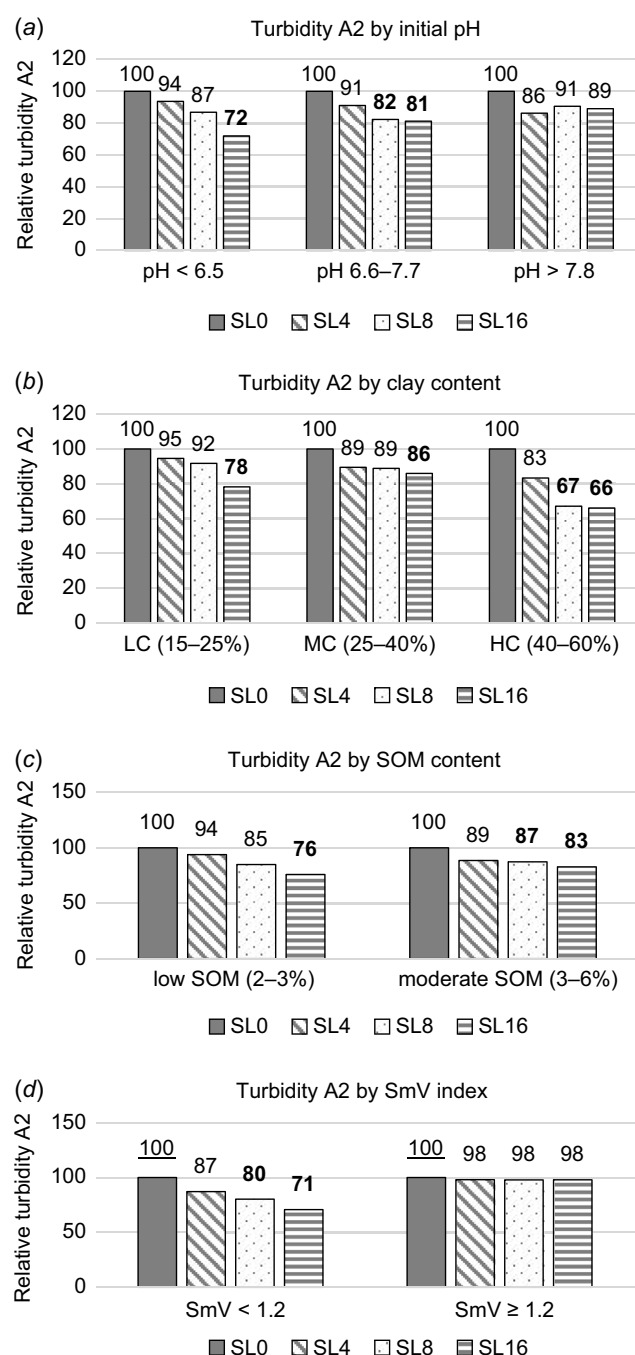


Fig. 3. Relative turbidity classified according to soil (a) initial pH, (b) clay content, (c) SOM content and (d) SmV index. Treatment SL0 = 100. Values in bold indicate a significant difference from treatment SL0. Treatment SL0 = control; treatments SL4, SL8 and SL16 = 4, 8 and 16 t ha⁻¹ structure lime, respectively. Initial pH on average: group pH < 6.5 – 6.3 (10 trials); group pH 6.6–7.7 – 7.1 (10 trials); group pH > 7.8 – 8.0 (10 trials). Clay content on average: light clay soils (LC), 20% (10 trials); medium clay soils (MC), 31% (16 trials); heavy clay soils (HC), 51% (four trials). SOM content on average: low, 2.5% (10 trials); moderate, 4.3% (20 trials). SmV index on average: SmV < 1.2 – 0.9 (15 trials); SmV > 1.2 – 2.4 (15 trials).

light clay soils (clay content 15–25%), but one trial had only 10% clay content and should therefore actually not have been included in the LC group. The clay content in the LC group was on average 20% (range 10–25%). There were significant differences between the treatments ($P = 0.020$) for this group, but no interaction between treatment and trial site ($P = 0.119$). Pairwise comparison showed that treatment SL16 in the LC group differed significantly from treatment SL0, with a turbidity decrease of 22%. The group of medium clay soils (MC) consisted of 16 trials where the clay content was on average 31% (range 26–38%). There were significant differences between the treatments for this group ($P = 0.027$), but no interaction between treatment and trial site ($P = 0.168$). Pairwise comparison showed that for the MC group, treatment SL16 differed significantly from treatment SL0, with a turbidity decrease of 14%. The group of heavy clay soils (HC) consisted of only four trials with an average clay content of 51% (range 44–61%). There were significant differences between the treatments ($P = 0.015$) but no interaction between treatment and trial site ($P = 0.309$). Pairwise comparisons for the HC group showed that treatments SL8 and SL16 differed significantly from treatment SL0, with a turbidity decrease of 33% and 34%, respectively.

Subdivision by SOM content (Fig. 3c) was made on the basis of the classification system for mineral soils used in Sweden: low SOM (2–3% SOM) and moderate SOM (3–6% SOM). The group of low SOM soils consisted of 10 trials with average SOM content of 2.5% (range 2.2–2.8%). There were significant differences between the treatments ($P = 0.005$) but with only a tendency ($P = 0.079$) for an interaction between treatment and trial site. Pairwise comparison showed that treatment SL16 in the low SOM group differed significantly from treatment SL0, with a turbidity decrease of 24%. The group of moderate SOM soils consisted of 20 trials with average SOM content 4.3% (range 3.3–7.1%). The trial with 7.1% SOM content did not really belong to the moderate SOM group but was the only exception to the 20 trials. There were also significant differences in this group between the treatments ($P = 0.003$) but no significant interaction between treatment and trial site ($P = 0.173$). Pairwise comparison showed that treatments SL8 and SL16 in the moderate SOM group both differed significantly from treatment SL0, with a turbidity decrease of 13% and 17%, respectively.

Subdivision by SmV index was made arbitrarily, by splitting the 30 trials into two groups (Fig. 3d) with the dividing point set at 1.2. In the group with SmV index <1.2 , there were significant differences ($P < 0.001$) between the treatments, with SL8 and SL16 showing lower turbidity than SL0. However, there was a significant interaction between treatment and trial site ($P = 0.031$) for this group, indicating that there were different reactions to structure liming within the group. Therefore, differences between treatments should not be over-interpreted. In the group with SmV index ≥ 1.2 , there were no significant differences between the treatments

($P = 0.569$) and no interaction between treatment and trial site ($P = 0.831$).

Discriminant analysis

To investigate whether the soil variables studied were able to predict the effect of structure liming, the 30 trials were classified into two classes: the seven trials that had a significantly higher value of $\log(\text{Turb A2})$ in treatment SL0 compared with the mean of treatments SL4, SL8 and SL16; and the 23 trials that did not have a significantly higher value for this difference. This comparison thus indicated whether structure liming as the mean of treatments SL4, SL8 and SL16 decreased or increased turbidity A2 (had an effect on aggregate stability) compared with the untreated control in treatment SL0. The t -value for this comparison is plotted on the y-axis in Fig. 4a, b. The seven fields where structure liming had a significant effect (red dots in Fig. 4) also formed their own group separately from the 23 non-significant fields (blue triangles).

Once the classification was made, discriminant analysis was performed using the software package R (package lda) in an attempt to classify the group to which each trial belonged (significantly or not significantly different from the control) using the independent variables. This discriminant score is shown on the x-axis in Fig. 4a, b. In the first analysis, the four soil variables initial pH, clay content, SOM content and SmV index were tested (Fig. 4a). In the second analysis, four more variables describing field conditions, tillage and management of the soil before and after structure liming (see Table S1) were added (Fig. 4b). The standardised coefficients of each variable used to calculate the discriminant score are compiled in Table 1, and the consequences of the outcome in Fig. 4a, b are summarised in Table 2. In Table 2, the soils are divided into four categories depending on whether liming would be recommended or not according to the outcome of the discriminant analyses, and whether the effect on turbidity was significant or not.

Based on the discriminant component calculated from the four soil variables (pH, clay content, SOM content and SmV index), structure liming would be recommended for 12 trials with a positive value of the discriminant component (to the right of the vertical red line in Fig. 4a). Of these 12 trials, five trials (Kra3, Kra4, Lon4, Bru and Bja) showed a significant effect of liming and seven a non-significant effect (Table 2). Negative values of the discriminant score were found for the remaining 18 trials; i.e. structure liming would not be recommended. Of these 18, the recommendation to avoid structure liming was correct for 16 trials (non-significant effect) and not correct for two trials (Lon1 and EkaLC), for which a positive significant effect of structural liming was observed. With these four soil variables, the recommendation would thus be correct for $16 + 5 = 21$ of the 30 trials (values in bold in Table 2), where 'correct' is defined as a recommendation not to lime

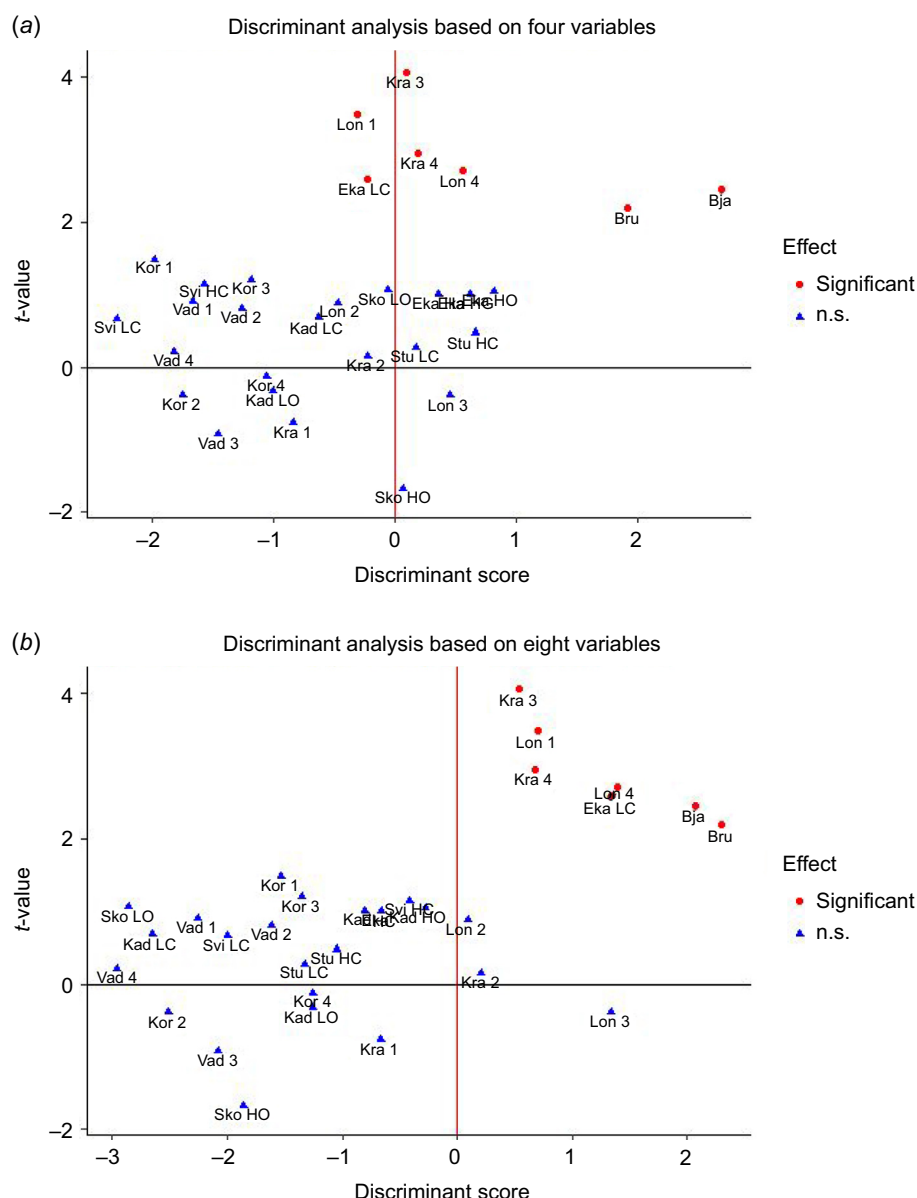


Fig. 4. Discriminant score (x-axis) calculated based on (a) four soil variables (pH, clay content, SOM content and SmV index) and (b) these four soil variables plus four tillage variables according to Table 1, and the corresponding t-value for the difference in turbidity A2 between the control treatment SL0 and the mean of the treatments SL4, SL8 and SL16 (y-axis). A t-value above 0 indicates that structure liming had a positive effect on turbidity (decreasing value) and a t-value below 0 that liming had a negative effect on turbidity. The red dots represent trials that showed a statistically significant positive effect of structure liming and the blue triangles represent trials that had no statistically significant effect. For trials with a positive discriminant score on the x-axis, the recommendation would be to structure lime based on the variables used in the discriminant score. For trials with a negative discriminant score on the x-axis, the recommendation would be not to structure lime.

where it would not give a significant positive change and to lime where it would lead to a significant positive change in aggregate stability (turbidity).

Basing the discriminant analysis on the four soil variables plus four other variables, characterising soil tillage before

and after spreading structure lime increased the accuracy of the analysis (Table 2). In 10 trials (positive discriminant score), structure liming would be recommended based on the discriminant component calculated from the total of eight soil and soil tillage variables (Fig. 4b, Table 2).

Table 1. Standardised coefficients of soil and tillage variables in the discriminant analysis presented in Fig. 4a, b.

Variable	Discriminant analysis – four variables	Discriminant analysis – eight variables
	Coefficient	Coefficient
Initial pH	−0.37	−0.73
Clay content	0.73	0.98
SOM content	0.12	0.50
SmV index	−0.54	−0.08
Tillage before spreading		−1.56
Tillage after spreading – tines		−0.90
Tillage after spreading – discs		−0.22
Tillage after spreading – combi		0.83

Table 2. Outcome of discriminant analyses using four soil variables (pH, clay content, SOM content and SmV index) and using the same four soil variables plus four soil tillage variables.

	Structure lime recommended?		Sum
	No	Yes	
Using four variables			
Significant effect turbidity A2	2	5	7
No significant effect turbidity A2	16	7	23
Sum	18	12	Σ30
Using eight variables			
Significant effect turbidity A2	0	7	7
No significant effect turbidity A2	20	3	23
Sum	20	10	Σ30

Data from Fig. 4a, b. Numbers in bold indicate that the recommendation was correct, where correct is defined as recommendation not to lime where it would not give a significant change and to lime where it would lead to a significant change in turbidity.

Of these 10 trials, seven trials showed a significant effect of liming and three a non-significant effect. The remaining 20 of the 30 fields had negative discriminant components, so the recommendation would be not to lime. This recommendation was correct for all 20 fields (non-significant effect). With the four soil variables supplemented with four tillage variables, the recommendation would thus be correct for $20 + 7 = 27$ of the 30 trials (values in bold in Table 2 lower), where 'correct' is again defined as a recommendation not to lime where it would not give a significant positive change and to lime where it would lead to a significant positive change in aggregate stability (turbidity). In the case with only four soil variables (Fig. 4a) or with four soil

variables plus four tillage variables (Fig. 4b), the trial site Lönhult B3 fell into the fourth quadrant; i.e. the recommendation would be to lime, but a post-liming decrease in aggregate stability was observed in this trial.

Discussion

In considering the results, it is appropriate to bear in mind that the trial soils had no liming requirements according to pH recommendations in Sweden, which for the trial soils, were in the range 6.2–6.5 depending on the clay content (with an additional 0.5 pH units if sugar beets are grown).

More stable aggregates on average

The primary interest in this study was the expected short-term effect on aggregate stability achieved by structure liming. Effects on aggregate stability using ground limestone (CaCO_3) have been reported to be significant (Chan and Heenan 1998) or not significant (Grieve et al. 2005). Chan et al. (2007) found statistically significant effects on aggregate stability 4 years after liming with CaCO_3 but also distinguished between different aggregate size ranges and observed that the increased macroaggregate ($>250 \mu\text{m}$) stability was entirely due to a significant increase in the fraction 0.25–2 mm and not in the fraction $>2 \text{ mm}$. A laboratory comparison of CaCO_3 and CaO showed no effect on aggregate stability with the use of CaCO_3 but a significant increase when applying CaO to three agricultural soils (Keiblinger et al. 2016), which agrees with results presented by Berglund (1971) and Bohne and Hartge (1984). However, to our knowledge, mixes of CaCO_3 and $\text{Ca}(\text{OH})_2$ have not been tested extensively.

As expected, the decrease in turbidity followed a step-like pattern, with aggregate stability increasing and soil losses decreasing accordingly (Fig. 2). Decreased turbidity is accompanied by a decreased risk of PP losses (Puustinen et al. 2005; Ulén et al. 2012). Results from this study confirmed findings in a previous study where structure lime in the form of the same mixed product, Nordkalk Aktiv Struktur, at an application rate of 12 t ha^{-1} also resulted in a significant decrease in turbidity of approximately 20% (Blomquist et al. 2018). The lowest application rate (treatment SL4) in this study did not decrease turbidity significantly, which also is in accordance with findings in Blomquist et al. (2018).

Turbidity decreases also corresponded well with increases in EC (Fig. 2), which is the mirror image of turbidity. The EC increase was steeper, clearer and showed greater amplitude than the turbidity decrease (Fig. 2). This can be interpreted as calcium ions being transported with the leachate without being bound to the clay aggregates.

Different reactions on different soils

The results imply that all soils do not react similarly to structure lime. It is therefore inappropriate to recommend structure liming for all clay soils in the expectation of reducing turbidity, increasing aggregate stability and decreasing soil losses, and thus mitigating the risk of P losses from agricultural fields.

The results showed that the effect of structure liming, measured as change in turbidity, was greater on soils with lower compared with higher initial pH values (Fig. 3a). In the group with initial pH < 6.5, both pH and Ca-AL increased significantly in treatments SL4–SL16 measured 1 year after liming. However, in the group with initial pH > 7.8, no significant changes were observed in Ca-AL and only SL16 showed a significant increase in pH compared with SLO (data not shown). Thus, the observed decrease in turbidity seemed to be a function of initial pH, and indirectly of the solubility and speed of release of Ca²⁺ ions from the structure lime.

Bivalent Ca²⁺ ions in the soil solution minimise the diffuse double layer (Vargas *et al.* 2019). The attraction between clay particles then increases, leading to flocculation, which is a prerequisite for aggregation (Payne 1988). The increase in concentration of Ca²⁺ in the soil matrix should be an indicator of aggregate stability and might explain why turbidity decreased more clearly with low as opposed to high initial pH. A higher degree of explanation would probably be possible to achieve if data on EC or base saturation before liming were available. This is, however, not the case but for future studies, such measurements are recommendable. Our results did not fully coincide with those of Olsson *et al.* (2019), although they sampled soil only 6 months after liming, which might explain the lack of consistency.

Aggregate stability increased at high clay and SOM content

The decrease in turbidity was greater on HC compared with LC and MC soils (Fig. 3b). Similarly, Keiblinger *et al.* (2016) observed increasing aggregate stability with increasing clay content after quicklime (CaO) application. Turbidity also decreased significantly at lower structure lime application rates (treatment SL8) on soils with moderate SOM content than on soils with low SOM content (Fig. 3c). SOM and clay content are often positively correlated, so the effect of greater SOM could actually be an effect of greater clay content. The pattern also suggests an interaction between Ca and SOM on aggregate stability, as proposed by Edwards and Bremner (1967) for a basic structural unit of clay size (<2 µm) consisting of clay–polyvalent cation–organic matter (C–P–OM). These compound building blocks unite to (C–P–OM)_x and further to [(C–P–OM)_x]_y reaching the magnitude of fine sand and silt-sized microaggregates (<250 µm). Muneer and Oades (1989c) integrated previous results on the role of Ca–SOM interactions with ¹⁴C-labelled

glucose (Muneer and Oades 1989a) and ¹⁴C-labelled wheat straw (Muneer and Oades 1989b) to create a conceptual model where Ca is involved in linking clay aggregates to SOM. If there is a quantitative relationship between Ca application and SOM present in soil, our results (Fig. 3c) fit well with previous findings. However, Cook and Batchelor (1996) suggest that SOM interferes with pozzolanic reactions in soil, hindering growth of cementing compounds, making the interaction between Ca and SOM unclear.

Clay mineralogy matters

The SmV index reflects the proportion of swelling clay minerals to non-swelling clay minerals in the soil. Our results suggest that SmV index can influence the outcome of structure liming (Fig. 3d). Olsson *et al.* (2011) found significant differences in CEC, clay content and EC between five different groups with SmV index value ranging from 0–0.9 up to >4. Clay content, CEC and EC generally increased with increasing SmV index. There was also a pH increase with increasing SmV index but there were no significant differences between the groups with respect to pH. High CEC and buffer capacity at high SmV index indicates a high lime requirement in order to raise the pH sufficiently to facilitate pozzolanic reactions (Cherian and Arnepalli 2015) but high initial pH at high SmV index indicates a low structure lime requirement. It is plausible that clay mineralogy and SmV index, either directly or indirectly through correlations with other inherent soil characteristics, determine the effect of structure lime on aggregate stability.

The effect of structure liming can be predicted

The division into different classes of pH, clay content, SOM content and SmV index led to the preliminary conclusion that structure liming in this set of trials had the most beneficial environmental impact on soils with low initial pH values, low SmV index and high clay and SOM content. These variables can also be used to predict soils in which a significant effect of structure liming on aggregate stability can be expected, as indicated by the results of the discriminant analysis (Fig. 4a, b). It is clear that the four soil variables alone (pH, clay content, SOM content, SmV index) were not sufficient to predict whether structure liming will have a beneficial effect (Fig. 4b). Combining them with four variables describing how the soil was tilled before and after liming gave slightly better accuracy (Fig. 4b). This is in line with studies by Blomquist and Berglund (2021) demonstrating the importance of timing and soil conditions at structure liming. Using eight variables, all seven trial sites that showed a significant effect of structure liming were correctly classified as suitable for structure liming.

For soil scientists and statisticians, it is gratifying and rewarding if structure liming gives significant positive changes in aggregate stability. For water conservation

purposes, it is beneficial if structure liming reduces the potential risk of P losses (above 0 on the y-axis in Fig. 4a, b) even if the effect is not statistically significant. For farmers, the best outcome would probably be if structure liming leads to decreased risk of P losses from arable land, combined with noticeable improvements in soil aggregate stability and positive yield effects, regardless of whether they are statistically significant or not. Structure liming of a soil in the fourth quadrant in Fig. 4a, b will not produce effects that satisfy any of these stakeholders, since aggregate stability was poorer (increased turbidity A2) on structure-limed soil compared with non-limed soil. The two trial sites (Skottlandshus HO and Lönhult B3) were found in this quadrant in the discriminant analysis with only four soil variables, but only Lönhult B3 remained in this quadrant when eight soil and tillage variables were used. This level of uncertainty must perhaps be accepted with the current level of knowledge.

Not all clay soils should be structure limed

An important outcome of the discriminant analysis was that it showed a way of predicting the effect of structure liming on the basis of soil variables but also showed that the conditions and soil management at the time of structure liming are important. The standardised coefficients in Table 1 show the relative importance of the variables. Clay content could be described as twice as important as SOM content ($0.98/0.50 \approx 2$) and clay content 12 times as important as SmV index ($0.98/0.08 \approx 12$).

There was no clear evidence on whether the optimum structure liming application rate is greater at higher clay content. Turbidity response for different clay content groups (Fig. 2b) showed that a higher application rate (treatment SL16) was required on light and medium clay soils to achieve a significant change, while a lower application rate (treatment SL8) gave a significant effect on the four trials with heavy clay soils. With results from more soils in the high clay content group, this interpretation may change.

The discriminant analysis showed that clay content contributed most to the composite discriminant score. The value of the discriminant score increased with increasing clay and SOM content, but decreased with increasing SmV index and increasing pH (Table 1). Since a positive value of the discriminant score entails a recommendation to structure lime, the results suggest that structure liming improves aggregate stability and is an effective measure against P losses on soils with high clay content, high SOM content, low SmV index and low pH. The results also indicate that soil tillage before and after spreading to incorporate the structure lime is of equal importance. In the future, data from more field experiments can fine tune the recommendations on which soils should and should not be structure limed. Our ongoing research will show if the admixture of 15–20% of slaked lime in 'structure lime' is

enough for a longer-term aggregate stabilisation to occur (Eades and Grim 1960; Choquette et al. 1987).

Conclusions

Increasing application rates of structure lime (from 0 to 16 t ha^{-1}) as a mix of 15–20% slaked lime and 80–85% ground limestone in 30 field trials resulted in:

1. Significantly increased aggregate stability, and thereby indirectly decreased risk of P losses, with 8 and 16 t ha^{-1} of structure lime, but with great variation between soils and a near-significant interaction between treatment and trial.
2. Significantly increased aggregate stability on soils with initial $\text{pH}_{(\text{H}_2\text{O})}$ below 7.7, but not on soils with initial pH above 7.7.
3. A more pronounced effect, and an effect on aggregate stability, at standard structure liming application rates (SL8) on soils with clay content exceeding 40%, as opposed to soils with clay content below 40%.
4. Significantly increased aggregate stability at standard structure liming application rates on soils with 3–6% SOM, but with significant aggregate stability increases only at double the standard structure liming application rate on soils with 2–3% SOM.
5. Significantly increased aggregate stability at standard and double structure liming application rates on soils with SmV index <1.2 , but no effect on soils with SmV index ≥ 1.2 .
6. Discriminant analyses using clay content, SOM content, initial pH, SmV index and four variables describing soil conditions and management before and after structure liming correctly classified the outcome of liming on aggregate stability for 27 of the 30 trials.

Supplementary material

Supplementary material is available [online](#).

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