AGRICULTURAL AND FOOD SCIENCE

Agricultural and Food Science (2023) 32: 139–153
https://doi.org/10.23986/afsci.130983

# Long-term effects of liming on crop yield, plant diseases, soil structure and risk of phosphorus leaching

Åsa Olsson Nyström[1], Jens Blomquist[2], Lars Persson[1], Anita Gunnarsson[3] and Kerstin Berglund[2]

[1]Nordic Beet Research Foundation, Borgeby slottsväg 11, SE-237 91 Bjärred, Sweden

[2]Department of Soil and Environment, Swedish University of Agricultural Sciences, Uppsala, Sweden

[3]Rural Economy and Agricultural Society in Scania, Kristianstad, Sweden

e-mail: asa@agriscience.se

This study examined the long-term effects of applying structure lime (mixture of ~80% $CaCO_3$ and 20% $Ca(OH)_2$) and ground limestone ($CaCO_3$) on soil aggregate stability and risk of phosphorus (P) losses 5–7 years after liming, incidence of soil-borne diseases and yield in winter wheat (*Tritium aestivum*), oilseed rape (*Brassica napus*) and sugar beet (*Beta vulgaris*). Lime was applied in 13 field trials in Sweden 2013–2015 and soil characteristics and crop yield were monitored until 2021. Seedbed (0–4 cm depth) aggregate (2–5 mm size) stability was improved to the same extent with both lime treatments compared to the untreated control, sampled 5–7 years after liming. Analyses and estimations of different P fractions (total P, $PO_4$-P and particulate P) in leachate following simulated rainfall events on undisturbed topsoil cores sampled 6–8 years after liming revealed lower total P and particulate P concentrations in both lime treatments compared to the untreated control. Two sugar beet trial sites with soil pH ≤7.2 before liming showed an increase in sugar yield for structure lime and ground limestone as an effect of increased concentration of soil potassium (K-AL) and/or lower *Aphanomyces* root rot potential compared to the untreated control. Yield of winter wheat was not affected by application of either type of lime at sites with pH >7.2 but yield of oilseed rape decreased after application of structure lime.

*Key words*: structure lime, ground limestone, aggregate stability, phosphorus, sugar beet, soil-borne disease

## Introduction

Liming has multiple effects on soil, influencing e.g. soil structure, plant nutrition and soil-borne diseases (Holland et al. 2018). The most used types of lime in Sweden are ground limestone (calcium carbonate, $CaCO_3$) and factory lime, which is a waste product from the sugar extraction process at sugar mills. Lime is predominantly used to prevent acidification and to maintain sufficiently high soil pH for optimal nutrient supply in most crops. The current recommendation to correct soil acidity in the sugar beet rotation is to use ground limestone corresponding to 2 ton CaO $ha^{-1}$ (Andersson et al. 2023). Kirchmann et al. (2020) investigated more than 12 000 soil samples collected during 1992–2011 from arable soils in Sweden. The survey showed that the average pH was 6.4 ±0.7 but that several large regions had pH values around 6. The present liming recommendations in Sweden has a target pH value of 6.5 which is based on results from field trials being performed during 1984–1990 (Haak and Simán 1992). The results showed that liming to 70% base saturation was sufficient for most crops and increasing the base saturation above 70% gave no additional increase in yield. During the last three decades, the use of lime in Swedish crop rotations has been hampered by the weak relationship between pH and yield responses on soils with pH >6.5 in various crops. In Sweden, and in other countries, e.g. UK (Goulding 2016), liming is too often omitted by many farmers for economical reasons and difficulties in seeing the long-term effects on soil fertility and crop yields. However, the development and use of new high yielding varieties in many crops has put new focus on soil pH and increased nutrient demand. Further, the differences in yield response on different soil types has been shown also to be caused by differences in geological origin (Olsson et al. 2010, Blomquist et al. 2018, Holland et al. 2018, Olsson et al. 2019, Kirchmann et al. 2020).

Liming affects the development of many soil-borne diseases, especially those caused by the genera *Pythium, Phytophthora* and *Aphanomyces* (Kao and Ko 1986, Sugimoto et al. 2008, Olsson et al. 2010). Aphanomyces root rot in sugar beet (*Beta vulgaris* L.), caused by *A. cochlioides*, is common on acidic soils with low calcium (Ca) content and shows variable occurrence in southern Sweden. Calcium has been shown to interfere with zoospore infectivity which is reduced (Kao and Ko 1986, Deacon and Donaldson 1993, Broembsen and Deacon 1996, 1997). Clubroot disease caused by *Plasmodiophora brassicae* Woronin is a serious disease of cruciferous crops. Soil pH <7 promotes spore germination and increases clubroot incidence, so liming is an important control measure for this disease (Struck et al. 2022).

Received 12 June 2023 / Accepted 16 September 2023
The Scientific Agricultural Society of Finland

During the period 2010–2020, around 60 000 hectares in Sweden were limed with structure lime, which is a blend of ground limestone and slaked lime (calcium hydroxide, $Ca[OH]_2$). One reason for using this product is to increase soil aggregate stability and thereby reduce losses of phosphorus (P) to lakes and seas, where it causes detrimental eutrophication. Aggregate stability is affected by three reactions: cation exchange, pozzolanic reactions and lime carbonation (Blomquist et al. 2018). Liming with structure lime is an environmental measure subsidised by the Swedish Water Authority and is recommended on soils with clay content >15%.

In the present study, ground limestone and structure lime (Fostop Aktiv Struktur) were applied in 13 field trials in southern Sweden during the period 2013–2015, as part of a larger study examining the effects of liming on aggregate stability, risk of P losses, plant nutrition, incidence of soil-borne diseases and crop yields in sugar beet, barley (*Hordeum vulgare* L.), oilseed rape (*Brassica napus* L.) and winter wheat (*Tritium aestivum* L.). Soil structure 1.5–2 years after liming, crop yield and plant nutrition in barley under four different fertilisation strategies in the 13 trials have been reported in an earlier paper by Gunnarsson et al. (2022). Increased aggregate stability in the first crop rotation with both types of lime was reported in that study, and structure lime did not increase aggregate stability more than ground limestone, although seedbed characteristics were shifted towards finer aggregates (<2 mm) by use of structure lime (Gunnarsson et al. 2022). Early growth in barley was increased by both types of lime, but grain yield was not affected (Gunnarsson et al. 2022). More knowledge on the underlying factors determining the effects of lime on different soils is crucial to optimise liming of agricultural soils to increase productivity.

The aim of the present study was to assess the long-term effects of structure lime and ground limestone on soil structure and risk of P losses 5–8 years after liming, incidence of soil-borne diseases and yield in winter wheat, oilseed rape and sugar beet.

# Materials and methods

## Field trials and experimental design

All 13 field trials were performed in the Swedish province of Scania, on soils with clay content >15%. The crop rotations at the sites are shown in Table 1 and soil characteristics before liming are presented in Table 2.

Table 1. Crop rotations in the 13 field trials, 2014–2021. Measurements and soil sampling were performed in the crops indicated in bold.

| | 2014 | 2015 | 2016 | 2017 | 2018 | 2019 | 2020 | 2021 |
|---|---|---|---|---|---|---|---|---|
| Linelund | SB | Barley | **OSR** | **WWh** | **SB** | Barley | **OSR** | |
| Hörte13 | SB | Potato | Barley | **OSR** | **WWh** | **SB** | Barley | 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** |
| Hörte15 | | | SB | Potato | Barley | **OSR** | WWh | **SB** |
| Västraby | | | SB | Barley | Oats | **WWh** | WWh | **SB** |

SB = sugar beet; WWh = winter wheat; SWh = spring wheat; OSR = winter oilseed rape; barley = spring barley

Soils in the trials were not classified according to any international taxonomical system but the majority of the soils in the province of Scania are classified as Inceptisols (USDA Soil taxonomy). All trials had three replicates in a randomised block design with three treatments: No lime (L0); ground limestone (GL, particle size 0–0.2 mm) at 8 ton $ha^{-1}$; and structure lime (SL, particle size 0–0.5 mm) at 7.8 ton $ha^{-1}$. The application rate of both lime products corresponded to 4 ton CaO $ha^{-1}$. In the two first trials in 2013 (Linelund, Hörte13), slaked lime was used, application rate 5.6 ton ha$^{-1}$ corresponding to ~4 ton CaO ha$^{-1}$. In the remaining 11 trials, Fostop Aktiv Struktur (slaked lime and ground limestone mixed to a content of approx. 20% non-carbonated lime) was used. In addition to Ca, Fostop Aktiv Struktur contains 2.5% K, 1% Mg and 0.07% P. Ground limestone contains, 0.2% K, 0.3% Mg and 0.06% P. Each main plot (replicate) was 24 × 500 meters in 2013, 24 × 100 m in 2014 and 12 × 100 meters in 2015. Within each of the nine main plots there were four subplots measuring 24 × 20 meters in which measurements and harvest was performed. The lime was applied 28–30 September and was incorporated with different types of cultivators (discs and/or tines) in three passes in opposite directions directly after each other. Most of the fields were ploughed during October to November.

Table 2. Soil characteristics before liming in the 13 field trials. Sampling depth 0–30 cm. All values are means (n=9).

| Trial | Year of lime application | CEC meq 100 g$^{-1}$ | Clay content % | $pH_{(H20)}$ | Ca-AL[1] mg 100 g$^{-1}$ soil | P-AL[1] | K-AL[1] | Mg-AL[1] |
|---|---|---|---|---|---|---|---|---|
| Linelund | 2013 | 8 | 18 | 7.9 | 464 | 18.0 | 10.0 | 8.9 |
| Hörte13 | 2013 | 11 | 18 | 7.4 | 314 | 7.1 | 9.5 | 13.0 |
| Billeberga | 2014 | 10 | 25 | 7.7 | 322 | 12.1 | 11.9 | 9.5 |
| Heddinge | 2014 | 10 | 27 | 7.4 | 382 | 6.4 | 13.4 | 16.2 |
| Lindbyholm | 2014 | 9 | 18 | 7.7 | 368 | 8.7 | 8.7 | 7.2 |
| Hammenhög | 2014 | 6 | 28 | 7.8 | 399 | 13.1 | 13.1 | 11.2 |
| Hönnedal | 2014 | 8 | 17 | 7.6 | 430 | 9.9 | 7.6 | 11.4 |
| Ekeberg | 2015 | 10 | 20 | 6.6 | 298 | 4.9 | 8.6 | 10.8 |
| Vallby | 2015 | 9 | 20 | 6.9 | 323 | 9.7 | 7.4 | 11.0 |
| Gislöv | 2015 | 11 | 25 | 7.0 | 380 | 51.4 | 27.7 | 11.6 |
| Vadensjö | 2015 | 9 | 20 | 7.2 | 276 | 17.1 | 15.4 | 7.4 |
| Hörte15 | 2015 | 9 | 15 | 6.8 | 216 | 5.2 | 7.0 | 9.1 |
| Västraby | 2015 | 6 | 25 | 7.1 | 284 | 6.9 | 10.6 | 14.0 |

[1] Recommended values for most crops are for Ca-AL >250 mg 100 g$^{-1}$ soil, P-AL >8.0 mg 100 g$^{-1}$ soil, K-AL >8.0 mg 100 g$^{-1}$ soil and Mg-AL 4-10 mg 100 g$^{-1}$ soil (Andersson et al. 2023).

## Yield of sugar beet, wheat and oilseed rape

In each subplot, two nine meter long beet rows were harvested in October. The sugar beets were analysed for sugar content (%) and root yield (ton ha$^{-1}$). Sugar yield (ton ha$^{-1}$) was calculated for each main plot as average over the four subplots. Twelve trials with sugar beet in the second rotation after liming were harvested 2018–2021, which was 4–5 years after liming except for Hönnedal which was 6 years (Table 1). In winter wheat and oil seed rape, the harvest area in each subplot measured 16.32 m$^2$. Thirteen trials with winter wheat were harvested 2016–2019 and yield and quality-determining parameters such as plant density, shoot and ear counts, lodging etc. were measured and graded. Nine trials with oilseed rape were harvested 2016–2019 and seed yield (kg ha$^{-1}$) was measured and raw fat yield calculated.

## Soil-borne diseases

Soil for extraction and identification of free-living nematodes was sampled in each main plot in spring 2018–2021, before drilling of the sugar beet crop. Soil was collected to a depth of 0-30 cm and the total sample was comprised of around 20 soil cores. Nematodes were extracted with Baermann funnels (EPPO PM7/119) and morphologically identified to genus/species. Disease incidence in the crop was assessed in the field during each spring/summer and in bioassays in the greenhouse where the focus was on root diseases. In the bioassays, soil from each main plot was sown with untreated seeds of sugar beet, winter wheat and Chinese cabbage (*Brassica rapa* ssp. pekinensis cv. Granaat), which were grown in a greenhouse at 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 roots and hypocotyl was assessed and classified into one of six groups according to discolouration: 0 = healthy plant without symptoms; 10 = around 10% of the root system discoloured; 25 = 50% of the root system discoloured; 50 = 100% of the root system discoloured; 75 = 100% of the root system and the hypocotyl discoloured; and 100 = dead plant. Average disease severity index (DSI) for replicate pots (n=6) was calculated for each soil as:

$DSI = (0*n_0 + 10*n_{10} + 25*n_{25} + 50*n_{50} + 75*n_{75} +100*n_{100})/=n_{tot}$

where $n_{xx}$ is number of seedlings in each group. The Chinese cabbage was assessed for prescence of club root.

In wheat, 50 plants and roots from each main plot were assessed for presence of diseases such as *Fusarium* spp., *Rhizoctonia* spp. and *Pythium* spp. in growth stage DC22–23, and again in growth stage DC83. In oilseed rape, diseases caused by *Sclerotinia* spp., *Verticillium* spp. and *Phoma* spp. were assessed at maturation of the crop, by counting the number of infected plants. Wilted plants without sclerotia or with half-sided wilt were counted as infected by *Phoma*. Roots and plant parts were studied under the microscope and present fungi were identified using selective agar media. Presence of vascular wilt caused by *V. longisporum* was analysed on oilseed rape plants using a qPCR assay (Intertek ScanBi Diagnostics, Alnarp).

## Aggregate and topsoil stability

In the spring 5–7 years after liming, immediately after seed bed preparation and sugar beet drilling, measurements were made of aggregate size distribution in the seed bed (approx. 0–4 cm layer) according to Kritz (1983), and under the prevailing field conditions regarding e.g. soil moisture. Volume fractions of each of three different size classes (<2 mm, 2–5 mm, >5mm) were determined. After drying of the medium-sized fraction (2–5 mm), aggregate stability was assessed by measuring turbidity ($Turb_A$) and electrical conductivity ($EC_A$) in leachate from aggregates subjected to two simulated rainfall events 24 h apart. Rainfall intensity for seedbed aggregates was 32–39 mm per 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.

Turbidity is an indication of suspended soil particles in water and is on clay soils closely correlated with losses of particulate P (Ulén et al. 2012). In the first year following the second sugar beet crop (i.e. 6–8 years after liming), 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 and undisturbed soil profiles were extracted from the topsoil. These were placed in a rain simulator, where they were subjected to two rainfall events 24 h apart to assess topsoil stability and risk of phosphorus leaching. Rainfall intensity for lysimeters was 8–11 mm per hour. The irrigation boom moved back and forth during six hours but stopped at the starting position for 120 s after each pass back and forth, so the lysimeters were subjected to simulated rainfall for only 10 minutes in the six-hour period.

The leachate after the second rainfall event was analysed for turbidity ($Turb_L$), electrical conductivity ($EC_L$) and also for concentrations of total P and dissolved phosphorus ($PO_4$-P). Total P was analysed as soluble molybdate-reactive P after acid oxidation with $K_2S_2O_8$ (ISO 2005), while $PO_4$-P was analysed after pre-filtration using Sarstedt Syringe filter, Filtropur S, PES, pore size: 0.2 µm, for sterile filtration (ISO 2013), both by colorimetric determination. Particulate P was estimated as the difference in total 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, as differences between treatments were clearer after the second rainfall event.

## Plant and soil analysis

Soil for chemical analyses was sampled to a depth of 0–30 cm in each subplot before application of lime and before drilling of sugar beet and barley in spring, giving a total of 36 samples per trial and sampling time. Each soil sample was comprised of around 20 soil cores. In winter wheat and oilseed rape, soil was sampled in spring in the growing crop. All soil samples were analysed for $pH_{(H2O)}$, plant-available phosphorus (P), potassium (K), magnesium (Mg) and calcium (Ca) by the ammonium acetate lactate (AL) method (Egnér et al. 1960); and for iron (Fe), manganese (Mn), zinc (Zn) and copper (Cu) by CAT-extraction (calciumchloride/DTPA extractable nutrients, CEN EN 13651:2001). For analysis of CEC, 1.5 g of dried and grinded soil per sample was dispersed in 50 ml deionised water and gently shaken for 30 minutes. Then 25 ml of 10 mM Cu-trien solution was added and the samples was again shaken for 2 hours. The samples were centrifuged and the absorbance of the supernatant was measured at 620 nm. The concentration of Cu-trien in the supernatant was obtained from a calibration curve. The difference between added amount of Cu-trien and the measured amount gaves the absorbed amount of Cu-trien and from this, CEC was calculated.

For analysis of plant nutrients, leaves from 20 plants in each replicate were sampled at the 4–6 leaf stage in sugar beet, at DC 30–31 in wheat and at DC 52–53 in oilseed rape (BBCH Monograph 2018). The leaves were collected adjacent to the harvest rows/area. The leaves were cut off from the root system and weighed to obtain the fresh weight. The plants were then put in pre-weighed Gemmer bags and dried for three days in 60–70 °C. The bag and plants were weighed immediately after drying to obtain the dry weight of the plants. The plants were analysed for N, S, P, K, Ca, Mg, Cu, Zn, Mn, Fe, Na, Mo (Yara Analytical Services, Pocklington, UK).

### Economy

An example of the economical outcome of liming with GL and SL is presented in Table 8. The calculations are based on sugar beet root yields ($RY_1$, $RY_2$) in trials with pH ≤7.2 in the two harvested crops after application of lime. The current price (445 SEK $ton^{-1}$ beets) agreed by the beet growers and sugar industry was used to calculate the additional income from GL and SL as the total increase in root yield in two rotations × 445 SEK minus cost for application:

Additional income (SEK) = ($RY_1$+$RY_2$) × 445 SEK – 4 × application cost SEK $ton^{-1}$ CaO.

Costs for GL (750 SEK $ton^{-1}$ CaO) and for SL (890 SEK $ton^{-1}$ CaO), including transport and subsidy from The Swedish water authorities was estimated by extension specialists at The Rural Economy and Agricultural Society.

### Statistical analyses

Differences between treatments for soil and plant nutrients, nematode counts, diseases and yield were tested using analysis of variance (ANOVA) (Sigma plot 14.5). Multiple comparisons between treatments within trials were tested using Fischer's protected LSD method. Trials were considered as single crop years in given locations and interactions between treatments and trials were tested. ANOVA was performed on aggregate size distribution (GLM in Minitab 19), and on turbidity and electrical conductivity ($Turb_{A2}$, $EC_{A2}$). For lysimeter data ($Turb_{L2}$, $EC_{L2}$) and P concentrations, 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 where control treatment L0 was given relative value 100. Relative values are relevant to present as absolute values of turbidity vary vastly between sites and years. Differences referred to are significant unless otherwise stated, while *p*-values between 0.05 and 0.1 were taken to indicate a tendency for a difference.

## Results

### Yield of sugar beet, wheat and oilseed rape

Liming had no significant effect on sugar yield, root yield or soil nutrients in the 12 sugar beet trials in 2018–2021. There were no interactions between treatment and trial meaning that the outcomes from different trials and crop years did not differ (Table 3). There was a treatment effect ($p$< 0.001) for pH (Table 3).

Sugar yields in the second rotation after liming in individual trials are shown in Figure 1.

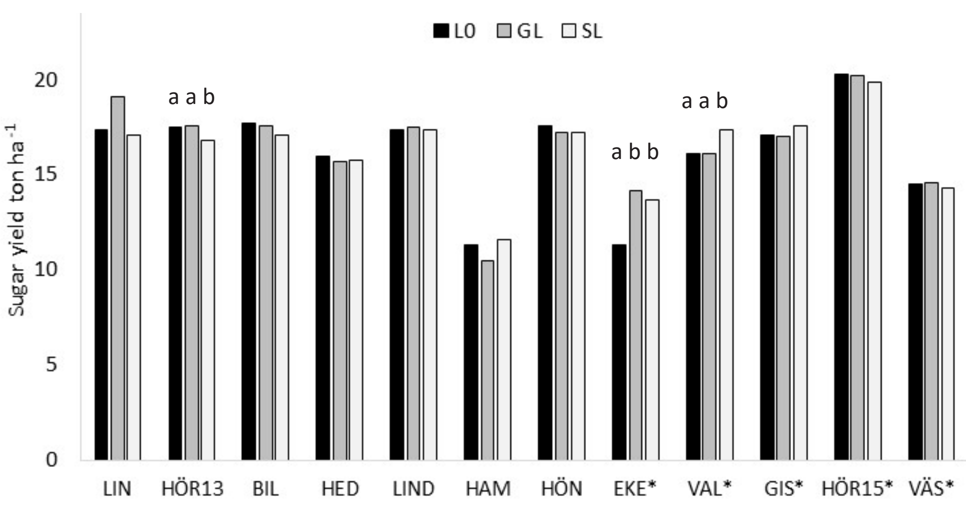


Fig. 1. Sugar yield in the second rotation after liming in individual trials. The trials are grouped according to initial pH before liming, > or ≤7.2 (marked with *). Significant differences between treatments are indicated by different letters above bars. Trials without letters above bars show no significant differences between treatments. L0= no lime, GL= Ground limestone and SL= structure lime

Two trials gave an increase in sugar yield, Ekeberg for both GL and SL and Vallby only for SL. Only one trial, Hörte13 in which slaked lime was used, gave a decrease in sugar yield for SL but not for GL. The remaining trials gave no differences between the treatments.

The trials were divided into two groups based on initial soil pH ≤7.2 or >7.2 before liming (Table 2), following findings by Kirchmann et al. (2020). They found that the threshold pH below which yield is constrained is pH 7.2 in sugar beet and pH 7.1 in winter wheat and winter oilseed rape. In the group of trials with initial pH ≤7.2, there were significant interactions between treatment and trial for sugar yield and root yield but not for sugar content or soil nutrients (Table 3). In this group there were differences between treatments for sugar yield, root yield and pH which were all higher in GL and SL than in L0. In the group of trials with initial pH >7.2, there were no interactions between treatment and trial and differences between treatments only for pH which were higher in GL and SL than in L0 (Table 3).

Table 3. Average sugar yield (SY), root yield (RY), sugar content (SC) and soil $pH_{(H2O)}$, soil Ca-, P-, K-, Mg-AL in the second rotation after liming. Soil sampling depth 0–30 cm.

| Treatment | SY | RY | SC | $pH_{(H2O)}$ | Ca-AL | P-AL | K-AL | Mg-AL |
|---|---|---|---|---|---|---|---|---|
| | ton ha$^{-1}$ | | % | | mg 100 g$^{-1}$ soil | | | |
| 12 trials[a] | | | | | | | | |
| No lime, L0 | 16.2 | 91.7 | 17.6 | 7.0 a | 336 | 13.9 | 14.0 | 13.1 |
| Ground limestone, GL | 16.4 | 92.9 | 17.7 | 7.4 b | 362 | 14.4 | 13.1 | 12.2 |
| Structure lime, SL | 16.3 | 92.3 | 17.7 | 7.4 b | 386 | 14.4 | 14.3 | 13.1 |
| *p* (trial) | <0.001 | <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 |
| 5 trials[b] with soil pH ≤7.2 before liming | | | | | | | | |
| No lime, L0 | 15.8 a | 89.7 a | 17.6 | 6.7 a | 307 | 18.3 | 16.9 | 14.1 |
| Ground limestone, GL | 16.4 b | 93.2 b | 17.6 | 7.1 b | 319 | 18.7 | 16.3 | 13.1 |
| Structure lime, SL | 16.6 b | 93.6 b | 17.7 | 7.0 b | 322 | 17.5 | 17.4 | 13.9 |
| *p* (trial) | <0.001 | <0.001 | <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 | <0.001 | ns | ns | ns | ns | ns | ns |
| 7 trials[c] with soil pH >7.2 before liming | | | | | | | | |
| No lime, L0 | 16.4 | 93.1 | 17.7 | 7.1 a | 356 | 10.8 | 11.9 | 12.4 |
| Ground limestone, GL | 16.4 | 92.8 | 17.8 | 7.5 b | 392 | 11.3 | 10.7 | 11.6 |
| Structure lime, SL | 16.1 | 91.3 | 17.7 | 7.6 b | 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 |

[a] Vallby, Ekeberg, Gislöv, Hörte15, Västraby, Linelund, Billeberga, Hammenhög, Heddinge, Lindbyholm, Hönnedal, Hörte13; [b] Vallby, Ekeberg, Gislöv, Hörte15, Västraby; [c] Linelund, Billeberga, Hammenhög, Heddinge, Lindbyholm, Hönnedal, Hörte13; Values with different letters are significantly different.

In winter wheat, there were no interactions between treatment and trial for yield or soil nutrients in the 14 trials (Table 4). pH showed a tendency ($p$= 0.073) for an interaction between treatment and trial. There was also a tendency for higher Ca-AL in GL and SL compared with L0 (Table 4). In both groups (pH ≤7.2 and >7.2), there were no differences in yield, but there was a difference between the treatments in pH ($p$ <0.001) and a tendency for higher Ca-AL in GL and SL than in L0. There was a tendency for an interaction between trial and treatment for pH in the group with pH >7.2.

Table 4. Winter wheat yield and soil nutrient concentrations 5–6 years after liming. Yield in 14 trials 2016–2019, pH and soil nutrients in 12 trials (Hörte13 and Ekeberg missing). Sampling depth 0–30 cm.

| Treatment | Yield | $pH_{(H20)}$ | Ca-AL | P-AL | K-AL | Mg-AL |
|---|---|---|---|---|---|---|
| | kg ha$^{-1}$ | | mg 100 g$^{-1}$ soil | | | |
| No lime, L0 | 9583 | 7.2 a | 319 | 14.5 | 14.7 | 11.5 |
| Ground limestone, GL | 9558 | 7.7 b | 394 | 15.3 | 14.3 | 11.4 |
| Structure lime, SL | 9588 | 7.6 b | 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 |

Values with different letters are significantly different.

In winter oilseed rape, there were no interactions between treatment and trial for yield or soil nutrients in the nine trials (Table 5). Seed and raw fat yield were lower (–101 and –95 kg ha$^{-1}$, respectively) for SL than for L0 and GL. In the group of trials with soil pH >7.2 (Table 5), there were also no interactions between treatment and trial meaning that the outcomes from different trials were the same. There was also in this group a tendency for lower seed and raw fat yield in SL compared with GL and L0 (273 kg ha$^{-1}$ lower seed yield and 99 kg ha$^{-1}$ lower raw fat yield compared with L0). CAT analysis of soil micronutrients showed that soil concentration of Fe was lower in SL than in L0 (Appendix 1). In the group of trials 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 5). CAT analysis of soil micronutrients showed a tendency for B concentration to differ between the treatments (Appendix 1).

Table 5. Seed and raw fat yield in winter oilseed rape, soil pH and soil Ca-AL, P-AL, K-AL and Mg-AL concentration in all nine trials, in six trials with pH >7.2 and in three trials with pH ≤7.2.

| Treatment | Seed | Raw fat | $pH_{(H20)}$ | Ca-AL | P-AL | K-AL | Mg-AL |
|---|---|---|---|---|---|---|---|
| | kg ha$^{-1}$ | kg ha$^{-1}$ | | mg 100 g$^{-1}$ soil | | | |
| 9 trials[a] | | | | | | | |
| No lime, L0 | 3670 a | 1791 a | 7.2 a | 376 | 11.0 | 12.2 | 12.2 |
| Ground limestone, GL | 3640 a | 1785 a | 7.7 b | 464 | 12.4 | 11.8 | 12.0 |
| Structure lime, SL | 3452 b | 1690 b | 7.7 b | 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 |
| 6 trials[b] with soil pH >7.2 before liming | | | | | | | |
| No lime, L0 | 3304 | 1620 | 7.4 a | 398 | 9.8 | 11.8 | 12.1 |
| Ground limestone, GL | 3345 | 1642 | 7.8 b | 477 | 11.3 | 11.7 | 12.1 |
| Structure lime, SL | 3096 | 1517 | 7.8 b | 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 |
| 3 trials[c] with soil pH ≤7.2 before liming | | | | | | | |
| No lime, L0 | 4402 | 2134 | 6.7 a | 312 | 14.7 | 13.5 | 12.4 |
| Ground limestone, GL | 4230 | 2073 | 7.5 b | 425 | 15.8 | 12.3 | 11.6 |
| Structure lime, SL | 4165 | 2035 | 7.2 b | 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 |

[a]Linelund, Hammenhög, Billeberga, Heddingedrift, Vadensjö, Vallby, Lindbyholm, Hörte15, Hörte13). pH and soil nutrients in 8 trials, Hörte15 missing. [b]Linelund, Hammenhög, Billeberga, Heddingedrift, Lindbyholm, Hörte13. [c]Vadensjö, Vallby, Hörte15. pH and soil nutrients in 2 trials, Hörte15 missing. Values with different letters are significantly different.

## Plant diseases

The free-living nematodes identified in the trials comprised two species of root lesion nematodes (*Pratylenchus thornei* and *P. neglectus*) and the pin nematode (*Paratylenchus* spp.). Needle nematode (*Longidorus* spp.) was found in two trials (Hörte13, Hönnedal) and *Trichodorus* spp. in only one trial (Hörte13). There were no differences between the treatments in nematode incidence at any of the trial sites.

*Aphanomyces* root rot was the most common disease in sugar beet, and there was a tendency for lower root rot potential after treatment with SL and GL in all 13 trials (DSI in L0, GL and SL = 63, 61 and 58, respectively; $p$= 0.096). Also differences in infection between trials ($p$< 0.001), meaning that some sites were more infested with *A. cochlioides* than others (Ekeberg and Västraby). At the start of the study (before liming), trials with soil pH ≤7.2 showed a higher root rot potential (DSI=72) than trials with pH >7.2 (DSI=55). In winter wheat, *F. culmorum*, *Microdochium nivale, Rhizoctonia cereale* and *Pythium* spp. were found but with no differences between the treatments. In oilseed rape, *V. longisporum*, *Sclerotinia sclerotiorum* and *Phoma* spp. were found but also here with no differences between treatments. No clubroot was found in any trial.

## Plant nutrients

The analysis of plant nutrients in sugar beet showed that there were no interactions between treatments and trials (Table 6), that is, the outcomes from different trials were the same. Differences between treatments were found for Ca, Mn, B and Mo, where Ca and Mo increased for GL and SL whereas Mn and B decreased. In the group with initial pH ≤7.2, B decreased for GL and SL compared to L0. In the group of trials with initial pH >7.2, Mn decreased for GL and SL whereas Mo increased compared to L0.

In five trials with oilseed rape and an initial pH >7.2, there was an interaction between treatment and trial for Mo, meaning that the outcomes from different trials were different (Table 7). For all other plant nutrients analysed in oil seed rape, there were no interactions and no differences between treatments.

Plant nutrient measurements in 13 trials with winter wheat revealed an interaction between treatment and trial for B ($p$= 0.032). There were differences ($p$= 0.001) between the treatments only for Mo, which was higher in SL and GL than in L0. For the other plant nutrients analysed, there were no differences between treatments.

Table 6. Plant nutrients analysed in the 4–6 leaf stage in sugar beet

| Treatment | Ca | Mg | S | P | K | N | Na | Mn | B | Cu | Mo | Zn | Fe |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | % | | | | | | | ppm | | | | | |
| 11 trials[a] | | | | | | | | | | | | | |
| No lime, L0 | 1.56 a | 0.61 | 0.29 | 0.36 | 4.4 | 4.4 | 2.2 | 98.3 a | 35.5 a | 8.4 | 0.68 a | 43.8 | 594 |
| Ground limestone, GL | 1.65 b | 0.58 | 0.30 | 0.38 | 4.4 | 4.4 | 2.3 | 78.1 b | 34.1 b | 8.7 | 0.91 b | 42.9 | 583 |
| Structure lime, SL | 1.60 ab | 0.59 | 0.29 | 0.38 | 4.5 | 4.4 | 2.3 | 79.1 b | 33.8 b | 8.5 | 0.84 b | 41.7 | 558 |
| *p* (trial) | <0.001 | <0.001 | <0.001 | <0.001 | <0.001 | <0.001 | <0.001 | <0.001 | <0.001 | <0.001 | <0.001 | <0.001 | <0.001 |
| *p* (treatm) | 0.003 | ns | ns | ns | ns | ns | ns | 0.005 | 0.042 | ns | <0.001 | ns | ns |
| *p* (trial x treatm) | ns | ns | ns | ns | ns | ns | ns | ns | ns | ns | ns | ns | ns |
| 5 trials[b] with pH ≤7.2 | | | | | | | | | | | | | |
| No lime, L0 | 1.53 | 0.62 | 0.29 | 0.33 | 4.45 | 4.3 | 2.06 | 106.5 | 35.6 a | 8.0 | 0.64 | 42.3 | 564 |
| Ground limestone, GL | 1.62 | 0.62 | 0.30 | 0.34 | 4.43 | 4.4 | 2.10 | 92.6 | 33.3 b | 8.4 | 0.77 | 42.0 | 588 |
| Structure lime, SL | 1.59 | 0.62 | 0.30 | 0.35 | 4.63 | 4.3 | 2.11 | 89.5 | 34.1 b | 8.2 | 0.74 | 40.5 | 574 |
| *p* (trial) | <0.001 | <0.001 | <0.001 | <0.001 | <0.001 | <0.001 | <0.001 | <0.001 | <0.001 | <0.001 | <0.001 | <0.001 | <0.001 |
| *p* (treatm) | 0.082 | ns | 0.073 | ns | ns | ns | ns | ns | 0.003 | ns | ns | ns | ns |
| *p* (trial x treatm) | ns | ns | ns | ns | ns | ns | ns | ns | ns | ns | ns | ns | ns |
| 6 trials with pH >7.2 | | | | | | | | | | | | | |
| No lime, L0 | 1.45 | 0.56 | 0.26 | 0.36 | 4.48 | 4.4 | 2.29 | 80.2 a | 33.8 | 8.3 | 0.66 a | 43.3 | 644 |
| Ground limestone, GL | 1.56 | 0.51 | 0.27 | 0.38 | 4.46 | 4.3 | 2.30 | 57.0 b | 32.2 | 8.4 | 0.96 b | 42.1 | 604 |
| Structure lime, SL | 1.50 | 0.51 | 0.26 | 0.38 | 4.57 | 4.3 | 2.34 | 56.5 b | 31.0 | 8.3 | 0.87 b | 40.7 | 564 |
| *p* (trial) | <0.001 | <0.001 | <0.001 | 0.002 | <0.001 | <0.001 | <0.001 | 0.004 | <0.001 | <0.001 | <0.001 | <0.001 | <0.001 |
| *p* (treatm) | ns | ns | ns | ns | ns | ns | ns | 0.019 | 0.074 | ns | <0.001 | ns | ns |
| *p* (trial x treatm) | ns | ns | ns | ns | ns | ns | ns | ns | ns | ns | ns | ns | 0.025 |

[a] Vallby, Ekeberg, Gislöv, Hörte15, Västraby, Linelund, Billeberga, Hammenhög, Heddingedrift, Lindbyholm, Hönnedal; [b] Vallby, Ekeberg, Gislöv, Hörte15, Västraby; [c] Linelund, Billeberga, Hammenhög, Heddingedrift, Lindbyholm, Hönnedal; Values with different letters are significantly different.

Table 7. Plant nutrients in oilseed rape in 5 trials with initial pH >7.2 before liming (Linelund, Hammenhög, Billeberga, Heddingedrift and Hörte13; Hörte15 and trials 2018 missing)

| Treatm. | Ca | Mg | S | P | K | N | Mn | B | Cu | Mo | Zn | Fe |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | % | | | | | | ppm | | | | | |
| No lime, L0 | 2.2 | 0.16 | 0.44 | 0.47 | 1.8 | 4.7 | 35.2 | 32.4 | 6.6 | 1.0 a | 39.9 | 141.7 |
| Ground limestone, GL | 2.1 | 0.16 | 0.44 | 0.46 | 1.9 | 4.7 | 37.4 | 33.6 | 6.1 | 1.3 b | 40.0 | 190.0 |
| Structure lime, SL | 2.1 | 0.16 | 0.46 | 0.46 | 1.8 | 4.7 | 36.5 | 32.4 | 6.5 | 1.4 b | 40.5 | 122.5 |
| *p* (trial) | <0.001 | <0.001 | <0.001 | <0.001 | <0.001 | <0.001 | <0.001 | <0.001 | 0.086 | <0.001 | <0.001 | ns |
| *p* (treatm) | ns | ns | ns | ns | ns | ns | ns | ns | ns | <0.001 | ns | ns |
| *p* (trial x treatm) | ns | ns | ns | ns | ns | ns | ns | ns | ns | 0.040 | ns | ns |

Values with different letters are significantly different.

## Economy

The cost of applying 4 ton CaO as SL is returned by higher sugar beet root yield in the two rotations with a net income of 980 SEK when cost for transport is deducted and value of P is added and a subsidy from the Swedish water authorities is included (Table 8). The net income for 4 ton CaO $ha^{-1}$ as GL was negative.

Table 8. Estimations of the economical outcome of liming in the trials. Root yields (RY) in the first and second rotations after application of GL and SL in trials with pH ≤7.2, total increase in RY and application cost for 4 ton CaO $ha^{-1}$.

| Treatment | RY in 1st and 2nd rotation ton $ha^{-1}$ | | Total increase in RY[1] ton $ha^{-1}$ (SEK) | Application cost[2] 4 ton CaO $ha^{-1}$ SEK | Additional income SEK |
|---|---|---|---|---|---|
| No lime, L0 | 94.5 | 89.7 | | | |
| Ground lime stone, GL | 96.2 | 93.2 | 5.2 (2314) | 4 x 750=3000 | –686 |
| Structure lime, SL | 100.8 | 93.6 | 10.2 (4540) | 4 x 890=3560 | 980 |

[1] In 2022, price per ton beets are 445 SEK; [2] Application cost ground limestone =750 SEK $ton^{-1}$ CaO, structure lime 890 SEK $ton^{-1}$ CaO

## Aggregate and top soil stability

There were differences in aggregate size distribution (*p*< 0.001) in all three size classes between the trials (Fig. 2). There were also treatment effects, with both limed treatments (GL and SL) showing a finer tilth in the seedbed compared with L0. The limed treatments 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 with 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 for any of the aggregate size classes (*p*= 0.569 for <2 mm; *p*= 0.185 for 2–5 mm; *p*= 0.399 for >5 mm).

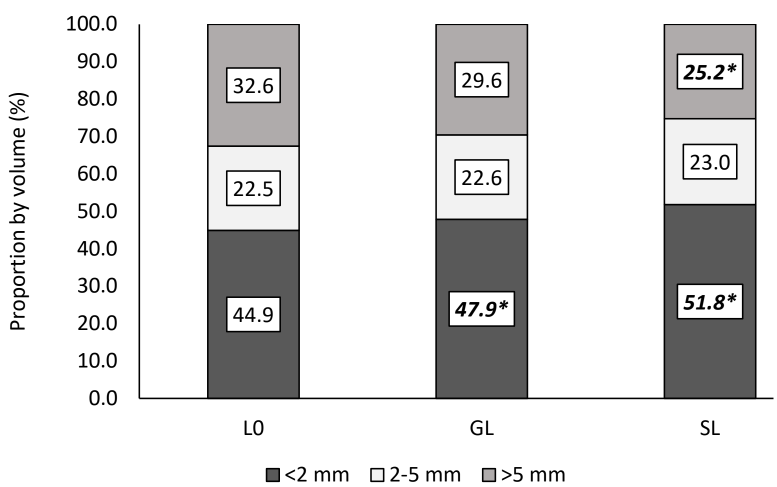


Fig. 2. Aggregate size distribution in three classes in the seedbed (0–4 cm depth) in spring immediately after drilling of sugar beet in 2018–2021. Results from 12 field trials. Differences (*p*< 0.001) in aggregate size classes compared with the untreated control (L0) are indicated in bold italics and with asterisks. GL = ground limestone, SL = structure lime

After simulated rainfall events on soil aggregates (2–5 mm), the leachate showed reductions in turbidity ($Turb_{A2}$) for both limed treatments compared with the unlimed control ($p$< 0.001) (Fig. 3). Statistical analysis also revealed an interaction between treatment and trial ($p$= 0.020), indicating that the different soils (trials) reacted differently to the lime products. Soil EC ($EC_{A2}$) showed increases in GL and SL compared with L0 ($p$= 0.001), but no interaction between treatment and trial ($p$= 0.083) (Fig. 3).

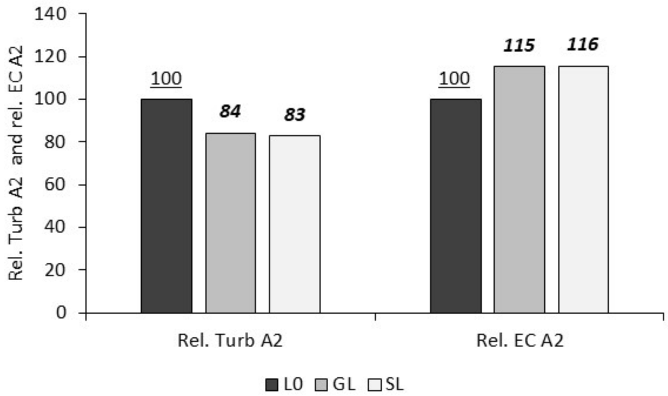


Fig. 3. Relative turbidity ($Turb_{A2}$) and relative electrical conductivity ($EC_{A2}$) of leachate from 2–5 mm soil aggregates after the second of two simulated rainfall events. Results from 12 field trials. Differences ($p$< 0.001) compared with the untreated control (L0) are indicated in bold italics. GL = ground limestone, SL = structure lime

Statistical analysis of the turbidity of leachate from the lysimeters ($Turb_{L2}$) showed only a tendency for a treatment effect ($p$= 0.077) and there was no interaction between treatment and trial ($p$= 0.917) (Fig. 4). For $EC_{L2}$, there was also a tendency ($p$=0.066) for a treatment effect and no interaction between treatment and trial ($p$= 0.362) (Fig. 4).

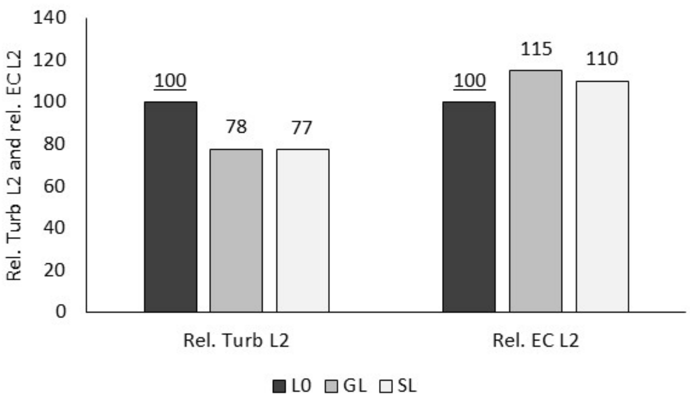


Fig. 4. Relative turbidity ($Turb_{L2}$) and relative electrical conductivity ($EC_{L2}$) in leachate from lysimeters (0–15 cm soil layer) after the second of two simulated rainfall events. Results from 10 field trials. GL = ground limestone, SL = structure lime

However, there were treatment effects on the concentrations of total-P ($p$= 0.008) and particulate-P ($p$= 0.031) (Fig. 5). Pairwise comparisons showed lower total-P concentrations in both limed treatments, and also lower particulate-P concentration in treatment SL compared with the unlimed control. There was no interaction between trial and treatment for either total-P ($p$= 0.935) or particulate-P ($p$= 0.753). For concentration of $PO_4$-P, there were no effects of treatment.

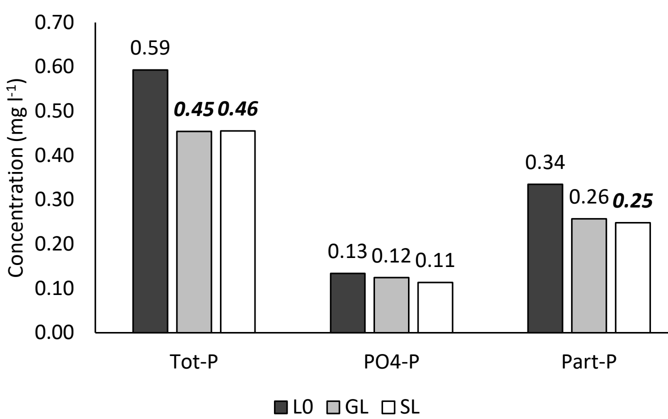


Fig. 5. Concentrations of total-P, $PO_4$-P and particulate-P in leachate from lysimeters (0–15 cm soil layer) after the second of two simulated rainfall events. Results from 10 field trials. Differences compared with the untreated control (L0) are indicated in bold italics, Total P: $p$= 0.008, particulate P: $p$= 0.031. GL = ground limestone, SL = structure lime

# Discussion

The results in the present study showed that the group of trials with pH ≤7.2 before liming gave an increase in sugar yield for both types of lime (Table 3). This is in line with findings by Kirchmann et al. (2020) who showed that the yield for sugar beet is constrained under the threshold pH 7.2. Two individual trials showed that K-AL was higher in SL than in GL or L0 (Västraby and Ekeberg, $p= 0.098$) and may be one important factor that could explain the increase in sugar yield for SL (Appendix 2). At Ekeberg, the infestation of Aphanomyces root rot was high and a combined effect of a decrease in DSI and higher levels of K-AL may explain the higher sugar yield in both GL and SL compared to the untreated control L0. At Västraby, there were no differences between the treatments in yield, P-AL or Ca-AL, and DSI was above 80 in all treatments and *A. cochlioides* was detected in the field. Despite the same amounts of GL and SL being applied in both trials, there was no effect on DSI at Västraby as was seen in the trial at Ekeberg. These two trials differ in CEC which was 10 meq 100 $g^{-1}$ at Ekeberg and 6 meq 100 $g^{-1}$ at Västraby. In an earlier study by Olsson et al. (2019), yield response in relation to soil characteristics in Scania was described and the importance of considering CEC in liming recommendations was pointed out. On soils with CEC ≥10, long-term effects of liming are expected. In contrast, liming effects are expected to be short, probably lasting only for around five to six years on soils with CEC <10. At the time of drilling of the second sugar beet crop after liming at Västraby, with a CEC of 6 meq 100 $g^{-1}$, there were no lingering effects on soil nutrients or DSI and no effects on yield of sugar beet. The effects of liming on Ekeberg, with a CEC of 10 meq 100 $g^{-1}$, were still notable in the second rotation after liming.

Continuous supply of poultry manure over the years at Gislöv has led to very high soil levels of K-AL (Appendix 2) and P-AL, which explains the high yield in all treatments. The K-AL and P-AL concentrations at Hörte15 were also above the recommended values in all treatments and this, in combination with irrigation, may explain the high sugar yield in all treatments in this trial. At Hammenhög, the low yield level (Fig. 1) was caused by poor performance of a new variety. However, there were also no differences between treatments in the second rotation after liming and the CEC at Hammenhög was low, 6 meq 100 $g^{-1}$, suggesting that only a short term effects of liming could be expected.

The analyses of winter wheat showed no differences between the treatments in yield, either in the total dataset of 14 trials (Table 4) or in the two groups with initial soil pH >7.2 and ≤7.2. Similar results were obtained in a study by von Tucher et al. (2018) investigating long-term effects of P fertiliser and lime application in rotations with wheat, barley and sugar beet. The results in that study indicated that sugar beet was more sensitive to low pH and low levels of P than wheat, and wheat also displayed stable yields over the 36-year study period. In our study, only one individual site (Västraby) showed a tendency ($p= 0.071$) for higher wheat yield three years after liming (+0.3 ton $ha^{-1}$ in GL and +0.6 ton $ha^{-1}$ in SL). The *Pythium* infection level was very high at that site and the lime treatments may have reduced the infection. For oilseed rape, there were no differences in soil or plant nutrients that may explain the lower yield in SL compared to GL and L0, and the mechanisms for the reduction in yield remains to be further investigated.

Our findings for soils with clay content of 15–25% suggests that for most crops, with the exception of winter oilseed rape, a target value of pH=7.2 would be optimal for crop productivity. However, concerns regarding availability of P and micronutrients have been raised when liming alkaline soils with pH >7.0. Analysis of soil and plant nutrients in the second rotation after liming in our study did not show lower availability of P or micronutrients in the trials. Also, in a study by Börjesson and Kirchmann (2022) of long-term field trials started in 1936 in Sweden it was shown that liming did not lower P availability in soils with clay content >38% and that yields of winter wheat, winter oilseed rape and peas actually increased when P was supplied together with lime. There was an increase in pH over the years from 6.2–6.9 to 6.9–7.5. Only spring oilseed rape showed no response to increased pH. Based on these findings, Börjesson and Kirchmann (2022) stressed the importance of updating Swedish pH recommendations and suggested a new target value of pH 7.5 for optimal crop production on soils with >38% clay.

For soil borne pests and diseases some trends were observed. The root lesion nematodes *P. thornei* and *P. neglectus,* that were found in the trials, cause serious yield reductions in wheat worldwide (Hollaway et al. 2000, Smiley et al. 2005, 2014). In sugar beet, they cause an extreme growth of lateral roots (forking), leading to yield losses (Westerdahl et al. 2023). In the present study, we found no differences between the two liming treatments (SL, GL) in terms of nematode density 4–5 years after liming. However, there was a general trend for lower populations of free-living nematodes in the treatment with slaked/structure lime (SL) than in treatment GL or L0. When the two groups of trials are compared for plant diseases, the group with pH >7.2 was generally healthier as implied by lower

Aphanomyces root rot potential. The tendency for a reduction in Aphanomyces root rot potential by liming in soils with lower pH than 7.2 has also been observed in previous field experiments in the area (Olsson et al. 2019). None of the pathogens found in oilseed rape (*V. longisporum*, *P. lingam*, *S. sclerotiorum*) could be linked to the reduced yield in oilseed rape in treatment SL compared to GL and the untreated control.

Analysis of seedbed aggregate size distribution (Fig. 2) showed that applying both types of lime improved the sugar beet seedbed in spring by producing a finer tilth, i.e. there was a higher proportion of aggregates <2 mm in the seedbed of soil where lime had been applied 5–7 years prior to measurements. Structure lime in treatment SL proved to be slightly more effective in producing a finer tilth than the ground limestone in treatment GL, as the fraction of coarse aggregates (>5 mm) in SL was significantly lower than in the unlimed control and also than in treatment GL. These results are in line with observed effects of structure lime in previous studies under Swedish conditions (Blomquist 2021). In the present study, seedbed soils were examined in the second crop rotation, in the period 2018–2021, 5–7 years after liming. The results can be compared with those reported for the first crop rotation in the trials, where seedbed soil was examined approximately 1.5 years after lime application (Gunnarsson et al. 2022). Surprisingly, comparisons showed a more pronounced effect of lime application on aggregate size distribution in the second compared with the first crop rotation. Overall, our data showed that SL resulted in a considerably finer seedbed. A finer tilth is not always a benefit and can increase the risk of surface crusting but more frequently supplies agronomic advantages from a management perspective, as seedbed preparation is simplified and as decreasing aggregate size has been shown to facilitate seedling emergence. This can be critically important in 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 finer seedbed results in less deep and less variable seed placement.

The decrease in turbidity in leachate from 2–5 mm soil aggregates following simulated rainfall events (Fig. 3, $Turb_{A2}$) demonstrated that aggregate stability had improved significantly on average, and to the same extent, with both lime treatments. This confirms findings in other studies on structure liming and aggregate stability under field conditions (Blomquist et al. 2022b). On average, increased aggregate stability reduces the risk of particulate-P losses. However, the interaction observed between lime treatment and trial illustrates that the reaction to liming can be vastly different on different soils. The underlying mechanism for these different reactions is not known and needs to be identified for better precision of structure liming as a cost-effective environmental measure. Comparison over time of aggregate stability is possible by collating results from the first (Gunnarsson et al. 2022) and second crop rotation (this study) at the trial sites. For the first crop rotation, when aggregates were sampled approximately 1.5 years after liming, Gunnarsson et al. (2022) reported decreases in turbidity of on average 43% and 35% in the GL and SL treatments, respectively, compared with the unlimed control, with no differences between the two limed treatments. For the second crop rotation (Fig. 3), the results in the present study showed a decrease in turbidity of 16–17% 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 when applying the same type of structure lime product as in this study were also reported by Blomquist et al. (2022a).

A novel component in analysis of the effect of liming in the second crop rotation compared with the first was the use of lysimeters (undisturbed soil cores) from the topsoil (0–15 cm) sampled 6–8 years after liming. Lysimeters can better reflect processes in the topsoil after liming and repeated incorporation, whereas aggregate sampling only reflects changes in the shallow-tilled seedbed. Turbidity results for the lysimeter leachate samples (Fig. 4) showed only tendencies for treatment effects, but analyses of different P fractions in leachate revealed lower total P concentrations in both limed treatments (Fig. 5). Treatment SL also showed significantly lower concentrations of particulate P. Few liming studies using lysimeters have been performed to date, but a suitable benchmark for our lysimeter results can be obtained by comparing them with results from field trials with individually drained plots where discharge and P concentrations are measured. Under Swedish conditions, three such studies have reported effects of structure lime on actual measured P losses via subsurface drainage (Svanbäck et al. 2014, Ulén and Etana 2014, Norberg and Aronsson 2022). Svanbäck et al. (2014) found that structure liming with calcium oxide reduced losses of total and particulate P from a clay soil (60% clay) by around 40%. Ulén and Etana (2014) observed reductions of approximately 50% in losses of total P and also $PO_4$-P (expressed as Dissolved Reactive Phosphorus, DRP) after liming with what they describe as calcium hydroxide on a clay soil (25% clay). Norberg and Aronsson (2022) reported reductions in losses of total P and $PO_4$-P following application of a mix of calcium hydroxide and calcium carbonate, compared with an unlimed control. The application rate and type of structure lime used in the latter study were identical to treatment SL in the 11 trials limed in 2014–2015 in our study. Therefore, our finding of an approximately 25% reduction in losses of total P and particulate P from limed treatments aligns well with previously reported values, although caution should be urged when comparing different methods (lysimeters versus field trials with individually drained plots).

Our results show no fundamental differences between the two liming products regarding the effect on soil, i.e. GL and SL showed only minor differences in aggregate size distribution, aggregate stability and the effect on total P losses. SL proved to produce a slightly finer tilth and a marginally better effect on particulate P, but from a practical point of view this distinction is negligible. From a water protection perspective, a subsidy for both types of liming products used in our study could therefore be justifiable, providing that the GL product is soft and finely ground (Mattsson 2010). If an environmental subsidy was introduced also for GL products the differences between in economical outcome the two products in Table 8 would turn out less favourable for the SL product.

# Conclusions

Liming with GL and SL resulted in increased sugar yield compared to the untreated control 5–7 years after application in one trial with high Aphanomyces root rot potential, pH ≤7.2 and CEC ≥10 meq/100 g before liming. In trials where *A. cochlioides* was not present, higher concentrations of K-AL may explain the increased sugar yield for SL compared to GL and L0. Our findings for soils with clay content of 15–25% suggests that for most crops, with the exception of winter oilseed rape, a target value of pH=7.2 would be optimal for crop productivity without hindering P or micronutrient availability. Application of GL and SL on soils with low CEC (<10) gave no long-term effects on yield.

There was a negative impact of SL on yield of oilseed rape in trials with initial pH >7.2. The reason for this yield reduction is not known and further research in needed. Structure lime should therefore be used with caution on soils with initial pH>7.2 when oilseed rape is included in the rotation. There were no negative effects of SL on yield of winter wheat, irrespective of initial soil pH before liming.

Liming with GL and SL resulted in a finer tilth in the sugar beet seedbed 5–7 years after application. On average, liming with GL and SL increased aggregate stability, but there was an interaction between treatment and site, meaning different reactions to lime on different soils. Analyses of different P fractions in leachate from undisturbed topsoil after simulated rain events revealed lower total P and particulate P concentrations in samples from both limed treatments compared to the untreated control. This makes liming an important environmental measure that can prevent euthropication of lakes and seas. Besides this, the improved soil structure gives agronomic advantages such as a better emergence, plant establishment and yield.

Economical calculations, although prices and costs may change over time, suggests that liming with SL corresponding to 4 ton CaO $ha^{-1}$ gave a positive total net income after two rotations. In contrast, the net income for application of GL corresponding to 4 ton CaO $ha^{-1}$ was negative. There were only minor differences in aggregate size distribution, aggregate stability and effect on total P losses between the lime products. An environmetal subsidy also for GL products would make the economical calculations turn out less favourable for the SL product.

## Acknowledgements

This study was funded by The Swedish Foundation for Agricultural Sciences, SLF (grant HI344085).

# References

Andersson, E., Frostgård, G., Hjelm, E., Kvarmo, P., Listh, U. & Malgeryd, J. 2023. Recommendations for fertilization and liming 2023. Jordbruksinformation 15-2022. The Swedish board of Agriculture.

BBCH monograph 2018. Growth stages of mono- and dicotyledonous plants. Ed. Meier, U. Julius Kühn-Institut (JKI) Quedlinburg 2018.

Blomquist, J., Simonson, M., Etana, A. & Berglund, K. 2018. Structure liming enhances aggregate stability and gives varying crop responses on clayey soils. Acta Agriculturae Scandinavica, section B - Soil &Plant Science 68: 311–322. https://doi.org/10.1080/09064710.2017.1400096

Blomquist, J. 2021. Effects of structure liming on clay soil. Doctoral thesis No 2021:86 https://publications.slu.se/?file=publ/show&id=114345. Swedish University of Agricultural Sciences. Uppsala.

Blomquist, J.E. & Berglund, K. 2021. Timing and conditions modify the effect of structure liming on clay soil. Agricultural and Food Science 30: 96–107. https://doi.org/10.23986/afsci.103422

Blomquist, J.E., Englund, J.-E. & Berglund, K. 2022a. Site characteristics determine the duration of structure liming effects on clay soil. Agricultural and Food Science 31: 136–148. https://doi.org/10.23986/afsci.115313

Blomquist, J., Englund, J.-E. & Berglund, K. 2022b. Soil characteristics and tillage can predict the effect of structure lime on soil aggregate stability. Soil Research 60: 373–384. https://doi.org/10.1071/SR21022

Börjesson, G. & Kirchmann, H. 2022. Interactive long-term effects of liming and P application on clay soil: crop yield increases up to pH 7.5(aq). Plant Soil 473: 407–421. https://doi.org/10.1007/s11104-021-05293-1.

CEN EN 13651:2001. Soil improvers and growing media - Extraction of calcium chloride/DTPA (CAT) soluble nutrients.

Deacon, J.W. & Donaldson, S.P., 1993. Molecular recognition in the homing responses of zoosporic fungi, with special references to Pythium and Phytophthora. Mycological Research 97: 1153v1171. https://doi.org/10.1016/S0953-7562(09)81278-1

Egnér, H., Riehm, H. & Domingo, W.R. 1960. Untersuchungen über die chemische Bodenanalyse als Grundlage für die Beurteilung des Nährstoffzustandes der Böden. II. Chemische Extraktionsmethoden zur Phosphor- und Kaliumbestimmung. (Investigations on soil chemical analysis as a basis of the evaluation of plant nutrient status of soils. II. Chemical extraction methods for phosphorous and potassium determination). Kungl. Lantbrukshögskolans annaler (The annals of the Royal agricultural college of Sweden) 26: 199–215. (in German).

EPPO PM7/119 Nematode extraction. EPPO Bulletin (2013) 43: 471–495. https://doi.org/10.1111/epp.12077

Goulding, K.T.H. 2016. Soil acidification and the importance of liming agricultural soils with particular reference to the United Kingdom. Soil Use and Management 32: 390–399. https://doi.org/10.1111/sum.12270

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. https://doi.org/10.1080/09064710.2022.2089590

Haak, E. & Simán, G. 1992. Field experiments with liming of mineral soils to different base saturation. Dept. Soil sciences. SLU. Report 188.

Holland, J.E., Bennett, A.E., Newton, A.C., White, P.J., McKenzie, B.M., George, T.S., Pakeman, R.J., Bailey, J.S., Fornara, D.A. & Hayes, R.C. 2018. Liming impacts on soils, crops and biodiversity in the UK: A review. Science of the total environment 610: 316–332. http://dx.doi.org/10.1016/j.scitotenv.2017.08.020

Hollaway, G.J., Taylor, S.P., Eastwood, R.F. & Hunt, C.H. 2000. Effect of field crops on density of Pratylenchus in Southeastern Australia; part 2: *P. thornei*. Journal of Nematology 32: 600–608.

ISO 2005. ISO6878. Water quality - Determination of phosphorus - Ammonium molybdate spectrometric method.

ISO 2013. ISO15923-1. Water quality - Determination of selected parameters by discrete analysis systems - Part 1: Ammonium, nitrate, nitrite, chloride, orthophosphate, sulfate and silicate with photometric detection.

Kao, C.W. & Ko, W.H. 1986. Suppression of *Pythium splendens* in a Hawaiian soil by calcium and microorganisms. Phytopathology 76: 215–220. https://doi.org/10.1094/Phyto-76-215

Kirchmann, H., Börjesson, G., Bolinder, M.A., Kätterer, T. & Djodjik, F. 2020. Soil properties currently limiting crop yields in Swedish agriculture - An analysis of 90 yield survey districts and 10 long-term field experiments. European Journal of Agonomy 120. https://doi.org/10.1016/j.eja.2020.126132

Kritz, G. 1983. Såbäddar för vårstråsäd. Physical conditions in cereal seedbeds. Reports from Division of Soil Management. Dep. of Soil Science Uppsala: Swedish University of Agricultural Sciences.

Mattson, L. 2010. Geologiskt ursprung och kornstorlek avgör kalkeffekten. Deparment of Soil and Environment. Reports Plant nutrition. Uppsala: Swedish University of Agricultural Sciences.

Norberg, L. & Aronsson, H. 2022. Mitigating phosphorus leaching from a clay loam through structure liming. Acta Agriculturae Scandinavica, Section B-Soil & Plant Science 72: 987–996. https://doi.org/10.1080/09064710.2022.2138528

Olsson, Å., Persson, L. & Olsson, S. 2010. Variations in soil characteristics affecting the occurrence of Aphanomyces root rot of sugar beet - risk evaluation and disease control. Soil Biology & Biochemistry 43: 316–323. https://doi.org/10.1016/j.soilbio.2010.10.017

Olsson, Å., Persson, L. & Olsson, S. 2019. Influence of soil characteristics on yield response to lime in sugar beet. Geoderma 337: 1208–1217. https://doi.org/10.1016/j.geoderma.2018.11.020

Smiley, R.W., Yan, G.P. & and Gourlie, J.A. 2014. Selected Pacific Northwest crops as hosts of *Pratylenchus neglectus* and *P. thornei*. Plant Disease 98: 1341–1348. https://doi.org/10.1094/PDIS-12-13-1296-RE

Smiley, R.W., Whittaker, R.G., Gourlie, J.A. & Easley, S.A. 2005. Suppression of wheat growth and yield by Pratylenchus neglectus in the Pacific Northwest. Plant Disease 89: 958–968. https://doi.org/10.1094/PD-89-0958

Struck, C., Rüsch, S. & Strehlow, B. 2022. Control Strategies of clubroot disease caused by *Plasmodiophora brassicae*. Microorganisms 10: 620. https://doi.org/10.3390/ microorganisms10030620

Sugimoto, T., Watanabe, S., Yoshida, M., Aino, M. & Irie, K. 2008. Select calcium compounds reduce the severity of *Phytophthora* stem rot of soybean. Plant Disease 92: 1559–1565. https://doi.org/10.1094/PDIS-92-11-1559

Svanbäck, A., Ulén, B. & Etana, A. 2014. Mitigation of phosphorus leaching losses via subsurface drains from a cracking marine clay soil. Agriculture Ecosystem and Environment 184: 124–134. https://doi.org/10.1016/j.agee.2013.11.017

von Tucher, S., Hörndl, D. & Schmidhalter, U. 2018. Interaction of soil pH and phosphorus efficacy: Long-term effects of P fertilizer and lime applications on wheat, barley, and sugar beet. Ambio 47: S41–S49. https://doi.org/10.1007/s13280-017-0970-2

Ulén, B., Alex, G., Kreuger, J., Svanbäck, A. & Etana, A. 2012. Particulate-facilitated leaching of glyphosate and phosphorus from a marine clay soil via tile drains. Acta Agriculturae Scandinavica, Section B-Soil & Plant Science 62: 241–251. https://doi.org/10.1080/09064710.2012.697572

Ulén, B. & Etana, A. 2014. Phosphorus leaching from clay soils can be counteracted by structure liming. Acta Agriculturae Scandinavica, Section B-Soil & Plant Science 64: 425–433. https://doi.org/10.1080/09064710.2014.920043

von Broembsen, S.L. & Deacon, J.W. 1996. Effects of calcium on germination and further zoospore release from zoospore cysts of Phytophthora parasitica. Mycological Research 100: 1498–1504. https://doi.org/10.1016/S0953-7562(96)80085-2 von Broembsen, S.L. & Deacon, J.W. 1997. Calcium interference with zoospore biology and infectivity of *Phytophthora parasitica* in nutrient irrigation systems. Phytopathology 87: 522–528. https://doi.org/10.1094/PHYTO.1997.87.5.522

Westerdahl, B.B., Rahman Khan, M., Olsson Nyström, Å. & Ahmad, I. 2023. Nematode problems in sugarcane and sugar beet and their sustainable management. In: Rahman Khan, M. & Quintanilla, M. (Eds.). Nematode diseases in crops and their sustainable managment. Oxford, UK. Academic Press. p. 565–585. https://doi.org/10.1016/B978-0-323-91226-6.00019-5

# Appendix

Appendix 1. CAT analysis of soil nutrients in oilseed rape trials

| Treatment | Mn | Cu | Fe | Zn | B |
|---|---|---|---|---|---|
| 6 trials with pH>7.2 (Linelund, Hammenhög, Billeberga, Heddingedrift, Lindbyholm, Hörte13) | | | | | |
| No lime, L0 | 75.6 | 2.4 | 398 a | 2.4 | 1.07 |
| Ground limestone, GL | 66.7 | 2.5 | 317 ab | 2.3 | 1.11 |
| Structure lime, SL | 61.9 | 2.4 | 253 bc | 2.4 | 1.10 |
| *p* (trial) | <0.001 | <0.001 | <0.001 | <0.001 | <0.001 |
| *p* (treatm) | ns | ns | 0.044 | ns | ns |
| *p* (trial x treatm) | ns | ns | ns | ns | ns |
| 2 trials with pH≤7.2 (Vadensjö and Vallby) | | | | | |
| No lime, L0 | 13.1 | 0.80 | 60.7 | 0.92 | 1.16 |
| Ground limestone, GL | 16.0 | 0.92 | 58.0 | 1.0 | 0.99 |
| Structure lime, SL | 12.4 | 0.82 | 57.8 | 0.92 | 1.20 |
| *p* (trial) | <0.001 | <0.001 | ns | 0.002 | ns |
| *p* (treatm) | ns | ns | ns | ns | 0.082 |
| *p* (trial x treatm) | ns | ns | ns | ns | ns |

Appendix 2. Concentration of potassium (K-AL mg 100 $g^{-1}$ soil) before growing sugar beet in the second rotation after liming

| | LIN | HÖR13 | BIL | HED | LIND | HAM | HÖN | EKE | VAL | GIS | HÖR15 | VÄS |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| No lime, L0 | 5.9 | 9.1 | 10.1 | 11.9 a | 11.6 | 19.0 | 15.6 | 7.7 | 6.7 | 48.7 | 8.7 | 13.0 a |
| Ground limestone, GL | 6.5 | 8.8 | 10.1 | 12.0 a | 10.7 | 16.0 | 11.0 | 8.7 | 7.1 | 43.7 | 9.6 | 12.7 a |
| Structure lime, SL | 5.3 | 8.9 | 9.9 | 16.3 b | 10.8 | 18.3 | 15.0 | 9.8 | 9.3 | 45.7 | 8.1 | 14.0 b |
| *p* (treatm) | ns | ns | ns | 0.013 | ns | ns | ns | 0.098 | ns | ns | ns | 0.018 |