

# Site characteristics determine the duration of structure liming effects on clay soil

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Adding carbonated or non-carbonated lime to clay soils can lead to changes in aggregate stability. In Sweden, 'structure liming' with a mixed product (normally 80–85% calcium carbonate and 15–20% calcium hydroxide) is subsidised through environmental schemes to increase aggregate stability, thereby mitigating losses of particulate phosphorus (PP). This study assessed the effects of structure liming on aggregate stability in eight clay soils in southern Sweden, using turbidity as a proxy for aggregate stability. Turbidity in leachate from simulated rain events performed on aggregates (2–5 mm) in the laboratory was measured one and six years after application of four treatments 0, 4, 8 and 16 t ha<sup>-1</sup> of a mixed structure liming product. The effect on turbidity was analysed for all application rates, but also as the contrast between the unlimed control and the mean of the limed treatments, to identify the general effect. A significant effect of structure liming on turbidity was found after one year. The effect decreased over time, but was still detectable after six years. However, there was a significant interaction between trial and treatment, indicating different reactions on different soils and suggesting that not all clay soils are suitable for structure liming if the desired objective is to lower the risk of PP losses. Clay content, initial pH and mineralogy may explain the different responses to structure liming. These findings show a need for a site-specific structure liming strategy. As a tentative recommendation, soils with a minimum clay content of approximately 25–30% and pH <7 should be preferred for structure liming.

*Key words:* structure liming, aggregate stability, pH, turbidity, clay

## Introduction

Adding non-carbonated lime (calcium oxide or calcium hydroxide) to clay soils leads to a series of reactions involving i) cation exchange, ii) flocculation, iii) carbonation and iv) pozzolanic reactions, as outlined by Choquette et al. (1987). Pozzolanic reactions are of a long-term nature (Firoozi et al. 2017), as new cementing products are formed when siliceous and aluminous materials react chemically with lime in the form of calcium hydroxide. Pozzolanic reactions are the main mechanism ensuring good soil-lime stabilisation, according to Choquette et al. (1987). These lime-soil reactions can result in changes in soil physical properties, as demonstrated in Swedish field trials with burnt (calcium oxide) and slaked (calcium hydroxide) lime during the 1960s and 1970s (Berglund 1977, Ledin 1981) and with ground limestone (calcium carbonate) used as reference in some later studies (Siman et al. 1984). The focus of these previous studies was normally on the agronomic aspects of liming, such as soil shrinkage, aggregation and penetration resistance, and they reported positive effects on the physical status of clay soils. However, use of liming with non-carbonated lime in Swedish agriculture remained limited, as burnt and slaked lime products entailed high investment costs (Wiklander 1963).

Interest in 'structure liming' with a mixed product, normally 80–85% calcium carbonate and 15–20% calcium hydroxide, emerged in Sweden around 2010, driven by national environmental schemes under the EU Water Framework Directive (EC 2021) that subsidise up to 50% of the costs of liming (HaV 2021). The focus in these environmental schemes is mainly on the environmental aspect, as losses of particulate phosphorus (PP) have been shown to decrease when lime is mixed with clay soil (Ulén and Etana 2014). The practice is therefore relatively widespread, with around 65,000 hectares in Sweden being structure limed between 2010 and 2021, corresponding to approximately 2.5% of the arable land.

Positive short-term effects on aggregate stability and a reduced risk of phosphorus (P) losses as a result of increasing application rates of structure liming products have been reported. For example, Blomquist et al. (2022) observed increased aggregate stability and an associated reduced risk of P losses about one year after structure liming, while Blomquist et al. (2018) detected effects of the same magnitude 2.5 years after structure liming. In contrast, Norberg et al. (2021) found no significant effect on aggregate stability one and two years after structure liming on a clay soil where effects could be expected. Thus the effect seems to depend on the inherent

characteristics of the soil and manifests as an interaction between soil type and lime treatment, with some soils responding to structure liming with markedly increased aggregate stability and other soils responding much less or remaining unaffected by structure liming (Gunnarsson et al. 2022). This is in line with findings by Keiblinger et al. (2016) of varying effects of liming on aggregate stability in soils with different clay content. Soil pH also plays a role, with soil structure being positively influenced on acid soils by an increase in base saturation through cation exchange and a decrease in distances between clay particles leading to aggregation (Wiklander, 1963). According to Bell (1996), pozzolanic reactions occur when the affinity of a soil for lime has been satisfied, which can be interpreted as a rise to 100% base saturation, with a simultaneous increase in pH. The possibility for pozzolanic reactions to occur should therefore be greater in naturally alkaline soils or in soils where the pH has been elevated due to liming as a management practice.

In this study, aggregate stability was measured one and six years after structure liming, in order to compare the duration of the effect in the slightly longer term. Specific objectives were i) to assess changes in aggregate stability over time after structure liming; ii) to determine whether different soils react differently to structure lime; and iii) to identify critical soil variables determining the effect of structure lime on aggregate stability.

## Materials and methods

### Study area and sites

Structure lime (Nordkalk Aktiv Struktur, Nordfalk Corp., Finland) was spread and incorporated in eight field trials at four sites (Krageholm, Lönhult, Vadensjö, Kornheddinge) in Scania County, southern Sweden, in August and September 2014. To assess the effect of structure liming on aggregate stability in soils with varying clay content, trials with low clay content (LC) and high clay content (HC) were selected at each site. All trials followed the crop rotation and management practices on the respective farm.

Site coordinates and date of structure liming are shown in Table 1, together with the crops grown in the two sampling years (2015 and 2020). After spreading in 2014, the structure lime was incorporated using different tillage non-inversion implements, working with discs, tines or combinations of these, to 5–15 cm depth. At all sites, incorporation was performed in 2–3 passes on the same day as spreading or within 1–2 days. At Vadensjö, an additional fourth pass was made approximately three weeks after spreading. No inversion mouldboard ploughing was performed at any of the sites in autumn 2014.

In the years from 2015 to the repeated sampling in 2020 the eight field trials carried a variety of crops such as winter wheat, spring barley, spring wheat, oats, sugar beet, winter oil seed rape and red fescue for seed production. At trial sites Krageholm and Lönhult the soil was mouldboard ploughed once in the autumn of 2018 and at trial site Vadensjö once in the autumn of 2015. Kornheddinge LC was mouldboard ploughed before and after sugar beet in 2016 and likewise Kornheddinge HC was ploughed before and after sugar beet in 2018, i.e. twice until the sampling in 2020. In all other years, when the trials were not mouldboard ploughed, the primary tillage in autumn was performed with non-inversion tillage.

Table 1. Site coordinates, dates of spreading-incorporation of structure lime in autumn 2014 and crops grown in the soil aggregate sampling years 2015 and 2020

Sites	Coordinates	Date lime application and incorporation	Crop 2015	Crop 2020
Krageholm	55.51 °N, 13.75 °E	5 September 2014	WW	WOSR
Lönhult	56.19 °N, 12.71 °E	28 August 2014	WW	SB
Vadensjö	55.92 °N, 12.86 °E	27 August 2014	SuB	SuB
Kornheddinge	55.63 °N, 13.29 °E	20 and 28 September 2014	WW	WW

WW = winter wheat; SuB = sugar beet; SB = spring barley; WOSR = winter oilseed rape

### Experimental design and liming product

The plots on each soil type were laid out in a randomised block design with three replicates, and subjected to one of four treatments with increasing application rates of structure lime. The standard application rate in Sweden is approximately 8 t ha<sup>-1</sup> of a mixed liming product. The treatments in the trials were: an unlimed control (SL0); half

the standard application rate (4 t ha<sup>-1</sup> structure lime; SL0.5), the standard application rate (8 t ha<sup>-1</sup>; SL1); and twice the standard application rate (16 t ha<sup>-1</sup>; SL2). The liming product used was a mixture of approximately 80–85% ground limestone and 15–20% slaked lime, with a water content of 15–25% and bulk density 0.8–1.0 t m<sup>-3</sup>. The chemical composition of the product is shown in Table 2.

Table 2. Chemical composition (dry matter basis) of the structure lime product Nordkalk Aktiv Struktur (approximately 80–85% ground limestone and 15–20% slaked lime) spread in field trials in August–September 2014. Water content 15–25% depending on storage. Particle size 0–0.5 mm with 99% passing through mesh size 0.5 mm. Source: Nordkalk Corp.

Macronutrient or compound	Conc. (%)	Micronutrient	Conc. (mg kg <sup>-1</sup> )
Total Ca as CaO	51	Cd	1.8
Mg	1.0	Co	9
SiO <sub>2</sub>	5.2	Cr	26
Al <sub>2</sub> O <sub>3</sub>	2.9	Cu	45
Fe <sub>2</sub> O <sub>3</sub>	1.1	Hg	< 0.02
K	1.5	Ni	26
Na <sub>2</sub> O	0.5	Pb	58
S	1.5	Zn	260
P	0.07	V	38

### Clay mineralogy determination

One topsoil sample (0–20 cm) per trial or site, consisting of a pooled sample from all plots on the particular trial, was examined with X-ray diffraction analysis to determine the mineralogy of the clay fraction. To assess 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 to calculate SmV index as: Intensity 14 Å/(Intensity 10 Å + Intensity 7 Å), as an estimate of the relationship between swelling and non-swelling clay minerals. SmV index 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 a high SmV index.

### Soil characteristics

Initial soil chemical characteristics, together with soil organic matter content, texture and clay mineralogy (SmV index) are summarised in Table 3 for the eight field trials. The SmV index varied between 0.6 and 3.1 at the trials, i.e. with the relative proportion of swelling clay minerals being five-fold higher in Kornheddinge LC than in Krageholm LC/HC.

Table 3. Mean (of 12 plots) soil texture, soil organic matter (SOM), nutrient status and clay mineralogy (SmV index) in topsoil (0–20 cm) in the eight field trials prior to structure liming in August–September 2014, HC/LC = high/low clay soil at each trial

Trial	SOM <sup>a</sup> %	Sand <sup>b</sup> >60 µm	Silt <sup>c</sup> 2–60 µm	Clay <sup>d</sup> <2 µm	pH H <sub>2</sub> O	P-AL <sup>e</sup> mg kg <sup>-1</sup>	K-AL <sup>e</sup> mg kg <sup>-1</sup>	Mg-AL <sup>e</sup> mg kg <sup>-1</sup>	K/Mg quota	Ca-AL <sup>e</sup> mg kg <sup>-1</sup>	SmV index
Krageholm LC	2.4	39.5	41.4	19.1	6.2	25	82	95	0.9	1566	0.6
Krageholm HC	2.5	19.5	52.7	27.8	6.6	29	111	151	0.8	1850	0.6
Lönhult LC	5.0	43.4	28.5	28.1	7.7	129	188	146	1.4	4042	1.1
Lönhult HC	3.9	29.1	24.2	46.8	8.2	127	307	353	0.9	10542	1.1
Vadensjö LC	4.0	46.3	32.8	20.9	7.2	130	97	121	0.8	3100	2.9
Vadensjö HC	3.3	44.1	29.5	26.4	8.2	89	148	229	0.7	11425	2.9
Kornheddinge LC	2.8	53.8	25.4	20.8	7.4	48	99	87	1.1	3042	3.1
Kornheddinge HC	2.6	45.8	25.8	28.5	7.8	114	203	218	1.1	7050	1.9

<sup>a</sup>soil organic matter, measured as loss of ignition corrected for clay content; <sup>b</sup>wet sieving; <sup>c</sup>calculated as difference between the sand and clay fractions; <sup>d</sup>hydrometer sedimentation; <sup>e</sup>extraction with 0.1 M ammonium lactate + 0.4 M acetic acid, pH 3.75 (Egnér et al. 1960)

Soil classification according to the FAO World Reference Base for Soil Resources (WRB) was not performed at the experimental sites, but has been done previously for neighbouring Swedish long-term soil fertility trials (Kirchmann et al. 1996, Carlgren and Mattsson 2001). According to the results, the Krageholm, Lönhult and Kornheddinge soils can be classified as Haplic Phaeozems and Vadensjö as a Eutric Cambisol. Data on pH and clay content for the eight field trials soils are depicted in Figure 1, to show the range in properties expected to be decisive for soil aggregate stability.

Follow-up analyses of soil chemical variables in all plots were performed in both 2015 and 2020.

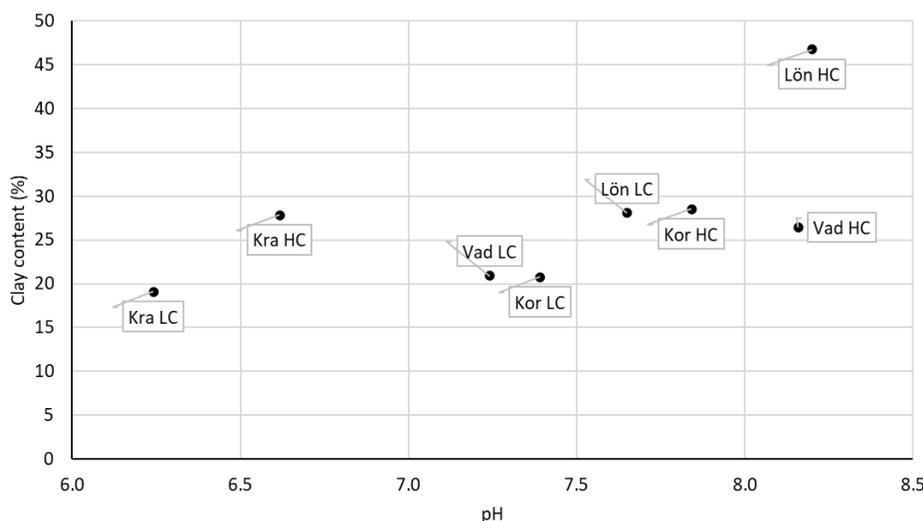


Fig. 1. Average initial  $\text{pH}_{\text{H}_2\text{O}}$  and clay content in the eight field trials at spreading and incorporation of structure lime in August–September 2014. Kra=Krageholm, Lön=Lönhult, Vad=Vadensjö, Kor=Kornheddinge, LC = lower clay content, HC = higher clay content. Actual clay content is given in Table 3.

### Aggregate stability, sampling and measurements

Soil sampling for aggregate stability measurements was performed in one year (2015) and six years (2020) after liming. Sampling at Vadensjö in 2015 was performed in spring, shortly after drilling of the sugar beet crop, and sampling in 2020 was performed in summer in the growing sugar beet crop, as autumn sampling was considered unsuitable. At all other sites, both samplings were performed in autumn after harvest of a cereal or oil-seed crop and shallow tillage to approximately 6–8 cm. Loose soil from the tilled depth was collected and sieved into three different size classes (with mean aggregate diameter >5 mm, 2–5 mm and <2 mm, respectively). The fraction of aggregates with diameter 2–5 mm was stored dry and aerated, and later transported to the laboratory at the Swedish University of Agricultural Sciences (SLU) in Uppsala. At the laboratory, the aggregates were air-dried again to equalise differences in water content and then subjected to two simulated rainfall events 24 hours apart, with a rainfall intensity of 32–39 mm per hour in each event. Each rainfall event lasted for one hour 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 five minutes in the one-hour period. The leachate was collected after each rainfall event for analysis of turbidity and electrical conductivity (EC). Only results for the samples collected after the second rainfall event, denoted Turbidity A2 and EC A2, respectively, are reported in this paper as they have shown less variation in earlier studies. The muddy leachate samples were shaken for 10 minutes and then allowed to sediment for 4.5 hours. After sedimentation, a supernatant sample was taken at 5.6 cm depth and turbidity measured with a turbidimeter (Hach TL 2360 Turbidimeter, Hach, Loveland, Co.). The turbidity values obtained provided an estimate of the clay concentration in the leachate (Etana et al. 2009) and were thus a proxy for aggregate stability and risk of particulate P (PP) losses (Puustinen et al. 2005, Ulén et al. 2012). Electrical conductivity in soil increases after liming, so the EC values in leachate were used as an indicator of presence of soluble calcium in the soil solution.

## Statistical analyses

The data obtained for pH, ammonium lactate (AL)-extracted calcium, turbidity and EC (Turbidity A2 and EC A2) were subjected to analysis of variance (ANOVA) (General Linear Model (GLM) in Minitab 18, Minitab Inc.). The mean values obtained were expressed in absolute and relative terms (unlimed control = 100).

In the GLM, 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  $p < 0.05$ .

To test the overall effect of liming versus the unlimed control, the control values were compared against the mean of the three structure lime treatments using a contrast. For the comparisons, SAS software (SAS 9.4) was used.

## Results

### pH and calcium changes

Soil pH and calcium content (Ca-AL) in the different treatments before liming (2014), one year after liming (2015) and six years after liming (2000) are shown in Figure 2.

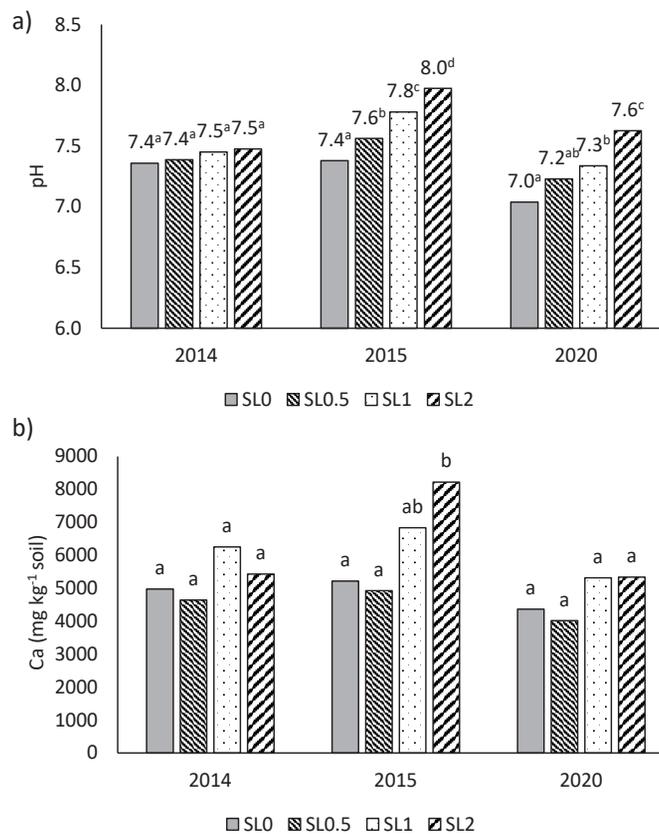


Fig. 2. (a) Soil pH and (b) ammonium lactate-extracted calcium (Ca-AL) content before structure liming (2014), one year after liming (2015) and six years after liming (2020) in the unlimed control (SL0) and in treatments receiving 4, 8 and 16 t ha<sup>-1</sup> structure lime (SL0.5, SL1 and SL2, respectively). Mean for all eight field trials. Different letters on bars indicate significant differences between treatments within the year.

One year after liming, pH was significantly higher ( $p < 0.001$ ) in all liming treatments compared with the unlimed control, with an increase in treatment SL0.5, SL1 and SL2 of 0.2, 0.4 and 0.6 pH units, respectively (Fig. 2a). However, further analysis revealed a significant interaction between trial and treatment ( $p = 0.007$ ) (Fig. 3).

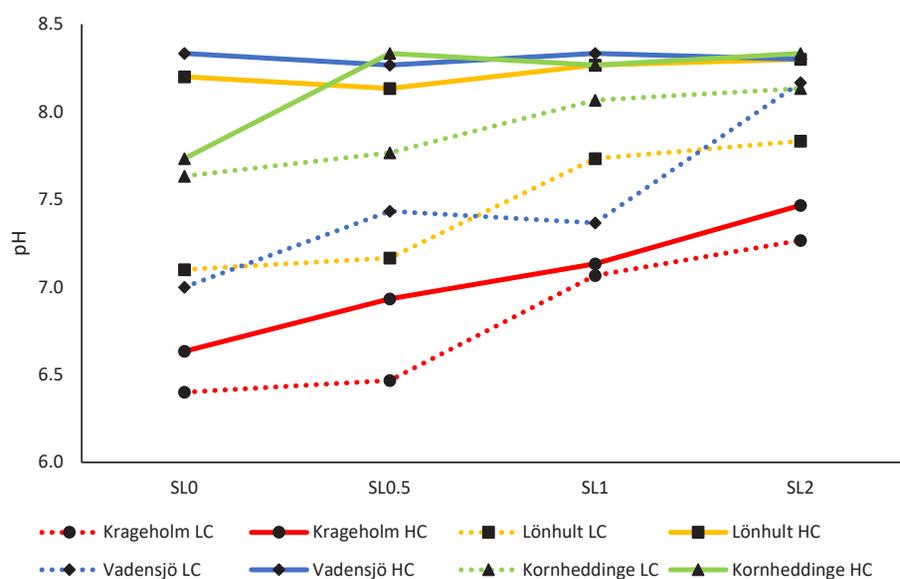


Fig. 3. Interaction plot for mean soil pH measured in 2015, one year after structure liming, in the unlimed control (SLO) and in treatments receiving 4, 8 and 16 t ha<sup>-1</sup> structure lime (SL0.5, SL1 and SL2, respectively) at the different experimental trials. HC/LC = high/low clay.

The soil at the different experimental trials showed different degrees of pH increase in the liming treatments (Fig. 3). The soils at the two Krageholm trials, both with initial pH of around 6.5 (see Fig. 1), reacted to increasing application rates with consistent pH increases, while the Lönhult HC and Vadensjö HC soils, with initial pH values above 8, did not show any further pH increase in the lime treatments.

Six years after liming, significant differences in pH were detected only in treatments SL1 and SL2 (Fig. 2a) compared with the unlimed control ( $p < 0.001$ ). There was no significant interaction between trial and treatment ( $p = 0.18$ ) at that time.

The initial calcium content (Ca-AL) varied widely between the treatments (Fig. 2b), but the differences were not statistically significant. In the first year after liming, only the double liming rate treatment (SL2) differed significantly ( $p = 0.001$ ) from the unlimed control and there was no significant interaction between trial and treatment ( $p = 0.70$ ). Six years after liming, the ANOVA results showed significant differences ( $p = 0.035$ ), but the pairwise comparisons showed no significant differences in soil calcium content between the treatments. There was no significant interaction between trial and lime treatment ( $p = 0.52$ ).

### Aggregate stability

Aggregate stability (Turbidity A2) of 2–5 mm aggregates from field trials sampled one and six years after liming are shown in Figure 4a, while the corresponding values of electrical conductivity in leachate (EC A2) are shown in Figure 4b.

One year after structure liming, there were statistically significant differences in turbidity between the field trials ( $p < 0.001$ ) and between the treatments ( $p = 0.001$ ). In treatments SL1 and SL2, turbidity decreased significantly, by 33% and 34%, respectively, while in treatment SL0.5 there was a non-significant decrease of 22% (Fig. 4a). There were no significant differences between the limed treatments (SL0.5–SL2). However, there was a significant interaction between treatment and trial ( $p = 0.049$ ), indicating that the eight field trials reacted differently to structure liming. Electrical conductivity (EC A2) also differed significantly between trials ( $p < 0.001$ ) and between treatments ( $p < 0.001$ ) (Fig. 4b), but with no significant interaction between site and treatment ( $p = 0.23$ ) (Fig. 4). In treatments SL1 and SL2, EC A2 increased significantly, by 18 and 29%, whereas treatment SL0.5 (10% increase) was not significantly different from the unlimed control (SLO).

Six years after structure liming, the significant differences in turbidity between trials persisted ( $p < 0.001$ ), but there was no longer a significant difference due to liming treatment ( $p = 0.102$ ) (Fig. 4a). However, there was still a significant interaction ( $p = 0.003$ ) between trial and treatment (Fig. 4a). For electric conductivity, no significant differences were found between the treatments ( $p = 0.55$ ) (Fig. 4b).

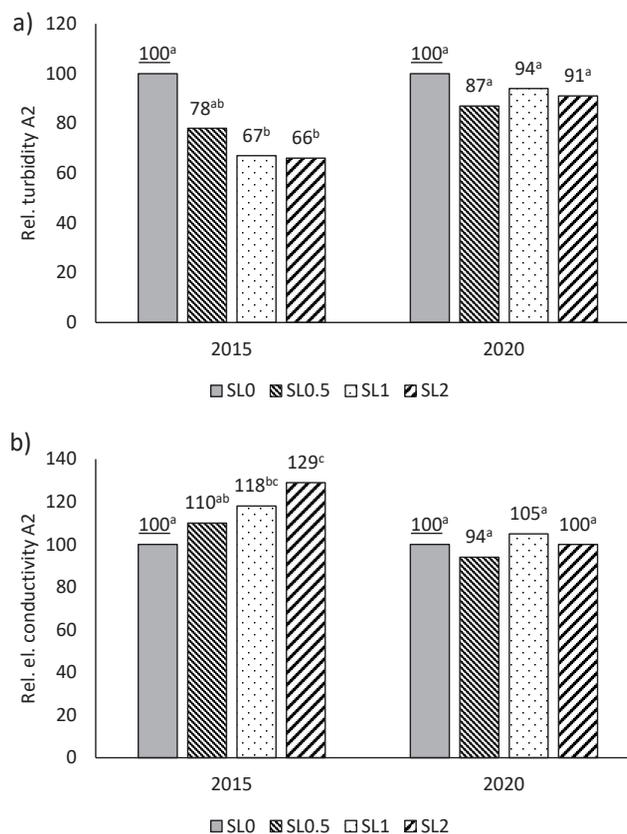


Fig. 4. (a) Relative turbidity and (b) relative electrical conductivity in leachate collected after a second simulated rainfall event on 2–5 mm aggregates of tilled soil collected one year (2015) and six years (2020) after structure liming at a rate of 4, 8 and 16 t ha<sup>-1</sup> (SL0.5, SL1 and SL2, respectively), calculated as a mean for all trials based on statistical analyses of original data (absolute values) and expressed relative to values obtained for the unlimed control (SL0 = 100). Different letters on bars indicate significant differences between treatments ( $p < 0.05$ ).

Due to the significant interactions on turbidity, it was not possible to draw general conclusions on aggregate stability from the average for the eight field trials in the first and sixth year after liming. To achieve higher resolution, the data were analysed for the individual sites and sampling years. The full results for the different sites in the sampling years 2015 and 2020 (see Table S1 in Supplementary information) revealed an interaction between site and treatment for both turbidity and electric conductivity. To further clarify these differences in response to structure liming in general compared with the unlimed control, the average values for the three limed treatments (SL0.5, SL1 and SL2) were compared against the control values for all trials and for each site separately (Fig. 5).

For the eight field trials combined, there was a significant effect of liming in 2015 ( $p < 0.001$ ) with a 29% decrease in turbidity in the limed treatments, and also in 2020, with a 10% decrease in turbidity persisting in the limed treatments ( $p = 0.032$ ). However, there was considerable variation between the sites, which was evident as an interaction between trial and treatment in both 2015 ( $p = 0.049$ ) and 2020 ( $p = 0.003$ ). In terms of the individual sites, structure liming only significantly affected the turbidity at Krageholm and Lönhult at the first measurements (in 2015). The soils at the two trials at Krageholm reacted with a 35% reduction in turbidity in that year and the limed treatments showed a significant difference from the control ( $p = 0.013$ ) (Fig. 5). In 2020, there was still a remaining significant difference compared with the control ( $p = 0.0018$ ) at that site. At the two trials at Lönhult, there was a 61% reduction in turbidity in 2015 ( $p = 0.018$ ), but the effect of structure liming was no longer significant in 2020 ( $p = 0.65$ ) (Fig. 5). The Vadensjö and Kornheddinge sites showed no signs of aggregate stability changes, either when grouped together or analysed individually, in either of the sampling years (Fig. 5).

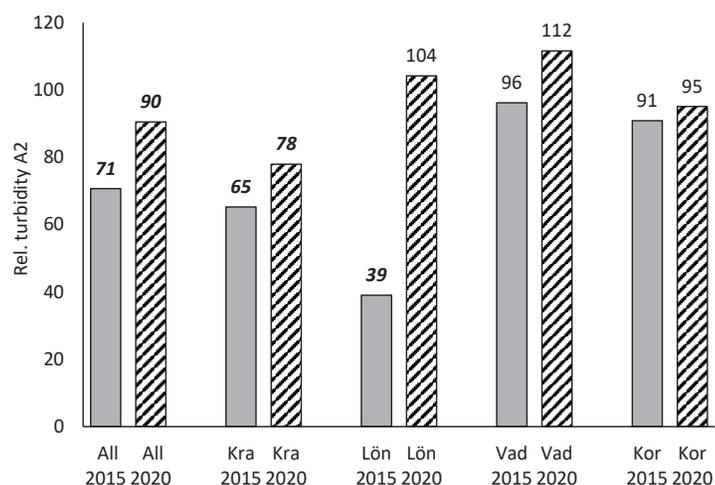


Fig. 5. Relative turbidity as a mean of the three structure liming treatments SL0.5–SL2 (applying 4, 8 and 16 t ha<sup>-1</sup> structure lime, respectively), compared with the value in the unlimed control (SL0), where SL0 = 100. Results from the second rainfall simulation on 2–5 mm aggregates of tilled soil collected one year (2015) and six years (2020) after structure liming. Results for all trials (All) and for the individual sites: Krageholm (Kra), Lönhult (Lön), Vadensjö (Vad) and Kornheddinge (Kor). Values in bold italics indicate a significant difference compared with the unlimed control.

The diminishing treatment effect over time, together with the obvious site-specific nature of the response to liming, demanded even higher resolution in the analysis, so the LC and HC trials at Krageholm and Lönhult were analysed separately (Fig. 6).

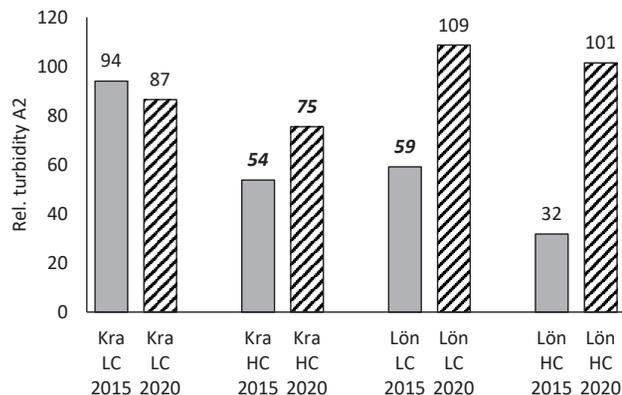


Fig. 6. Relative turbidity as a mean of the three structure liming treatments SL0.5–SL2 (applying 4, 8 and 16 t ha<sup>-1</sup> structure lime, respectively), compared with the unlimed control (SL0), where SL0 = 100. Results from the second rainfall simulation on 2–5 mm aggregates of tilled soil collected one year (2015) and six years (2020) after structure liming in trials with low clay content (LC) and high clay content (HC) at Krageholm (Kra) and Lönhult (Lön). Values in bold italics indicate a significant difference compared with the unlimed control.

Structure liming (average of treatments SL0.5–SL2) had no significant effect on turbidity in leachate from Krageholm LC soil aggregates in 2015 ( $p = 0.76$ ) or 2020 ( $p = 0.44$ ). In contrast, for Krageholm HC soil the turbidity decreased significantly (by 46%) in 2015 ( $p = 0.012$ ) and still showed a significant decrease (by 25%) in 2020 ( $p = 0.003$ ). The trials at Lönhult displayed significant ( $p = 0.026$  at Lönhult LC) and close to significant ( $p = 0.062$  at Lönhult HC) reductions in turbidity in 2015, but no significant effects in 2020 ( $p = 0.47$  at Lönhult LC,  $p = 0.91$  at Lönhult HC). See Table S2 in Supplementary information for full results.

In a previous study examining the effect on turbidity approximately one year after structure liming at the eight trials used in the present study together with another 22 field sites, we found that structure liming had the most pronounced short-term effect on soils with high clay content and low initial pH (Blomquist et al. 2022). Therefore,

further analysis was performed on the eight trials in the present study divided into two groups, with low clay content (LC) and high clay content (HC) (Table 4), where low and high refer to the relative clay content at each site (see Table 3).

Table 4. Turbidity A2 and electrical conductivity A2 in 2015 and 2020 for the four trials with relative low clay content (LC) and the four with high clay content (HC). Significant differences are indicated by different letters ( $p < 0.05$ ).

Treatment	Turbidity A2				Electrical conductivity A2			
	2015		2020		2015		2020	
Year	Abs.	Rel.	Abs.	Rel.	Abs.	Rel.	Abs.	Rel.
Low clay content (LC)								
SL0	4.21 <sup>a</sup>	<u>100</u>	54.8 <sup>a</sup>	<u>100</u>	66 <sup>a</sup>	<u>100</u>	122 <sup>a</sup>	<u>100</u>
SL0.5	4.20 <sup>a</sup>	100	51.0 <sup>a</sup>	93	74 <sup>ab</sup>	113	118 <sup>a</sup>	97
SL1	3.09 <sup>a</sup>	73	54.1 <sup>a</sup>	99	92 <sup>ab</sup>	140	123 <sup>a</sup>	101
SL2	3.27 <sup>a</sup>	78	62.4 <sup>a</sup>	114	100 <sup>b</sup>	153	132 <sup>a</sup>	108
p Trial	0.000		0.051		0.000		0.000	
p Treatm	0.046		0.259		0.008		0.652	
p Trial*Treatm	0.524		0.467		0.845		0.963	
High clay content (HC)								
SL0	8.78 <sup>a</sup>	<u>100</u>	121 <sup>a</sup>	<u>100</u>	117 <sup>a</sup>	<u>100</u>	200 <sup>a</sup>	<u>100</u>
SL0.5	5.96 <sup>ab</sup>	68	102 <sup>ab</sup>	84	127 <sup>ab</sup>	109	185 <sup>a</sup>	93
SL1	5.67 <sup>b</sup>	65	111 <sup>ab</sup>	92	124 <sup>ab</sup>	106	215 <sup>a</sup>	107
SL2	5.35 <sup>b</sup>	61	96.5 <sup>b</sup>	80	136 <sup>b</sup>	116	192 <sup>a</sup>	96
p Trial	0.002		0.000		0.000		0.000	
p Treatm	0.012		0.015		0.040		0.549	
p Trial*Treatm	0.111		0.010		0.012		0.558	

In the LC group, consisting of the trials with the lowest clay content at each site, the clay content varied from 19 to 28 % (group mean 22%). For this group, there was a significant effect on turbidity in 2015 ( $p = 0.046$ ), but no significant differences between the treatments in pairwise comparisons, while there was no significant effect of treatment in 2020 ( $p = 0.259$ ). Likewise, the LC group showed a significant treatment effect on electrical conductivity in 2015 ( $p = 0.008$ ), but no remaining effect in 2020 ( $p = 0.652$ ).

The clay content in soils in the HC group, consisting of the trials with the highest clay content at each site, varied between 26 and 47 % (group mean 32%). For the HC group, there were significant treatment effects on turbidity in both 2015 ( $p = 0.012$ ) and 2020 ( $p = 0.015$ ). In 2015, treatments SL1 and SL2 both gave significant reductions, of 35 and 39% respectively compared with the control, whereas in 2020 a significant decrease (of 20%) remained only in SL2. However, in 2020 there was a significant interaction ( $p = 0.010$ ) between trial and treatment. For this group, there was a significant effect of structure liming on electrical conductivity ( $p = 0.040$ ) in 2015 and also a significant interaction ( $p = 0.012$ ) between trial and treatment, but no remaining effect on electrical conductivity at the sampling in 2020 ( $p = 0.549$ ).

## Discussion

This analysis of soil aggregates from eight trials showed clear positive effects of structure lime on soil pH and aggregate stability one and six years after application.

### Declining pH effect

The comparison between 2015 and 2020 showed that changes in both pH and Ca-AL as a result of structure liming diminished over time. In 2015, there was a significant pH effect in all limed treatments in comparison with the unlimed control, but in 2020 there was only a statistically significant pH effect in treatments SL1 and SL2. This is in line with Blomquist et al. (2018), who reported a time-dependent rise and fall in pH over three years as a result of structure liming. Similarly, Norberg et al. (2021) found an initial rise in soil pH in the first year after structure liming, followed by a decrease in the second year.

The initial pH increases in 2015 also differed between the soils in the different trials, resulting in a significant interaction between treatment and trial whereby the lower the initial pH value in the soil, the greater the increase in pH as a result of structure liming (Fig. 3). A similar interaction was found by Siman et al. (1984), although they concentrated on the difference between trials and did not perform statistical analyses on interactions in the grouped data. The interaction observed in the present study could be due to the fact that calcium carbonate dissolves less readily in alkaline soils than in acidic soils.

For soil Ca-AL content there was a less pronounced reaction to structure liming, with a significant increase at the highest liming rate (treatment SL2) compared with the control in 2015, but no remaining statistically significant differences between treatments in 2020. This fits well with results reported by Olsson et al. (2019), who detected significant increases in soil Ca-AL content with increasing application rate of ground limestone (calcium carbonate) from 0 to 32 t ha<sup>-1</sup>.

### Decreasing aggregate stability

The significantly improved aggregate stability observed in 2015, approximately one year after structure liming, had decreased by the time of the repeated sampling five years later (Fig. 4). Thus, on average for the eight field trials the initial effect was transient. However, there were great differences in reaction to liming between the soils (Figs. 5 and 6), suggesting that it is inappropriate to use average values of the effects of structure liming in general advice and recommendations to farmers. The great variation in aggregate stability observed following structure liming means that it can be a blunt tool when used to reduce the risk of phosphorus losses from clay soils at national level. In fact, the variation seen indicates a need for a site-specific application strategy and for soil characteristics to be taken into consideration. In a previous study, we observed this type of interaction between liming treatment and trial in the short term (Blomquist et al. 2022) and suggested that the interaction derives from soil properties such as clay content and soil organic matter, clay mineralogy, initial pH and management factors such as tillage before and after structure liming.

### Neighbouring trials with opposing results

This inherent soil properties perspective was applied to the two sites where an effect on aggregate stability was actually detected (Krageholm and Lönhult). When the Krageholm HC and LC trials were analysed together, the liming treatment gave a significant treatment effect compared with the unlimed control in both 2015 and 2020 (Fig. 5), i.e. structure liming had an initial and a lingering effect. However, further analysis revealed that the effect on aggregate stability at Krageholm derived only from the trial with higher clay content (Krageholm HC, clay content 28%), which showed an increase in aggregate stability in both sampling years, while the soil at Krageholm LC trial (clay content 19%) did not show any improvement in aggregate stability in either year. Despite the difference in clay content, these two field soils are situated close to each other (within 200 m). The contrasting behaviour of the two soils at the Krageholm site shows the importance of clay content in determining the duration of structure liming effects. Similarly, Keiblinger et al. (2016) found that the effect of quicklime (CaO) on aggregate stability was related to the clay content, and attributed this to the flocculating effect of applying calcium ions to a higher surface area (clay content) and also to greater availability of exchange sites (cation exchange capacity, CEC).

### Clay is crucial

The importance of clay content is emphasised further by the results in Table 4. The group of LC soils (mean clay content 22%) showed significant treatment effects on aggregate stability (turbidity) initially, but transient effects over time. In the HC group (mean clay content 32%), the effects of structure liming were greater and significant in both sampling years. Electrical conductivity, used here as an indicator of presence of soluble calcium in the soil solution, showed significant increases in 2015 and non-significant effects in 2020 for both the LC and HC groups. Considering these differences between the groups in effect on turbidity but not EC, it can be deduced that more calcium ions were consumed in aggregate stability reactions in the soils in the HC group.

The initial pH was lower and soil organic matter content was higher in the LC group than in the HC group. Based on suggestions by Blomquist et al. (2022) that structure liming may be more effective in stabilising aggregates on soils with low pH and high SOM, stronger responses could have been expected for the LC group, which was not the case (Table 4). Thus, it appears that clay content, rather than pH and organic matter, was the conclusive soil property for the differences between the LC and HC groups in this study.

## Initial pH also has an effect

The Lönhult site produced some intriguing results regarding aggregate stability. Lönhult HC and LC trials analysed together showed a significant treatment effect compared with the unlimed control in 2015, but this effect had vanished by 2020 (Fig. 5). Both trials showed the same pattern in 2015 (Fig. 6), although the effect for Lönhult HC was only close to statistical significance ( $p = 0.062$ ). The clay content was sufficiently high in both cases (28% and 47% in LC and HC soil, respectively) for a liming response to be detected, as discussed above using the clay content in Krageholm HC soil (clay content 28%) as the yardstick. The transient effect can possibly be explained by the high initial pH in both Lönhult soils (pH 7.7 in Lönhult LC, pH 8.2 in Lönhult HC) compared to mean pH of 6.4 in Swedish arable soils (Kirchmann et al. 2020). On comparing aggregate stability of three clay soils after addition of quicklime, Keiblinger et al. (2016) found the lowest increase for the soil with the highest initial pH, which they attributed to presence of calcium carbonate in the initial soil. We did not measure soil calcium carbonate content in this study, but the high pH in both Lönhult soils point to very high base saturation. In such alkaline conditions, the solubility of structure lime consisting of approximately 80% calcium carbonate would be low and dissolution would be retarded. Therefore, the loss over time of the initial increase in aggregate stability at Lönhult can be attributed to initially high pH. In contrast, the initially much lower pH at Krageholm (6.2–6.6) most likely allowed continuous release of calcium ions over time, resulting in gradually increased base saturation and a significant effect on aggregate stability in the sixth year after structure liming. It is known that an increase in base saturation on acidic soils leads to better soil structure (Wiklander 1963).

## Cation exchange short-lived

The cation exchange mechanism, proposed as the reason for increased aggregate stability at Krageholm, is relatively short-lived and needs continuous release of calcium ions to counteract losses through leaching down the soil profile. Pozzolanic reactions, on the other hand, are of a more long-term nature (Firoozi et al. 2017). A prerequisite for pozzolanic reactions to occur is that the affinity (i.e. base saturation) for calcium is satisfied (Bell 1996), as otherwise the calcium ions are consumed in cation exchange, leaving fewer available for pozzolanic reactions. Soil affinity for calcium was satisfied initially at the Lönhult site and the 15–20% of calcium hydroxide in the structure lime possibly resulted in pozzolanic reactions from the start, as a significant increase in aggregate stability was observed in 2015. However, an alkaline environment with elevated pH of >10.5 (Akula and Little 2020) or approximately 12 (Beetham 2015) is essential for the occurrence of modifying and stabilising pozzolanic reactions. Whether such alkaline conditions prevailed in the soil at any of the sites at application of structure lime or directly afterwards was not measured in this study.

## Discriminating mineralogy

If pozzolanic reactions actually took place at Lönhult, the lack of persistent aggregate stability increase in 2020 is surprising and the initial aggregate stability increase in 2015 is even more confusing. It is possible that pozzolanic reactions occurred, but that the amount of non-carbonated lime in the structure lime product (15–20% calcium hydroxide) was too low to give a sufficient and long-lasting effect detectable in aggregate stability measurements using turbidity as a proxy. The initial pH at the Vadensjö and Kornheddinge sites was also >7.5, so if pozzolanic reactions occurred at Lönhult they should also have occurred at those two sites. However, no corresponding aggregate stability increase was observed at Vadensjö and Kornheddinge, possibly because the higher clay content (average 37%, acting as the pozzolan) at Lönhult was the discriminating variable compared with Vadensjö and Kornheddinge (average clay content 24% and 25%, respectively). Another discriminating soil property was clay mineralogy, with a much lower SmV index at Lönhult (1.1) and higher values, indicating more expansive and swelling clay minerals, at Vadensjö (2.9) and Kornheddinge (1.9–3.1) (Table 3). Higher SmV index also indicates higher CEC, requiring more calcium ions to raise the base saturation level. The SmV index value at Lönhult may have been sufficiently low to saturate the affinity for calcium ions, leaving surplus ions for pozzolanic reactions. It has been suggested that differences in mineralogy between soils can influence the effectiveness of stabilisation processes (Kassim and Chern 2004).

The mechanisms involved in aggregate stabilisation can be examined in detail using e.g. X-ray diffraction or differential thermogravimetric analysis (Akula and Little 2020). Such an approach was beyond the scope of this study and therefore further work is needed to confirm the mechanisms involved in the observed increase and decrease in aggregate stability following structure liming of field soils.

## Conclusions

This study compared the effects of applying structure lime (approximately 80–85% ground limestone and 15–20% slaked lime) to clay soils on aggregate stability, using laboratory-measured turbidity as a proxy, one and six years after liming. As a mean for the three structure lime doses tested (4, 8 and 16 t ha<sup>-1</sup>), there were significant increases in aggregate stability compared with the unlimed control after one year and also after six years, although the effect declined over time. However, in both years there was a significant interaction between trial and treatment, indicating differences in response to structure liming on different soils. Thus, a site-specific application strategy is required, if the desired objective is to increase aggregate stability in order to mitigate phosphorus losses. Soil clay content and initial pH seemed to be decisive for a more persistent effect of liming on aggregate stability. Based on the results, we propose that soils with a minimum clay content of approximately 25% and pH <7 should be preferred for structure liming with the mixed product used in this study. The results also indicated that cation exchange was the main mechanism involved in aggregate stabilisation with the structure lime product used, since stabilisation by pozzolanic reactions and carbonation would require products with higher solubility and the ability to create very high pH (above 10–12).

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