Final report

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Long-term effects of liming on crops, soil and environment generates new knowledge on breadth and depth

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Introduction

During the last 15 years, several research projects at Nordic Beet Research (NBR) have shown that soils respond differently to liming in both crop yield and soil nutrient availability. To further study these effects on clay soils above 15%, field trials were set up on 13 fields during 2013 to 2015 (SLF-project HI344085). The used products were ground limestone ($CaCO_3$) and structure lime (Fostop Aktiv Struktur, a mixture of $CaCO_3$ and $Ca(OH)_2$). In the previous SLF-project, (O-15-20-357), effects on yield in spring barley, winter oilseed rape and winter wheat were studied in the 13 trials during 2015-2017. In 2018, the second rotation after liming began, starting with sugar beets on one of the farms. The aim of this project was to study yield in sugar beet in the second rotation and to further study yield in winter wheat and oil seed rape. The overall aim of this project was to study the long-term effects of liming on diseases, plant nutrients and soil structure including effects on phosphorus leaching.

Materials and methods

The 13 field trials are situated in Skåne on soils with a clay content exceeding 15%. The crop rotations and soil characteristics before liming are presented in Tables 1 and 2. Each trial consists of 3 blocks each with three treatments: No lime (L0), ground limestone (GL) 8 ton/ha, and structure lime (SL) 7.8 ton/ha. The application rate of lime in both products correspond to 4 ton CaO/ha. In the two first trials 2013, Linelund and Hörte13, slaked lime was used as structure lime. In the remaining 11 trials Fostop Aktiv Struktur, a mixture of slaked lime and ground limestone mixed to a content of approx. 20% non-carbonated lime was used.

Table 1. Crop rotations in the 13 field trials 2014-2021. SB = sugar beet, WWh = winter wheat, SWh=spring wheat, OSR = winter oil seed rape, Barley= spring barley. Harvested trials in green

	2014	2015	2016	2017	2018	2019	2020	2021
Linelund	**SB**	Barley	OSR	WWh	**SB**	Barley	OSR	
Hörtegården13	**SB**	Potato	Barley	OSR	WWh	**SB**	Korn	Potato
Hammenhög		**SB**	Barley	OSR	WWh	WWh	**SB**	Barley
Lindbyholm		**SB**	Barley	WWh	OSR	WWh	**SB**	
Hönnedal		**SB**	Potato	WWh	Strawberry	Strawberry	Strawberry	**SB**
Heddingedrift		**SB**	Barley	OSR	WWh	WWh	**SB**	Barley
Billeberga		**SB**	WWh	OSR	WWh	**SB**	Barley	
Ekeberg			**SB**	Barley	WWh	SWh	**SB**	
Vadensjö			**SB**	Barley	OSR	WWh	WWh	**SB**
Vallby			**SB**	Barley	OSR	WWh	**SB**	
Gislöv			**SB**	Barley	OSR	WWh	WWh	**SB**
Hörtegården15			**SB**	Potato	Barley	OSR	WWh	**SB**
Västraby			**SB**	Barley	Oat	WWh	WWh	**SB**

Yield in sugar beet, wheat and oil seed rape. 12 sugar beet trials in the second rotation after liming were harvested 2018-2021. Root weight, cleanness and sugar content were analysed and yield calculated. 13 trials with winter wheat were harvested during 2016-2019. Yield and quality determining parameters, such as plant density, shoot and ear counting, lodging etc was measured and graded. 9 trials with winter oil seed rape were harvested 2016-2019. Seed (kg/ha) and raw fat yield was measured. Two trials (Heddingedrift and Hörte13) suffered from technical problems during harvest and this in combination with diseases resulted in pod shattering of a large part of the seeds making the estimation of yield uncertain.

Table 2. Soil characteristics before liming in the 13 field trials. All values are averages of 9 measurements

Trial	Year of lime application	Clay content %	pH (H_2O)	Ca-AL	P-AL	K-AL	Mg-AL
				mg/100 g soil			
Linelund	2013	18	7.9	464	18.0	10.0	8.9
Hörte13	2013	18	7.4	314	7.1	9.5	13.0
Billeberga	2014	25	7.7	322	12.1	11.9	9.5
Heddinge	2014	27	7.4	382	6.4	13.4	16.2
Lindbyholm	2014	18	7.7	368	8.7	8.7	7.2
Hammenhög	2014	28	7.8	399	13.1	13.1	11.2
Hönnedal	2014	17	7.6	430	9.9	7.6	11.4
Ekeberg	2015	20	6.6	298	4.9	8.6	10.8
Vallby	2015	20	6.9	323	9.7	7.4	11.0
Gislöv	2015	25	7.0	380	51.4	27.7	11.6
Vadensjö	2015	20	7.2	276	17.1	15.4	7.4
Hörte15	2015	15	6.8	216	5.2	7.0	9.1
Västraby	2015	25	7.1	284	6.9	10.6	14.0

Free-living nematodes and plant diseases. Soil for extraction and identification of free-living nematodes was sampled in each plot in the spring. Diseases on the crops were assessed in field during each spring/summer and in bioassays in greenhouse where focus was on root diseases. Soil from each plot were sown with untreated seeds of sugar beet, winter wheat, and Chinese cabbage variety Granaat. The plants were grown in greenhouse, 23/19°C day/night regime and watering to water holding capacity. After four weeks, the roots of the plants were washed and infection of the plants were assessed. In wheat, growth stage DC 22-23, plants and roots were assessed for infection of diseases. Field plots were again at DC 83 assessed for diseases. Winter oil seed rape was assessed for diseases at the time of maturing. Roots and plants parts were studied using selective agar media and microscope.

Soil structure. In the spring, immediately after sugar beet drilling, measurements of aggregate size distribution in the seedbed (approximately 0–4 cm) were performed. Volume fractions of each of three different size classes (<2 mm, 2–5 mm and >5mm) were measured. After drying of the middle-sized fraction, 2–5 mm, the aggregate stability was assessed by measuring turbidity (Turb. A2) and electrical conductivity (EC A2) in the leachates from aggregates after two repeated simulated rainfall events, 24 h apart. Turbidity is an indication of suspended soil particles in water and in turn closely correlated with losses of particulate phosphorus. In the 1^{st} year following the sugar beet crop lysimeters consisting of PVC pipes (height 150 mm, inner diameter 190 mm) were gently forced perpendicularly into the soil using a loader mounted on a tractor. The undisturbed soil profiles from the topsoil were placed in a rain simulator where they were subjected to two rainfall events, 24 h apart. The leachate after the second rainfall event was analysed for turbidity (Turb. L2), electrical conductivity (EC L2) and also for concentrations of total phosphorus (Tot-P) and dissolved phosphorus (PO_4-P). Particulate phosphorus (Part-P) was estimated as the difference between Tot-P before and after filtration of leachate with the same filters. Only turbidity and EC data from the second simulated rainfall event (Turb. A2, Turb. L2, EC A2, EC L2) are reported.

Plant nutrients. Soil for chemical analyses were sampled in each replicate before drilling of the crops and analysed for $pH_{(H2O)}$, plant-available P, K, Mg and Ca by the ammonium acetate lactate (AL) method (Egnér *et al.*, 1960); Fe, Mn, Zn and Cu with CAT-extraction (CEN EN 13651:2001). For analysis of plant nutrients, leaves from each replicate plot were sampled from sugar beet in the 4-6 leaf stage and from wheat in DC30-31. The samples were sent for analysis of concentrations of P, K, Ca, Mg, S, Mn, B, Zn, Cu and Fe.

Statistical analyses. Analysis of variance (ANOVA) was performed on yield, nematodes and plant diseases in sugar beet, winter wheat and oil seed rape using Sigma plot 14.5. ANOVA was performed on aggregate size distribution (GLM in Minitab 19), and on turbidity A2 and electrical conductivity (EC A2) and phosphorus concentrations. For lysimeter data (turbidity L2, electrical conductivity EC L2) log transformation was necessary to meet the requirement of normal distribution of residuals with the same variance. Following ANOVA, the averages were back-transformed, and are reported as relative values. Differences referred to are significant unless otherwise stated, while *p*-values between 0.05 and 0.1 were taken to indicate tendencies.

Results

Yield in sugar beet, wheat and oil seed rape. Sugar yield, root yield and soil nutrients in 12 trials 2018-2021 are presented in Table 3. There were no interactions between treatment and trial. There was a difference only for pH, which was 7.4 in GL, and SL compared to 7.0 in L0.

Table 3. Sugar yield (SY), root yield (RY), sugar content (SH), soil pH and soil Ca-, P-, K-, Mg-AL in the second rotation, i.e. 5-6 years after liming, in 12 trials

Treatment	SY	RY	SH %	pH (H_2O)	Ca-AL	P-AL	K-AL	Mg-AL
	ton/ha				mg/100 g soil			
L0	16.2	91.7	17.6	7.0	336	13.9	14.0	13.1
GL	16.4	92.9	17.7	7.4	362	14.4	13.1	12.2
SL	16.3	92.3	17.7	7.4	386	14.4	14.3	13.1
P (trial)	*<0.*	*<0.001*	*<0.001*	*<0.001*	*0.021*	*<0.001*	*<0.001*	*<0.001*
P (treatm)	*ns*	*ns*	*ns*	*<0.001*	*ns*	*ns*	*ns*	*ns*
P (trial x treatm)	*ns*	*ns*	*ns*	*ns*	*ns*	*ns*	*ns*	*ns*

The trials were divided into two groups based on initial pH ≤7.2 or >7.2 before liming (Table 2), due to findings by Kirchmann et al., (2020). There were interactions between treatment and trial for sugar yield and root yield in the group with pH ≤7.2 (Table 4). Sugar yield was 0.6 ton/ha higher in GL and 0.8 ton/ha higher in SL than in L0 (p=0.016). There was no difference in sugar content between the treatments or soil nutrients but pH increased from 6.7 to 7.1 in GL and 7.0 in SL. There were no interactions between treatment and trial except for pH in the group with initial pH >7.2 (Table 5). In this group there was a difference in pH which increased from 7.1 in L0 to 7.5 in GL and 7.6 in SL.

Table 4. Sugar yield (SY), root yield (RY), sugar content (SH), soil pH and soil Ca-, P-, K-, MgAL in the second rotation after liming in 5 trials (Vallby, Ekeberg, Gislöv, Hörte15, Västraby) with pH ≤7.2 before liming

Treatment	SY	RY	SH %	pH (H_2O)	Ca-AL	P-AL	K-AL	Mg-AL
	ton/ha				mg/100 g soil			
L0	15.8	89.7	17.6	6.7	307	18.3	16.9	14.1
GL	16.4	93.2	17.6	7.1	319	18.7	16.3	13.1
SL	16.6	93.6	17.7	7.0	322	17.5	17.4	13.9
P (trial)	*<0.00*	*<0.0*	*<0.001*	*0.008*	*<0.001*	*<0.001*	*<0.001*	*<0.001*
P (treatm)	*0.016*	*0.006*	*ns*	*<0.001*	*ns*	*ns*	*ns*	*ns*
P (trial x treatm)	*0.002*	*<0.0*	*ns*	*ns*	*ns*	*ns*	*ns*	*ns*

Table 5. Sugar yield (SY), root yield (RY), sugar content (SH), soil pH and soil Ca-, P-, K-, MgAL in the second rotation after liming in 7 trials (Linelund, Billeberga, Hammenhög, Heddinge, Lindbyholm, Hönnedal, Hörte13) with pH >7.2 before liming

Treatment	SY	RY	SH %	pH (H_2O)	Ca-AL	P-AL	K-AL	Mg-AL
	ton/ha				mg/100 g soil			
L0	16.4	93.1	17.7	7.1	356	10.8	11.9	12.4
GL	16.4	92.8	17.8	7.5	392	11.3	10.7	11.6
SL	16.1	91.3	17.7	7.6	431	12.3	12.1	12.5
P (trial)	*<0.001*	*<0.001*	*<0.001*	*0.044*	*ns*	*<0.001*	*<0.001*	*<0.001*
P (treatm)	*ns*	*ns*	*ns*	*0.005*	*ns*	*ns*	*ns*	*ns*
P (trial x treatm)	*ns*	*ns*	*ns*	*ns*	*ns*	*ns*	*ns*	*ns*

In winter wheat, there were no interactions between treatment and trial for yield and soil nutrients (Table 6) except pH which was 7.2 in L0 and 7.7 in GL and 7.6 in SL (p<0.001) and there was a tendency to interaction between treatment and trial. There was also a tendency for higher Ca-AL in GL and SL compared to L0. In both groups, ≤7.2 and >7.2, there were no difference in yield but a difference between the treatments for pH (p<0.001) and a tendency to higher Ca-AL in GL and SL than in L0. There was a tendency to interaction between trial and treatment for pH in the group with pH >7.2.

Table 6. Yield and soil nutrients in the second rotation, i.e. 5-6 years after liming in winter wheat, 13 trials 2016-2019, 11 trials for soil nutrients (Hörte13 and Ekeberg missing)

Treatment	Yield	pH (H_2O)	Ca-AL	P-AL	K-AL	Mg-AL
	kg/ha		mg/100 g soil			
L0	9583	7.2	319	14.5	14.7	11.5
GL	9558	7.7	394	15.3	14.3	11.4
SL	9588	7.6	369	14.9	15.3	11.6
P (trial)	*<0.001*	*<0.001*	*0.004*	*<0.001*	*<0.001*	*<0.001*
P (treatm)	*ns*	*<0.001*	*0.052*	*ns*	*ns*	*ns*
P (trial x treatm)	*ns*	*0.073*	*ns*	*ns*	*ns*	*ns*

In winter oilseed rape, there were no interactions between treatment and trial for yield and soil nutrients in 9 trials (Table 7). There were lower seed and raw fat yield for SL than in L0 and GL, 101 and 95 kg/ha respectively.

Table 7. Yield and soil nutrients in winter oilseed rape, 9 trials yield (Linelund, Hammenhög, Billeberga, Heddingedrift, Vadensjö, Vallby, Lindbyholm, Hörte15, Hörte13). 8 trials pH etc (Hörte15 missing)

Treatment	Seed	Raw fat	pH (H_2O)	Ca-AL	P-AL	K-AL	Mg-AL
	kg/ha	kg/ha		mg/100 g soil			
L0	3670	1791	7.2	376	11.0	12.2	12.2
GL	3640	1785	7.7	464	12.4	11.8	12.0
SL	3452	1690	7.7	460	12.3	13.2	13.0
P (trial)	*<0.001*	*<0.001*	*<0.001*	*0.044*	*<0.001*	*<0.001*	*<0.001*
P (treatm)	*0.026*	*0.036*	*<0.001*	*ns*	*ns*	*ns*	*ns*
P (trial x treatm)	*ns*	*ns*	*ns*	*ns*	*ns*	*ns*	*ns*

In the group with pH >7.2 (Table 8), there were no interactions between treatment and trial but a tendency to lower seed and raw fat yield in SL compared to GL and L0, for seed yield

273 kg/ha and raw fat 99 kg/ha compared to L0. There were also a difference in pH which was 7.8 in GL and SL and 7.4 in L0. There were also a difference in pH which was 7.8 in GL and SL and 7.4 in L0. CAT analysis of micro soil nutrients showed that the amount of Fe was lower in SL than in L0 (data not shown). In the group with initial pH ≤7.2, there were no interactions between treatment and trial and no difference in seed or raw fat yield between the treatments (Table 9). CAT analysis of micro soil nutrients showed a tendency that B differed between the treatments (data not shown).

Table 8. Yield in winter oilseed rape, 3 trials yield pH ≤ 7.2 (Vadensjö, Vallby, Hörte15), 2 trials pH etc (Hörte15 missing)

Treatment	Seed	Raw fat	pH (H_2O)	Ca-AL	P-AL	K-AL	Mg-AL
	kg/ha	kg/ha		mg/100 g soil			
L0	4402	2134	6.7	312	14.7	13.5	12.4
GL	4230	2073	7.5	425	15.8	12.3	11.6
SL	4165	2035	7.2	360	15.5	15.3	13.0
P (trial)	*<0.001*	*<0.001*	*ns*	*0.021*	*0.006*	*<0.001*	*<0.001*
P (treatm)	*ns*	*ns*	*0.006*	*ns*	*ns*	*ns*	*ns*
P (trial x treatm)	*ns*	*ns*	*ns*	*ns*	*ns*	*ns*	*ns*

Table 9. Yield in winter oil seed rape, 6 trials pH >7.2 (Linelund, Hammenhög, Billeberga, Heddingedrift, Lindbyholm, Hörte13)

Treatment	Seed	Raw fat	pH (H_2O)	Ca-AL	P-AL	K-AL	Mg-AL
	kg/ha	kg/ha		mg/100 g soil			
L0	3304	1620	7.4	398	9.8	11.8	12.1
GL	3345	1642	7.8	477	11.3	11.7	12.1
SL	3096	1517	7.8	493	11.2	12.6	13.1
P (trial)	*<0.001*	*<0.001*	*ns*	*ns*	*0.001*	*<0.001*	*<0.001*
P (treatm)	*0.058*	*0.070*	*0.003*	*ns*	*ns*	*ns*	*ns*
P (trial x treatm)	*ns*	*ns*	*ns*	*ns*	*ns*	*ns*	*ns*

Free-living nematodes and plant diseases. The species of free-living nematodes identified in the trials were two species of root lesion nematodes, *Pratylenchus thornei* and *P. neglectus*, the pin nematode *Paratylenchus* spp. Needle nematodes, *Longidorus* spp.were found in two trials, Hörte13 and Hönnedal and *Trichodorus* spp. only in one trial, Hörte13. There were no differences between the treatments in any of the trials. Aphanomyces root rot was the most common disease on sugar beet. There was a tendency to lower DSI in SL for all 13 trials (p=0.096), and differences in infection between trials (p<0.001). The DSI in L0 for the 6 trials with pH ≤7.2 was 72 compared to 55 in the 6 trials with pH >7.2. In winter wheat, *Fusarium culmorum*, *Rhizoctonia cereale* and *Pythium* spp were common in the root system. There were no differences of the treatments in DSI in the field or in the bioassay, and no difference in fresh weight of the plants. Pathogens found in the head of the plant at DC83 were *F. culmorum, Microdochium nivale*, and *R. cereale*. There were no differences in fusarium head blight between the treatments. The number of whiteheads (wh) showed a tendency to interaction between trial and treatment (p=0.06). Västraby was the site with the highest wh/m^2. Västraby was also the site with highest DSI of field plants (DSI = 42), caused by *F. culmorum, R. cerealis* but especially by *Pythium* spp. with high occurrence of oospores in the roots. Plants with half sided wilt, *Verticillium longisporum*, were found more frequently in 2018 compared to 2017. A PCR test for *V. longisporum* was also performed in 2017 on collected stems, which verified the field assessments. Wilted plants with sclerotia of *Sclerotinia sclerotiorum* were found in three fields in 2017, and most in Hörte13 and Heddingedrift, where also pod shattering and seeds falling to the ground could be seen. Wilted plants without sclerotia or half sided wilt were counted as infected by *Phoma*.

Soil structure. There were differences in aggregate size distribution (p <0.001) between the trials in all three size classes (Figure 1). There were also treatment effects and both limed treatments GL and SL showed a finer tilth in the seedbed compared to L0. Treatments GL and SL had a higher proportion of aggregates with the finest average diameter <2 mm (p<0.001). Treatment SL also had a lower proportion of aggregates in the coarsest fraction >5 mm (p<0.001) whereas treatment GL showed no difference compared to L0. In the fraction with aggregates 2–5 mm there were no differences between the treatments (p=0.773). There were no interactions between treatment and trial in any of the size classes (p=0.569 for <2 mm; p=0.185 for 2–5 mm; p=0.399 for >5 mm).

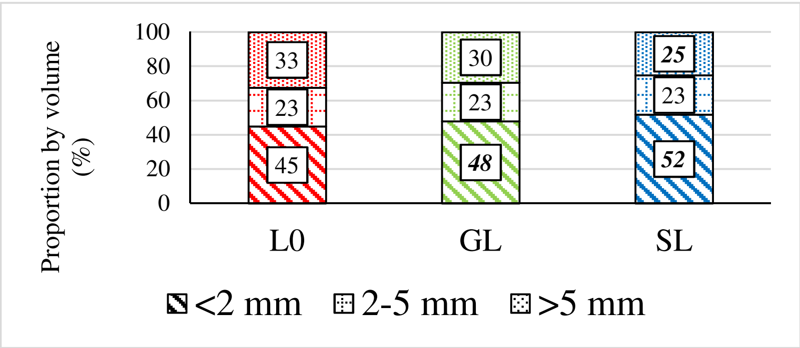

Figure 1. Aggregate size distribution in sugar beet seedbeds in spring immediately after drilling in 2018–2021. Results from 12 field trials. Differences (p<0.001) in aggregate size classes compared with the untreated control (L0) are indicated in bold italics.
GL = ground limestone
SL = structure lime.

The electrical conductivity EC A2 showed increases in GL and SL compared with L0 (p=0.001) without an interaction between treatment and trial (p=0.083) (Figure 2).
On average both limed treatments showed reductions in turbidity A2 compared with the unlimed control (p<0.001). However, the statistical analysis also revealed an interaction between treatment and trial (p=0.020), indicating that the different soils (trials) reacted differently to the lime treatments.

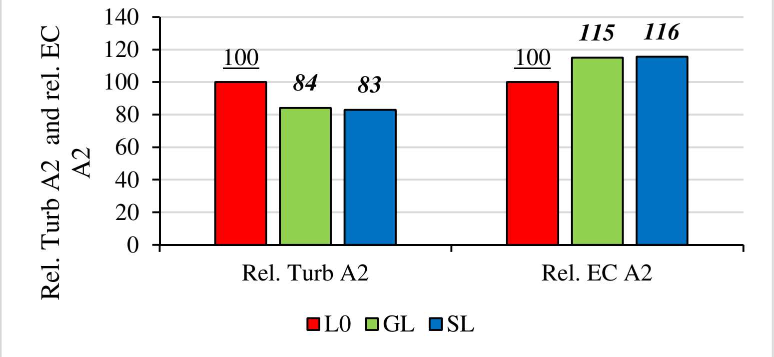

Figure 2. Relative turbidity A2 and relative electrical conductivity EC A2 of leachate from aggregates 2–5 mm after 2nd rain simulation. Results from 12 field trials. Differences (p<0.001) compared with the untreated control (L0) are indicated in bold italics.
GL = ground limestone
SL = structure lime.

For lysimetric turbidity L2 (Figure 3) the statistical analysis showed treatments effects (p=0.035). However, the pairwise comparison showed no differences between the treatments. There was no interaction between treatment and trial (p=0.829). For EC L2 there was a tendency (p=0.061) for treatments effects, and no interaction between treatment and trial (p=0.156) (Figure 3). There were treatments effects on concentrations of total-P (p=0.017) and particulate-P (p=0.027) (Figure 4). The pairwise comparison showed lower total-P and particulate-P concentrations in treatment SL compared to the unlimed control L0 but not between L0 and treatment GL. There was no interaction between trial and treatment for neither total-P (p=0.972) nor particulate-P (p=0.756). For concentrations of PO_4-P there were no effects of lime treatment.

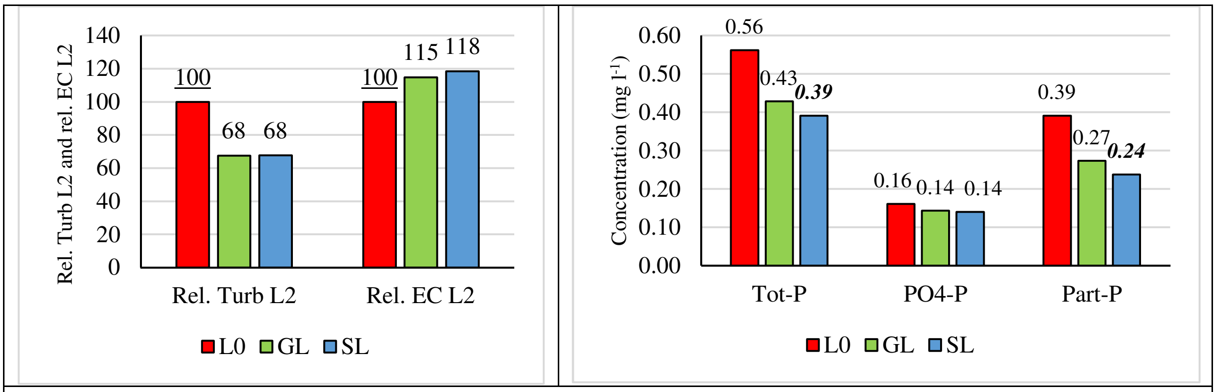

Figure 3 and 4. Relative turbidity L2 and relative electrical conductivity EC L2 of leachates from lysimeters and concentrations of total-P, PO_4-P and particulate-P in leachates after second rain simulation. Results from 6 field trials. Differences compared with the untreated control (L0) are indicated in bold italics, Tot-P (p=0.017) Part-P (p=0.027). GL = ground limestone, SL = structure lime.

Plant nutrients. There were no interactions between treatment and trial (12 sugar beet trials). Differences between treatments were found for Ca, Mn, B and Mo. Ca and Mo increased whereas Mn and B decreased in the plants. In the group with pH $\leq$7.2, a difference between treatments were found for B which was lower in GL and SL than in L0 (p=0.003). There was a tendency to higher Ca and S in GL and SL than in L0 (p=0.082 and 0.073, respectively). In the group with pH >7.2, there was an interaction between treatment and trial for Fe. Differences between treatments were found for Mn (p =0.019) and Mo (p<0,001). Mn decreased in GL and SL whereas Mo increased in GL and SL. There was a tendency to lower B in GL and SL than in L0 (p=0.074. Plant nutrients were measured in 5 trials with oil seed rape, all with an initial pH before liming >7.2. There was an interaction between treatment and trial for Mo. Mo was higher in GL and SL than in L0 (p <0.001). For other plant nutrients (Mn, B, Cu, Zn, Fe, Ca, Mg, S, P, K, N) there were no differences between treatments.

Discussion

Liming of trials with an initial pH >7.2 and a clay content >15% showed no differences in sugar yield or root yield for either types of lime (Table 3) except for Hörte13 where there was lower sugar yield for SL than in GL and L0. In this trial, slaked lime was used instead of structure lime. Both GL and SL showed a similar pH at Hörte13, 7.8 and 7.9 respectively. There were no differences in plant nutrients that can explain the lower yield. In contrast, trials with pH $\leq$7.2 before liming gave an increase in sugar yield for both types of lime 0.6 ton/ha for GL and 0.8 ton/ha for SL as an effect of higher root yield (Table 4) and pH increased from 6.7 in L0 to 7.1 in GL and 7.0 in SL. There were interactions between trial and treatment for sugar yield and root yield in the group with pH $\leq$7.2 before liming which included five trials (Ekeberg, Vallby, Gislöv, Hörte15 and Västraby). At Ekeberg, with a history of problems with Aphanomyces root rot, sugar yield (p<0.001) and root yield (p<0.001) increased for GL and SL compared to L0. K-AL increased from 7.7 mg/100 g soil in L0 to 8.8 in GL and 9.8 in SL (p<0.05) which may partly explain the increase in sugar yield. Plant weight in the 4-6 leaf stage was higher in GL and SL compared to L0. At Vallby, sugar yield (p<0.05) and root yield (p<0.05) increased for SL and pH (p<0.05) increased in both liming treatments. The 3 remaining trials, Gislöv, Hörte15 and Västraby, showed no differences in sugar yield or root yield. At Västraby and Gislöv, pH increased from 6.8 and 6.7 to 7.2 and 7.1 respectively. At Hörte15 there was no increase in pH which was below 7 in all treatments and the sugar yield was very high in all treatments, around 20 ton/ha. For oilseed rape, there was no difference in raw fat yield in the group with pH$\leq$7.2. In contrast, there was a tendency (P=0.058) to lower raw fat yield in the group with initial pH>7.2 which was lower in SL (app. 100 kg/ha) than in

L0 and GL (Table 9). There were no differences in soil or plant nutrients that can explain the lower yield in SL and this remains to be further investigated.

Sugar beet is sensitive to low pH and current recommendations aim at pH=7 when sugar beets are grown in the rotation. In the study by Kirchmann et al., (2020) it was concluded that a threshold pH below which yields were constrained was 7.2 for sugar beet and winter wheat and 7.1 for winter oil seed rape. The results shown in the present study are in line with these findings for sugar beet and winter oil seed rape. The results from the analysis of winter wheat showed no differences between the treatments in yield, neither in the total data set of 14 trials nor in the two groups with pH >7.2 or ≤7.2. Only one individual trial, Västraby, showed a tendency (p=0.071) to higher wheat yield in GL with 0.3 ton/ha and 0.6 ton/ha for SL. In this trial, the infestation of *Pythium* was very high and the lime treatments may have reduced the infection.

The seedbed aggregate size distribution (Figure 1) showed that applying both types of lime ameliorated the sugar beet seedbed in spring by producing a finer tilth, i.e. the seedbeds showed a higher proportion of the aggregate size <2 mm where lime had been applied 5–6 years prior to measurements. Structure lime in treatment SL turned out to be a slightly sharper weapon in producing a finer tilth compared to treatment GL as also the fraction of coarse aggregates >5 mm was lower with SL, not only compared to the unlimed control L0, but also compared to ground limestone in treatment GL. The result from this study is in line with observed effects from structure lime in previous studies under Swedish conditions (Blomquist, 2021). The seedbeds in this study were examined in the 2nd crop rotation in the years 2018–2021, 5–6 years after liming. Thus the results can be compared with results from the 1st crop rotation where seedbeds were examined approx. 1.5 year after lime application (Gunnarsson et al., 2022). Surprisingly, the comparison showed a more pronounced effect of lime application on aggregate size distribution over time. Altogether our results showed that SL contributed with a distinct improvement of the seed bed characteristics. From a management perspective this means agronomic advantages as seed bed preparation is facilitated, and as decreasing aggregate size has been shown to increase emergence. This contribution can be utterly important under dry conditions where a finer tilth delivers crop security by protecting the seedbed from evaporation. Crop establishment can also most likely be improved by liming as a coarser seedbed results in deeper and a more variable seed placement.

Decreased turbidity in the leached water in the rain simulation of aggregates 2–5 mm (Figure 2, turbidity A2) demonstrated that aggregate stability was improved on average, and to the same extent with both lime treatments. This observation matches well results from other studies on structure liming and aggregate stability under field conditions (Blomquist et al., 2022b). The increased aggregate stability implies that the risk of particulate P losses on average is reduced. However, the interaction between lime treatment and trial illustrates that the reaction to liming is vastly different on different soils. The underlying mechanism for different reactions is illusive and needs to be addressed for better precision if the aim of structure liming is to be a cost-effective environmental measure. Also regarding aggregate stability a comparison over time is possible collating results from the 1st and the 2nd crop rotation. Gunnarsson et al. (2022) reported decreased turbidity by on average 43 and 35 percent in GL and SL treatments compared to unlimed control, with no differences between the two limed treatments. In the 1st crop rotation aggregates were sampled approximately 1.5 years after liming. Results from the present study in the 2nd crop rotation (Figure 2) showed a decrease in turbidity of 16–17 percent in the limed treatments compared with the unlimed control, i.e., similar effects on aggregate stability of both liming products, but decreasing effects over time. Diminishing effects with the structure lime product used also in this study was demonstrated by Blomquist et al. (2022a).

A novelty in the analysis of the effect of liming in the 2nd compared to the 1st crop rotation was the sampling of lysimeters – undisturbed soil cores from the topsoil (0–15 cm). Lysimeters can better reflect processes in the topsoil after liming and repeated incorporation, as opposed to aggregate sampling that only reflects what happens in the shallowly tilled seedbed. Turbidity results of the lysimeter leachates (Figure 3) showed treatment effects, even though the following pairwise comparison did not reveal statistically differences between treatments. However, analyses of different P fractions in leachates displayed lower total and particulate P concentrations in the structure limed treatment SL (Figure 4). It must however be underlined that these are preliminary results emanating from 6 of the 13 field trials. Complementary results from 4 more trials, expected in the first quarter of 2023, can modify conclusions.

Few studies have been performed with lysimeters in the field of liming. Therefore, a better benchmark to our lysimeter results can be achieved by comparing them with results from field trials with individually drained plots where discharge and P concentrations were measured. Under Swedish conditions three such studies have reported effects of structure lime where the actual P losses from subsurface drainage were measured. Svanbäck et al. (2014) found that structure liming with calcium oxide reduced losses of total and particulate P with approx. 40 percent on a clay soil (60% clay). Ulén and Etana (2014) observed reductions (approx. 50 percent) in losses of total P and also PO_4-P (expressed as dissolved reactive phosphorus (DRP)) after liming with what is reported as calcium hydroxide on a clay soil (25% clay). Recently Norberg and Aronsson (2022) reported reductions in losses of total P and PO_4-P from applications with a mix of calcium hydroxide and calcium carbonate, compared with an unlimed control. The application rate and type of structure lime is identical to treatment SL in our study in the 11 trials limed in 2014–15. Therefore, our tentative results, pointing at a 30–40 % reduction of total and particulate P from treatment SL, align well with what previously was reported.

The root lesion nematodes *P. thornei* and *P. neglectus* cause serious yield reductions in wheat worldwide. In sugar beet, they cause severe development of lateral roots leading to substantial harvest losses. We found no differences between the lime treatments in nematode densities 4 to 5 years after liming in this study. However, there was a general trend that populations of free-living nematodes were lower in the treatment with structure lime (SL) than in GL or L0. The short and long term effects of structure lime on soil biota has been known to have a negative effect on microbial communities.

In sugar beet, *Aphanomyces* spp. is causing plant loss and root rot. The bioassays indicated a high presence of spores and root rot potential in the soils, especially in the group of trials with at initial pH ≤7.2, (DSI = 72), compared to the group with pH >7.2 (DSI = 55). This has been reported earlier (Olsson et al., 2010) and there are also studies indicating that calcium is reducing the production of zoospores which is the main infecting unit of *Aphanomyces*. There was a tendency for reduction of Aphanomyces root rot from DSI = 63 in L0 to DSI = 58 in SL, mean for 13 field trials second rotation of sugar beet. A further result is that Ca-AL in the second rotation of sugar beet has not increased in any field trial except on one, indicating that the effect of the applied lime is reduced and possibly also the effect on *Aphanomyces*. In winter wheat there were no impact on yield and also no impact on diseases of GL or SL. The high initial pH in the 13 field trials is probably the cause for absence of *P. brassicae* causing clubroot in oilseed rape in the soil. None of the found diseases, *V. longisporum*, *P. lingam* and *S. sclerotiorum*, could be connected to the reduced yield in treatment with SL.

The cost of applying 4 ton CaO/ha as GL is 1180 x 4 = 4720 SEK (transport included) and as SL 890 x 4 = 3560 SEK (including LOVA subsidy and transport). For the group of trials with initial pH ≤7.2 the increases in root yield gives an additional income in the second rotation with 1558 SEK per hectare for GL and 1736 SEK for SL. When the income from the increases in root yield from the first rotation are added, 772 SEK for GL and 2776 SEK for SL, the total additional income is 2330 SEK for GL and 4512 SEK for SL. The cost of applying 4 ton CaO as SL is returned by higher yield in sugar beet in the two rotations with a net income of 952 SEK. The present recommended application rate of lime in the sugar beet rotation is to apply low rates, 2 ton CaO/ha, once in the rotation on soils with initial pH=6.5 to prevent suboptimal pH below 7. Liming of the type of alkaline soils with clay content >15% studied in this project has until now shown an increase in root yield in sugar beet in two rotations after liming. Repeated measurements of yield in different crops and soil characteristics in these trials are important and will further elucidate the long term effects on yield and economy of liming.

Conclusions

- Liming with GL and SL resulted in a finer tilth in sugar beet seedbeds, when measured 5-6 years after application.
- On average, liming with GL and SL increased aggregate stability but with an interaction between treatment and trial meaning different reactions to lime on different soils.
- Concentrations of Total-P and Particulate-P were reduced in leachates from lysimeters in treatment SL.
- There was a negative impact of structure lime on yield of oilseed rape in trials with initial pH >7.2. The reason for the yield reduction is not known and needs more research. It is concluded from these results that structure lime should be used with caution on soils with initial pH >7.2.
- There were no negative effects on yield in winter wheat, irrespective of initial pH before liming.
- Sugar yield was increased for both types of lime on soils with initial pH ≤7.2. Liming is recommended on soils with pH ≤7.2.

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Result dissemination:

Scientific publications, *published*	*Gunnarsson, A., Blomquist, J., Persson, L., Olsson, Å., Hamnér, K. & Berglund, K. 2022. Liming alkaline clay soils: effects on soil structure, nutrients, barley growth and yield. Acta Agriculturae Scandinavica, Section B—Soil & Plant Science, 72, 803-817*
Scientific publications, *submitted*	*Author(s), title*
Scientific publications, *manuscript*	*Olsson, Å, Persson, L, Blomquist, J., Berglund, K. Long-term effects of liming on crops, soil and environment. Man. In prep.*
Conference publications/ presentations	*Olsson Nyström, Å., Persson, L. 2022. Long term effects of structure lime on sugar beet growth and yield. 78th IIRB congress, Mons BL.*
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Student theses	*Author/Student, co-authors/supervisors, year, title, type of thesis (doi/link if applicable)*
Other including	*Patents, book chapters, reference group meetings etc.*

Patents	