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Citation for the published paper:

Jens Blomquist, Magnus Simonsson, Ararso Etana, Kerstin Berglund.
(2018) Structure liming enhances aggregate stability and gives varying crop
responses on clayey soils. *Acta Agriculturae Scandinavica, Section B — Soil &
Plant Science*. Volume: 68, Number: 4, pp 311-322.
<http://dx.doi.org/10.1080/09064710.2017.1400096>.

Access to the published version may require journal subscription.
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Standard set statement from the publisher:

"This is an Accepted Manuscript of an article published in *Acta Agriculturae
Scandinavica, Section B – Soil & Plant Science* on 15 Nov 2017, available online:
<http://www.tandfonline.com/10.1080/09064710.2017.1400096>."

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Structure liming enhances aggregate stability and gives varying crop responses on clayey soils

Jens Blomquist*, Magnus Simonsson, Ararso Etana, Kerstin Berglund

*Corresponding author: jens.blomquist@slu.se

Department of Soil and Environment, Swedish University of Agricultural Sciences, PO Box 7014, SE-750 07 Uppsala, Sweden

Abstract

It has been suggested that liming can improve soil structure and thereby decrease losses of particles and associated nutrients. In this study, two types of structure lime, slaked lime ($\text{Ca}(\text{OH})_2$) and a mixed product of calcium carbonate (CaCO_3) and slaked lime ($\text{Ca}(\text{OH})_2$), were applied at three different rates in field trials on clayey soils (24-40% clay). A combination of primary tillage and structure liming was also studied, in a split-plot trial on a clayey soil (25% clay).

Aggregate (2-5 mm) stability, measured as reduction in turbidity (which is strongly correlated with losses of particulate phosphorus), was significantly increased with the highest application rates of both structure lime products. Aggregate size distribution was also improved with structure lime, creating a finer tilth in the seedbed.

Yield response to structure lime was not consistent, with both negative and positive responses over the four-year study period. Positive yield responses can possibly be attributed to the finer tilth preventing evaporation in two dry growing seasons. Negative yield responses were probably an effect of impaired phosphorus availability associated with limited precipitation in May-July in 2011 and 2013.

Two years after liming, soil pH levels were significantly elevated in plots with the highest application rate of structure lime, whereas no significant increases were found three years after liming. However, a lingering effect of liming was still detectable, as manganese concentration in barley grain was significantly lower in plots with the highest application rates of both structure lime products in the fourth study year.

These results indicate that structure liming can be used as a measure to mitigate phosphorus losses from clayey soils, thereby preventing eutrophication of nearby waters. However, the yield response was varying and unpredictable and thus further investigations are needed to determine the circumstances in which field liming can act efficiently not only to prevent phosphorus losses, but also to ensure consistent yield increases.

Keywords: structure lime; aggregate stability; turbidity; phosphorus; aggregate size distribution, yield

Introduction

Structure lime in the form of calcium oxide (CaO) and hydroxide (Ca(OH)₂) can react with clay minerals in soils, thereby influencing the physical properties and modifying soil structure and aggregate formation. The effect has been attributed to three reactions (Berglund, 1971): cation exchange, pozzolanic reactions (cementation) and lime carbonation.

Cation exchange is a relatively rapid reaction, resulting in flocculation and agglomeration and associated improvements in characteristics associated with soil water content (Choquette et al., 1987). Pozzolanic reactions result in formation of calcium aluminate silicate hydroxide (CASH), calcium silicate hydroxide (CSH) and/or calcium aluminate hydroxide (CAH) (Åhnberg, 2006). These reactions occur upon dissolution of the silicate tetrahedra and the aluminate octahedra of the clay minerals in the highly alkaline environment (~pH 12.4) created

when calcium oxide and/or calcium hydroxide is added (Al-Mukhtar et al., 2010). The pozzolanic reactions can result in a more permeable microstructure (Al-Mukhtar et al., 2012), but also enhanced soil strength for several years (Kavak and Baykal, 2012). Lime carbonation, where carbon dioxide reacts with calcium hydroxide, is a long-term reaction running in parallel and after the pozzolanic phase (Witt, 2002). Eight years after liming a field with calcium oxide, Ledin (1981) detected calcium carbonate crystals as cutans covering microaggregates, but also distributed in the clay matrix and filling up pores. The combined strength-enhancing effect of these three different reactions was exploited in construction in ancient China and Egypt (Ballantine and Rossouw, 1972). Today, the effect is still exploited, in Sweden and world-wide, in road construction and engineering.

In Swedish agriculture, use of calcium oxide and calcium hydroxide to improve the structure of clay soil is currently limited, despite reports of improvements in e.g. sugar beet yield (Berglund and Blomquist, 2002). However, there is growing interest in one of the side-effects of improved soil structure through liming, namely a possible decreased risk of phosphorus (P) losses as a consequence of enhanced aggregate stability. Phosphorus is the growth-limiting nutrient for algae in inland waters such as the Baltic Sea Proper and inputs must be reduced to alleviate eutrophication and repeated cyanobacteria blooms (Boesch et al., 2006). Swedish agriculture and forestry are the two largest sources of total nitrogen (N) and P loads to the Baltic Sea, accounting for roughly 60% of the total load (Ejhed et al., 2016).

With recognition of structure liming as an environmental protection measure, various mixed products containing a blend of calcium carbonate (CaCO_3) and calcium hydroxide have become available on the Swedish market. However, little is known about how such mixed products affect aggregate stability, crop yield and crop micronutrient content.

Aggregate stability can be evaluated roughly by turbidity measurements determining suspended soil particles (Dexter and Czyz, 2000). Aggregates with a low level of stability break down

when submerged in water. The turbidity of water has also been shown to be closely correlated with losses of particulate phosphorus (PP) (Etana et al., 2009).

The aim of this study was to investigate the effects of a mixed lime product on aggregate stability, aggregate size distribution at drilling and crop yield. A set of field trials were established in which a mixed liming product was compared with calcium hydroxide. The hypotheses tested were that applying a mixed structure-liming product containing both calcium hydroxide and calcium carbonate significantly increases aggregate stability and improves crop yield.

Materials and methods

Field trials

Four field trials (8501A, 8501B, 8502 and 8503) treated with different structure liming products were established approximately 400 m apart at sites, south of Uppsala (59.84°N, 17.71°E) in October 2010. Despite the close proximity, topsoil organic matter content and texture at the sites (Table 1) and nutritional status, including soil pH (Table 2) showed great variation between the trial sites, with 8502 and 8503 showing a higher level of fertility than 8501A and 8501B. Degree of base saturation (BS) was markedly lower in 8501A, 8501B had low levels of plant-available P (P-AL) and 8503 had very high levels of P. Mean monthly air temperature and precipitation at a nearby climate station are summarised in Table 3 for the trial period (2010-2014) compared with the 30-year average (1961-1990).

[Tables 1, 2 and 3 near here]

Treatments

Three of the trials (8501A, 8501B and 8502) had four replicates in a randomised block design in which different levels of slaked lime ($\text{Ca}(\text{OH})_2$) and a mixed product named Nordkalk Aktiv Struktur (NKAS) consisting of $\text{Ca}(\text{OH})_2$ together with calcium carbonate (CaCO_3) were tested. Application rates were based on providing an equal supply of calcium (Ca), irrespective of the lime product and its solubility (water solubility is approximately 130-fold higher for calcium hydroxide than for calcium carbonate at 18 °C). The liming rates in the trials corresponded to 1, 2 and 6 t ha⁻¹ CaO. The treatment with 1 t ha⁻¹ CaO (0.7 t ha⁻¹ Ca) was equal to a dose of 1.4 t ha⁻¹ slaked lime or 2 t ha⁻¹ mixed lime.

The fourth field trial (8503) tested combinations of primary tillage (plough and tine stubble cultivator) as factor 1 and structure liming (0 and 2 t ha⁻¹ CaO as calcium hydroxide as factor 2) in a randomised split-plot design with four replicates (Table 4).

[Table 4 near here]

Spreading, incorporation and soil tillage

The structure lime was spread in the four field trials on 13-21 October 2010 using a lightweight machine originally designed for spreading sand. The different rates were applied by multiple passes in the plots. The structure lime was then incorporated once (trials 8501A and 8502) or twice (trials 8501B and 8503) to a shallow depth (5-7 cm) with a disc cultivator (Väderstad Carrier) on the same day as spreading or the following day. Mouldboard ploughing was carried out 0-4 days after incorporation of the structure lime. In following years, mouldboard ploughing was carried out after harvesting in autumn in all trials except 8503, where primary tillage was part of the split-plot design. In that trial, non-inversion primary tillage was carried out with two passes with a tine cultivator (Väderstad Cultus Quattro) to a depth of 12-15 cm in October 2011, 2012 and 2013. In spring of each year, normal seedbed preparation was carried out with a

spring-tine harrow before sowing in all four trials. The same procedure was carried out in trial 8502 in autumn 2011, before drilling the winter wheat crop harvested in 2012 (Table 5).

[Table 5 near here]

Crops and fertilisation

Over the four-year study period, all crops grown in the trials were harvested to determine yield response. The crops grown and the levels of N, P and sulphur (S) applied in fertiliser are presented in Table 5.

Seedbed aggregate size distribution

In spring 2013, the seedbed at all four trial sites was investigated in the window after cultivation and drilling, but before emergence. These investigations included measuring the cultivation depth of the secondary tillage, the water content of different aggregate sizes and the volumetric aggregate size distribution in three different fractions.

Aggregate stability measured as clay dispersion

Soil aggregates with mean diameter 2-5 mm were sampled in spring 2013 by sieving the seedbed with different mesh sizes (Kritz, 1983). The soil aggregates were air-dried and 80 g were placed in a PVC beaker with a 0.6 mm mesh at the base. Over approximately 5 s, the beaker was immersed manually three times in a larger beaker containing synthetic rainwater. The moist soil aggregates were left for 24 hours at 20 °C and then the procedure was repeated. The turbidity of the resulting suspension was measured with a turbidimeter (Hach 2100N Turbidimeter, Hach, Loveland, Co.).

pH and electrical conductivity

Sampling and measurements of pH were carried out on nine different occasions in 2011, 2012 and 2013, at 5-15 cm below the soil surface. On the last occasion, the electrical conductivity (EC) was also measured.

Soil water content and plant emergence

Soil water content was measured with a Wet Sensor (Delta-T devices Ltd., Cambridge, UK) in spring 2013, just before secondary tillage, with 10 measurements in undisturbed ploughed furrows, diagonally over each plot, to a depth of approximately 10 cm. In the non-inverted plots in trial 8503, the Wet Sensor measurements were made in autumn-tilled soil, also to a depth of 10 cm and on the same occasion as in the ploughed treatments. Plant counts were carried out after emergence in spring 2013.

Infiltration, dry bulk density, hydraulic conductivity and shrinkage

After harvest of spring barley, but before primary tillage in autumn, water infiltration rate was measured in late September/early October 2013 in undisturbed stubble in all four trials according to a method described by Berglund & Bjuréus (2008). On the same occasion, in trial 8501A samples were collected with steel cylinders (diameter 72 mm, length 102 mm) from the undisturbed topsoil (sampling depth 50-150 mm) for laboratory determination of dry bulk density, hydraulic conductivity and shrinkage.

Plant nutrient content

In 2014, the nutrient content in grain (spring barley) was measured in trial 8502. Grain samples were milled, digested in concentrated nitric acid (HNO₃) and analysed using an ICP-OES (PerkinElmer Optima 7300DV) for potassium (K), phosphorus (P), sulphur (S), calcium (Ca),

magnesium (Mg), zinc (Zn), manganese (Mn) and copper (Cu). Dry matter content was determined on every fifth sample by drying at 105 °C for 24 h.

Statistical analyses

Analysis of variance (ANOVA) was performed using the procedure *mixed* in the SAS System. In analyses by year and trial (within site), the model included the fixed factors *treatment* and *block*. In analyses of multi-year data, the model included the main fixed factors *trial*, *site*, *year*, *treatment* and *block*, and all significant interactions. The significance level was set at $p < 0.05$. Reported probability values (p) refer to the factor *treatment*. Treatment means differing by more than the least significant difference (LSD) were taken as significantly different. Since pairwise comparisons should only be made when $p < 0.05$, LSD is shown in brackets when $p > 0.05$. In certain cases, the difference between the unlimed control treatment and the average of the structure-limed treatments was tested.

Results

Aggregate stability

Relative turbidity in trials 8501A, 8501 and 8502, and thereby the loss of soil from aggregates, was significantly lower in treatments applying 6 t ha⁻¹ CaO as slaked lime (26% reduction) and mixed lime (21% reduction) (Figure 1). In the remaining liming rate treatments (1 and 2 t ha⁻¹ CaO of the two products), there were no significant changes in turbidity compared with the untreated control.

[Figure 1 near here]

Figure 1. Relative turbidity of 2-5 mm aggregates from the drilled seedbed in May 2013 in treatments applying CaO as calcium hydroxide (Ca(OH)₂) (Slaked) or as a mixture of calcium carbonate (CaCO₃) and calcium hydroxide (Ca(OH)₂) (Mixed) in trials 8501A, 8501B and

8502. Control treatment (A) = 100. Significant reductions in turbidity in comparison with the control are indicated in bold.

Seedbed aggregate size distribution

In trials 8501A, 8501B and 8502, there were no significant effects of structure lime application on aggregate size distribution either when the trials were studied individually or as a group. There were also no significant effects on cultivation depth or water content (weight-%) in the aggregates collected.

In contrast, trial 8503 showed significant changes in aggregate size distribution in spring 2013 (Figure 2), both as a result of primary tillage (factor 1) and as an effect of the calcium hydroxide supplied in October 2010 (factor 2). The proportion of coarse aggregates (5-16 mm) was significantly lower ($p=0.044$) and the proportion of very fine aggregates (<2 mm) was significantly higher ($p=0.004$) when the plots were ploughed in autumn compared with two passes with a tine cultivator. The medium-sized fraction (2-5 mm) showed no significant differences as a result of primary tillage. The proportion of very fine aggregates (<2 mm) increased significantly ($p=0.002$) as a result of the treatment with calcium hydroxide. There was also a strong tendency ($p=0.057$) for a lower share of coarse aggregates (5-16 mm) in the plots that had received calcium hydroxide in 2010.

[Figure 2 near here]

Figure 2. Seedbed aggregate size distribution in trial 8503, May 2013. Plough and stubble cultivator (factor 1) refer to primary tillage conducted in autumn 2010, 2011 and 2012. Structure lime with CaO levels of 0 and 2 t ha⁻¹ (factor 2) refers to application in October 2010. Results are grand means within factor 1 and factor 2, respectively. Significant differences within size classes are indicated in bold.

pH and electrical conductivity

There was a distinct time-dependent variation in pH over the trial period (Tables 6-7). The first measurements in April 2011 in trial 8501A, 6 months after spreading, showed a tendency for increasing pH with structure liming, but no significant differences. Approximately one year after spreading, at measurements in December 2011 in trial 8502, there were however significant increases in pH. Another year later (two years after spreading), measurements in September 2012 in trials 8501A, 8501B and 8503 also showed significant increases in pH. However, when pH was measured in all four trials on the same occasion in October 2013, three years after liming, there were no longer any significant differences in pH. There were significant differences in EC on this last occasion as an effect of the lime applied three years earlier.

In addition to the time-dependent changes in pH, there was also a clear dose response in pH as an effect of increasing level of structure lime. In trials 8501A and 8501B, at the measurements in September 2012, only treatments with the highest input (6 t CaO ha⁻¹) as slaked and mixed lime showed significantly higher pH. The same pattern was observed in trial 8502 at measurements in December 2011.

[Tables 6 and 7 near here]

Soil water content and plant emergence

There were no significant differences in water content between the different treatments with structure lime in spring 2013 before the start of cultivation and drilling. The only notable difference was lower water content in autumn-ploughed treatments compared with tine-tilled treatments, but it was not statistically significant. Plant counts after emergence showed

significant increases in all liming treatments except 6 t CaO ha⁻¹ as slaked lime compared with untreated plots in trial 8501A, but in all other trials no significant differences were observed.

Infiltration, dry bulk density, hydraulic conductivity and shrinkage

Measurements of water infiltration rate revealed no significant differences between the different structure lime treatments. Trial 8503 showed a statistically significant increase in water infiltration rate in the treatment without autumn ploughing. No significant effects were noted for dry bulk density, shrinkage or hydraulic conductivity in trial 8501A.

Yield response of structure lime in 8501A, 8501B and 8502

In trials 8501A, 8501B and 8502, no interaction between structure lime treatment and year was found ($p=0.208$), i.e. the different crops (=years) did not react differently to the structure lime treatments. Statistical analysis showed no significant positive yield response for the full four-year period ($p=0.393$) or for any individual year, not even in trial 8501A with its relatively acidic soil reaction and low base saturation (Table 2). On the contrary, the yield response in trial 8501B was significantly negative during two of four years in some structure-limed treatments (Table 8). Statistical analysis using contrasts revealed a significant negative yield response of 170 kg ha⁻¹ ($p=0,021$) over the four-year study period when comparing the average of the six limed treatments to the untreated control in trial 8501B.

[Table 8 near here]

Yield response of calcium hydroxide and different primary tillage (trial 8503)

Trial 8503 combined two different methods of primary tillage with or without calcium hydroxide in a split-plot design. Yearly yield responses and the average for the trial period are

shown in Table 9. Yield was not significantly affected by primary tillage method ($p=0.707$), but was significantly increased by application of 2 ton ha^{-1} CaO as calcium hydroxide over the four-year period ($p=0.006$). However, the positive yield effect was only evident in the last two years (2013-2014). In 2013, yield increased by 490 kg ha^{-1} ($p=0.007$) as a result of calcium hydroxide application and as an average of the two primary tillage methods, with both tillage methods responding in the same way. In 2014, calcium hydroxide application increased yield by 230 kg ha^{-1} ($p=0.019$) on average for the two primary tillage methods. In this last year, an interaction was observed where the two primary tillage methods reacted differently to application of calcium hydroxide. A significant yield increase as a result of the calcium hydroxide was noted only with non-inversion tillage, and not in ploughed trial plots.

Over the four-year period, statistical analysis showed a significant yield increase ($p=0.006$) of 160 kg ha^{-1} in response to calcium hydroxide as an average for the two primary tillage methods. However, for the different tillage methods there were discrepancies, e.g. in the non-ploughed treatment the yield increase was significant (190 kg ha^{-1}) ($p=0.018$), while in the ploughed treatment there was merely a tendency for a yield increase (up to 130 kg ha^{-1}) but it was not statistically significant ($p=0.099$). Hence application of calcium hydroxide gave a more positive yield response when the soil was not ploughed than when it was ploughed.

[Table 9 near here]

Plant nutrient content

Nutrient content of the grain (spring barley) was analysed in trial 8502 in 2014. For the macronutrients Ca, K, Mg, P and S, there were no significant differences between the treatments (Table 10). However, the content of the micronutrient Mn was significantly lower in treatments with the highest application rates of slaked and mixed lime in comparison with the untreated

control, indicating that applying structure lime at high rates can also decrease the content of this micronutrient.

Of the nutrients analysed, only the content of Mn was found to be critically low, i.e. at a level where yield depression can occur (Reuter, 1997). All other elements were well above the critical level. Positive correlations between yield and content of K ($p=0,005$) and Mg ($p=0,048$) were found, despite the content of these elements not being significantly influenced by liming treatments.

[Table 10 near here]

Discussion

Structure lime enhanced aggregate stability

Aggregate stability, measured as reduction in turbidity, increased significantly with the highest application rate of both structure liming products (Figure 1). Similar findings under Swedish conditions have been reported previously for clay soils at Bornsjön (Ulén et al., 2012) and Wiad (Ulén and Etana, 2014) where illite is the dominant clay mineral. Illite-dominated clay mineralogy has also been reported from Kungsängen (Simonsson et al., 2009) in close vicinity to the clay soils of the trial sites (Table 1) in the present study, making comparison of results relevant. Structure liming in the study by Ulén et al. (2012) involved application of calcium oxide ($5 \text{ t ha}^{-1} \text{ CaO}$) to a heavy clay soil (59% clay in topsoil) and the study by Ulén and Etana (2014) application of a commercially available product with active lime in slaked form (Ca(OH)_2), equivalent to $2 \text{ t ha}^{-1} \text{ CaO}$ to a clay loam (26% clay in topsoil). Whether or not the latter also contained calcium carbonate (CaCO_3) is unclear. In the present study, both slaked lime and mixed lime (containing a high percentage of CaCO_3), had a positive effect on the aggregate stability of clay soils.

Turbidity decreased significantly only in treatments with the highest application rates of lime products. While structure lime may affect aggregate stability at lower application rates, it was not possible to detect that effect with the methods used in this study. The results in Figure 1 can therefore be interpreted as a dose-response relationship, where significant aggregate stability could only be detected above a critical level of structure lime application.

Surprising, both structure lime products, applied at the highest rate, gave a similar aggregate stabilisation effect despite the fact that, although the same quantity of calcium (Ca) was applied, the proportion of calcium hydroxide ($\text{Ca}(\text{OH})_2$) in the mixed product NKAS was only 18% of the total quantity of Ca in the product (Table 4). Further research is needed to validate these findings.

Structure lime created a finer tilth

Another indication of the inherent capacity of structure lime to improve soil structure was found in seedbed investigations. The aggregate size distribution in trial 8503 (Figure 2) showed a significant increase in volume of fine aggregates (<2 mm) in the seedbed and a clear tendency for a lower proportion of coarse aggregates (5-16 mm) with the application of calcium hydroxide ($\text{Ca}(\text{OH})_2$). This finer tilth in the seedbed may have decreased evaporation from the soil by acting as a cap (Heinonen, 1985). In combination with very low precipitation of only 15 mm in May 2013 (Table 3), the water balance in the spring barley crop might have been advantageous in treatments with structure lime. This improved water regime could be the reason why treatments with structure lime increased crop yield of spring barley by 9%. Regression analysis pointed to a significant negative correlation ($R^2=0.33$; $p=0.020$) between the proportion of coarse aggregates (5-16 mm) and yield response, together with a positive but non-significant correlation ($R^2=0.20$; $p=0.086$) between the proportion of fine aggregates (<2 mm) and yield response (Figure 3).

[Figure 3a near here]

[Figure 3b near here]

Figure 3. Correlation between aggregate size in seedbed and yield in 2013 in trial 8503. a) aggregates 5-16 mm ($R^2=0.33$; $p=0.020$) and b) aggregates <2 mm ($R^2=0.20$; $p=0.086$). Black circle=plough, 0 t ha⁻¹, black box=plough, 2 t ha⁻¹, white circle=tine, 0 t ha⁻¹, white box=tine, 2 t ha⁻¹.

Liming gave an overall significant yield response when the two primary tillage methods were taken together. It also gave a significant yield response when the soil was not ploughed and a lower, non-significant, yield response when the soil was ploughed. Under the dry conditions prevailing in 2013 the structure lime may have counteracted the otherwise coarser seedbed resulting from omission of ploughing.

Structure lime gave varying yield response

The different crops (=years) in Table 5 reacted in the same way to the structure lime treatments. Yield response to structure lime was on the other hand inconsistent in the different trials, with both positive and negative yield responses. As mentioned above, structure lime increased yield significantly in trial 8503 (Table 9), possibly owing to the finer seed bed tilth withstanding dry conditions in 2013. However, as a general average, no significant positive yield responses were observed from structure lime application over the four-year period in trials 8501A, 8501B and 8502. The averages conceal however differing reactions to the treatments in the different trials, as is evident from the significant interaction in yield response between structure lime treatment and trial ($p=0.025$) over the four-year period. There was a significant interaction between lime treatment and trial in the years 2011 ($p=0.008$) and 2013 ($p=0.023$), i.e. the reaction to the

structure lime treatments differed in the trials in those years. However in 2012 ($p=0.822$) and 2014 ($p=0.659$) no such interactions were observed.

In trials 8501A and 8502 no significant yield responses were observed over the period, even though the soil at site 8501A had a slightly acidic soil reaction. The trial-treatment interaction was instead the result of a negative yield response in trial 8501B in 2011 and 2013 (Table 8). The reason for the negative yield response is unclear, but apparently trial 8501B reacted differently in terms of yield.

Phosphorus uptake was possibly dampened

When interpreting the results obtained, base saturation (BS) and phosphorus availability in the topsoil (P-AL) can shed light on the negative yield response in 8501B (Figure 4). Yield depression attributed to P deficiency after liming has been reported (Vickers and Zak, 1978).

[Figure 4 near here]

Figure 4. Degree of base saturation and available phosphorus (P-AL) in two of four untreated plots at the trial sites in October 2013.

The four trial sites were situated close to each other (within 400 m), but the soils differed in BS and P availability. Regarding base saturation, Bell (1996) pointed out that the affinity of the soil for lime must first be satisfied for structural changes to occur, i.e. in a non-base saturated soil, added lime is used to neutralise soil acidity instead of increasing the pH to the point where pozzolanic reactions can occur. Thus high base saturation may be a prerequisite for the pozzolanic reactions to take place. Our results indicate that BS could have been decisive in trial 8503 with the highest BS of the four trials, where the structure lime resulted in a seedbed with a higher proportion of finer aggregates, probably leading to a positive yield response.

Regarding P availability, Havlin et al. (2005) showed that P solubility varies with pH and that liming up to slightly acidic or neutral pH enhances P availability in soils. This has also been reported in Swedish long-term trials on liming (Haak and Simán, 1997), where readily available phosphorus (P-AL) 26 years after liming increased by approximately 50% and 80% with an increase in pH to 70% and 100% BS, respectively. This was also recently reported for soils from the same long-term trials in laboratory experiments (Simonsson et al.). In the short term, however, contrasting results of liming have been reported, such as minimum P solubility at pH 5-7 (Devau et al., 2011) and suppressed P solubility under high concentrations of Ca^{2+} in the soil when Ca and P together are sorbed onto Fe oxides (Weng et al., 2011). Hence it follows that claims of increased P availability as a result of liming do not always apply in the short term. However, it is clear that P uptake in plants is mainly a result of diffusion, e.g. according to Havlin et al. (2005), 94% of the P uptake in maize derives from diffusion. As the diffusion rate increases with increasing proportion of water in the soil volume, this implies that P uptake in plants is dependent on sufficient water supply. Brown et al. (2012) tested different genotypes of barley under a combination of P-deficit and water-deficit treatments and found that the impact of increasing water and P availability separately was similar, while the impact of providing both P and water in combination was greater.

Dry years made P less available

In the three trials with different rates of lime products, liming caused significant yield depression only in 8501B, while yields were indifferent to liming in trials 8501A and 8502. Trial 8501B had a lower level of available P than trials 8501A and 8502 (Table 2, Figure 4). The significant yield depression in trial 8501B might therefore have been an effect of decreased P availability due to structure liming in combination with low precipitation in 2011 and 2013. Figure 5 shows the relationship between mean relative yield in structure-limed treatments

(compared with the untreated control) and May-July precipitation in trials 8501A, 8501B and 8502. There was a significant correlation only for trial 8501B, suggesting that a combination of structure lime application and low precipitation can limit crop yield in a soil poor in available P.

[Figure 5a near here]

[Figure 5b near here]

[Figure 5c near here]

Figure 5. Mean relative yield in structure-limed treatments (B-G) relative to the untreated control (A=100) in relation to yearly precipitation 2011-2014 in May-July in trials a) 8501A ($R^2=0.07$; $p=0.741$), b) 8501B ($R^2=1.0$; $p=0.002$) and c) 8502 ($R^2=0.30$; $p=0.454$).

Yield response to liming in relation to precipitation was indifferent in trial 8501A ($R^2=0.07$; $p=0.741$) and slightly negative in trial 8502 ($R^2=0.30$; $p=0.454$). In sharp contrast to this, the effect of liming in trial 8501B showed a close relationship with precipitation in May-July ($R^2=1.0$; $p=0.002$). If liming caused limitations in P availability as proposed, the adequate water supply, and consequently the sufficient P diffusion in 2012 and 2014, might have overshadowed this, whereas in 2011 and 2013 lack of water, and thereby diminished diffusion of P to the roots, can have caused the significant yield depression.

Manganese content decreased

Despite the pH not being significantly elevated three years after application, i.e. in October 2013 (Tables 6-7), there was a significant reduction in grain content of the pH-sensitive nutrient Mn in the last trial year (Table 10), implying that lingering effects on micronutrients can be unwanted side-effects of structure liming. In the case of Mn, this may have limited yield of the

crop in trial 8502. Nutrient content in grain is a poor indicator of the nutritional status in earlier stages, when yield components are founded and formed (Mengel et al., 2001). Nevertheless, the possibly yield-limiting significantly lower content of Mn in this study is a noteworthy finding in the context of structure liming.

Combined positive and negative effects

According to the results, structure lime in the form of a mixed product containing a blend of CaCO_3 and Ca(OH)_2 can significantly increase soil aggregate stability, confirming one of our starting hypotheses. The mixed structure lime had the potential to mitigate P losses from clay soils, making it a means to combat eutrophication from an environmental and societal perspective. The slaked structure lime also showed the potential to modify topsoil aggregate size distribution, creating a finer tilth that is favourable from a farm management point of view, as it facilitates seedbed preparation.

However, the hypothesis that mixed structure lime can significantly improve crop yield was not proven, as there were positive and negative effects of structure liming. From a farm management point of view, the varying crop response to structure lime is undesirable. Our results indicate a positive crop response as an effect of a seedbed with a finer tilth, preventing water losses. Negative crop responses can be the result of impaired P availability, possibly particularly in dry growing conditions, when diffusion of P is probably restricted. The negative crop response can also be the result of lower Mn availability, as this was observed as an undesirable side-effect of structure lime application. These unpredictable crop responses indicate a need for further investigations to clarify the circumstances in which structure liming not only acts to reduce P losses, but also to increase crop yield.

Acknowledgements

Thanks are expressed to Berth Mårtensson and co-workers who carried out the field work, Sixten Gunnarsson and Johannes Forkman (statistical analyses and advice) along with Christina Öhman and Ana Maria Mingot Soriano in the soil physical lab (routine analyses and aggregate stability analyses).

Funding

Financial support for the project (H1070272) was provided by SLF (Stiftelsen Lantbruksforskning) - the Swedish Farmers' Foundation for Agricultural Research.

Disclosure statement

No potential conflict of interest was reported by the authors.

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Table 1. Soil organic matter (SOM) and soil texture (% of all material <2 mm) in the topsoil at the four trial sites. Texture analysis by laser scanning, which generally gives lower levels of clay than conventional sedimentation analysis

Trial	SOM	Sand (>2000 μm)	Silt (200-2000 μm)	Silt (20-200 μm)	Clay (<2 μm)	Coarse clay (0.1-2 μm)	Fine clay (0.1-0.2 μm)	Ultrafine clay (<0.1 μm)
8501A	2.6	0.4	28.6	43.1	27.9	23.8	3.8	0.25
8501B	3.8	0.6	24.4	52.4	22.6	19.8	2.7	0.15
8502	4.7	0.1	13.0	47.4	39.5	31.8	7.0	0.70
8503	1.9	0.5	17.5	56.9	25.1	21.5	3.4	0.25

Table 2. Nutritional status in topsoil of untreated control plots at the four trial sites. Sampling in October 2013 in two of four replicate plots

Trial	CEC (pH7) me kg ⁻¹	Base sat. %	pH H ₂ O	P-AL ¹ (class) mg kg ⁻¹	P-HCl ² (class) mg kg ⁻¹	K-AL ¹ (class) mg kg ⁻¹	K-HCl ² (class) mg kg ⁻¹	Mg-AL ¹ mg kg ⁻¹	Ca-AL ¹ mg kg ⁻¹	K/Mg quota	Cu-HCl ² mg kg ⁻¹
8501A	160	64	5.60	57 (III)	830 (5)	160 (III)	3900 (4)	93	1450	1.7	22
8501B	220	82	6.25	27 (II)	660 (4)	120 (III)	3150 (4)	270	2350	0.5	23
8502	320	89	6.75	45 (III)	730 (4)	200 (IV)	5450 (5)	240	3850	0.8	37
8503	200	92	7.05	165 (V)	940 (5)	250 (IV)	5950 (5)	190	2750	1.3	35

¹Extraction with 0,1 M ammonium lactate + 0,4 M acetic acid, pH 3,75 (Egnér et al., 1960)

²Extraction with 2 M hydrochloric acid, 100 °C (Egnér et al., 1960)

Table 3. Mean monthly mean (1961-1990) air temperature (°C) and precipitation (mm) in the growing season at a climate station near the trial sites (Ultuna), 2010-2014. Normal refers to period 1961-1990 with data from Karlsson and Fagerberg (1995)

Year	Jan.	Feb.	March	April	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
Temperature												
2010	-9.0	-6.8	-1.6	5.3	11.0	15.0	20.4	16.5	11.0	5.3	-1.1	-8.0
2011	-2.9	-6.6	0.1	8.5	11.5	16.9	18.5	16.4	13.2	7.6	5.1	1.8
2012	-2.5	-4.2	3.7	4.4	11.4	13.3	16.9	15.8	11.6	5.7	3.8	-4.6
2013	-4.3	-2.4	-3.9	4.2	13.6	16.1	17.7	16.8	11.8	7.4	3.3	2.6
2014	-2.6	2.0	3.9	6.6	10.7	13.6	20.0	16.7	12.0	8.4	4.4	-0.9
<i>Normal</i>	<i>-4.4</i>	<i>-4.6</i>	<i>-1.1</i>	<i>3.9</i>	<i>10.2</i>	<i>15.0</i>	<i>16.3</i>	<i>15.1</i>	<i>10.8</i>	<i>6.4</i>	<i>1.2</i>	<i>-2.8</i>
Precipitation												
2010	26.5	26.1	41.7	29.1	54.1	38.0	68.5	89.0	43.4	40.8	72.1	41.0
2011	31.3	20.7	14.7	12.6	24.5	62.1	14.2	116.2	69.7	68.6	27.3	67.1
2012	42.8	45.9	13.9	61.9	44.7	120.7	60.7	116.7	74.7	63.8	54.0	66.6
2013	24.0	31.6	1.3	54.3	14.6	51.1	17.6	52.1	52.8	70.2	49.3	54.9
2014	42.6	42.3	45.5	35.1	59.0	71.2	24.0	93.0	54.4	83.7	41.2	30.8
<i>Normal</i>	<i>34.0</i>	<i>25.0</i>	<i>26.0</i>	<i>29.0</i>	<i>33.0</i>	<i>46.0</i>	<i>70.0</i>	<i>66.0</i>	<i>57.0</i>	<i>50.0</i>	<i>51.0</i>	<i>41.0</i>

Table 4. Treatments with liming levels and levels of products in trials 8501A, 8501B, 8502 (Treatments A–G) and trial 8503 (Treatments P0–P2, S0–S2). Numbers 1, 2 and 6 in Treatment designation refers to liming level (CaO t ha⁻¹)

Treatment	Levels of liming product ^{1,2}
A. Control	-
B. Slaked lime 1	1.4 t ha ⁻¹ Ca(OH) ₂
C. Slaked lime 2	2.8 t ha ⁻¹ Ca(OH) ₂
D. Slaked lime 6	8.4 t ha ⁻¹ Ca(OH) ₂
E. Mixed lime 1	2 t ha ⁻¹ NKAS CaCO ₃ /Ca(OH) ₂
F. Mixed lime 2	4 t ha ⁻¹ NKAS CaCO ₃ /Ca(OH) ₂
G. Mixed lime 6	12 t ha ⁻¹ NKAS CaCO ₃ /Ca(OH) ₂
P0. Plough 0	-
P2. Plough 2	2.8 t ha ⁻¹ Ca(OH) ₂
S0. Stubble cultivation 0	-
S2. Stubble cultivation 2	2.8 t ha ⁻¹ Ca(OH) ₂

¹In trial 8501B the absolute levels of products were 10-15% (slaked lime) and 30% (mixed lime) lower than planned.

²The mixed lime NKAS consisted of 82% CaCO₃ and 18% Ca(OH)₂ by weight.

Table 5. Crops and levels of fertiliser (kg ha⁻¹) in the field trials 2011-2014. Supply of N and P was as NP 26-4 in 2011 and supply of N and S was as NS 27-4 (Axan) in 2012-14.

Trial	2011			2012			2013			2014						
	Crop	N	P	S	Crop	N	P	S	Crop	N	P	S	Crop	N	P	S
8501A	Oats	82	13	13	Oats	85	0	12	Sp barley	85	0	12	Sp barley	85	0	12
8501B	Oats	82	13	13	Oats	85	0	12	Sp barley	85	0	12	Sp barley	85	0	12
8502 ¹	Oats	82	13	13	W wheat	122	0	17	Sp barley	85	0	12	Sp barley	85	0	12
8503	Oats	82	13	13	Oats	85	0	12	Sp barley	85	0	12	Sp barley	85	0	12

Table 6. pH (H₂O) in December 2011 and September 2012 and pH (H₂O) and electrical conductivity (EC) in October 2013 in trials 8501A, 8501B and 8502. Significant differences compared with the control are indicated in bold.

Treatment	8501A				8501B			8502		
	pH Apr -11	pH Sept -12	pH Oct -13	EC Oct -13 (μ S/cm)	pH Sept -12	pH Oct -13	EC Oct -13 (μ S/cm)	pH Dec -11	pH Oct -13	EC Oct -13 (μ S/cm)
A. Control	6.11	5.92	6.47	95	6.34	6.86	94	6.82	7.12	133
B. Slaked lime 1	6.28	6.29	6.07	140	6.39	6.92	98	7.14	6.91	143
C. Slaked lime 2	6.49	6.05	6.26	124	6.65	6.87	100	7.41	6.87	140
D. Slaked lime 6	6.63	6.77	6.35	141	7.33	6.77	151	7.87	6.95	166
E. Mixed lime 1	6.16	6.17	6.3	99	6.44	6.83	100	7.02	6.80	147
F. Mixed lime 2	6.22	5.90	6.36	110	6.49	6.87	96	7.15	6.92	126
G. Mixed lime 6	6.56	6.81	6.34	150	7.13	6.83	148	7.50	6.92	203
Mean	6.35	6.27	6.31	123	6.68	6.85	112	7.27	6.93	151
CV %	4.6	5.1	3.3	12	3.4	2.2	15	3.5	2.8	14
p	0.114	0.003	0.280	0.000	0.000	0.859	0.000	0.000	0.436	0.001
LSD	0.43	0.49	0.31	21	0.34	0.22	25	0.38	0.29	31

Table 7. pH (H₂O) in September 2012 and pH (H₂O) and electrical conductivity (EC) in October 2013 in trial 8503. Significant differences are indicated in bold.

Treatment	pH Sept -12	pH Oct -13	EC Oct -13 (μ S/cm)
P0. Plough, 0 t ha ⁻¹ CaO	7.30	7.12	101
P2. Plough, 2 t ha ⁻¹ CaO as Ca(OH) ₂	7.63	7.01	113
S0. Stubble cultivator, 0 t ha ⁻¹ CaO as Ca(OH) ₂	7.28	6.76	146
S2. Stubble cultivator, 2 t ha ⁻¹ CaO as Ca(OH) ₂	7.85	7.02	186
P. Plough	7.47	7.07	107
S. Stubble cultivator	7.56	6.89	166
0. 0 t ha ⁻¹ CaO as Ca(OH) ₂	7.29	6.94	123
2. 2 t ha ⁻¹ CaO as Ca(OH) ₂	7.74	7.02	149
Mean	7.52	6.98	136
CV %	4.6	2.6	13
p F1, Plough/Stubble cultivator	0.613	0.225	0.023
p F2, 0/2 ton CaO ha ⁻¹	0.040	0.446	0.025
p F1*F2	0.518	0.091	0.151
LSD F1	0.55	0.37	43
LSD F2	0.42	0.22	21

Table 8. Yield response (kg ha⁻¹, 15% water content, and relative (Rel) to control) in trial 8501B in 2011-2014, including four-year average. Significant values compared with the control are indicated in bold. LSDs within brackets indicate a non-statistically significant value.

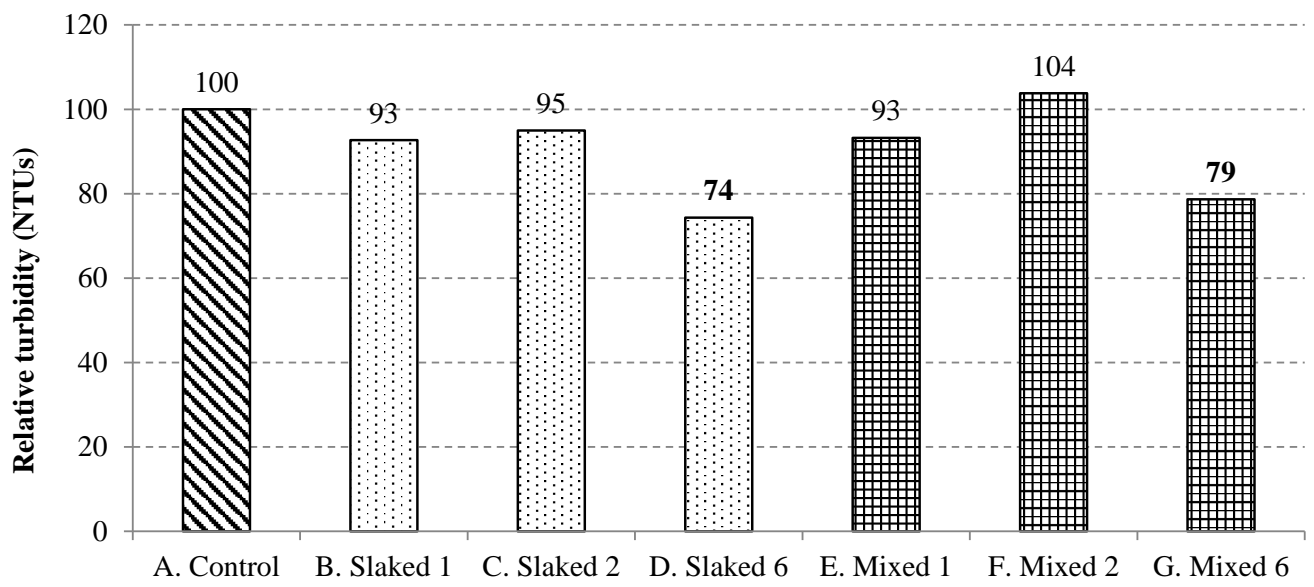
Treatment	2011 (oats)		2012 (oats)		2013 (sp barley)		2014 (sp barley)		2011–2014	
	Yield.	Rel.	Yield.	Rel.	Yield.	Rel.	Yield.	Rel.	Yield.	Rel.
A. Control	5310	<u>100</u>	5310	<u>100</u>	5810	<u>100</u>	5020	<u>100</u>	5360	<u>100</u>
B. Slaked lime 1	4730	89	5150	97	5700	98	4910	98	5120	96
C. Slaked lime 2	5060	95	5340	101	5610	97	5010	100	5250	98
D. Slaked lime 6	5240	99	5550	105	5300	91	5080	101	5290	99
E. Mixed lime 1	5130	97	5450	103	5390	93	4720	94	5180	97
F. Mixed lime 2	4860	92	5450	103	5390	93	4830	96	5130	96
G. Mixed lime 6	5040	95	5490	103	5280	91	4920	98	5180	97
p	0.045		0.176		0.001		0.146		0.107	
LSD	360		(310)		250		(270)		(180)	

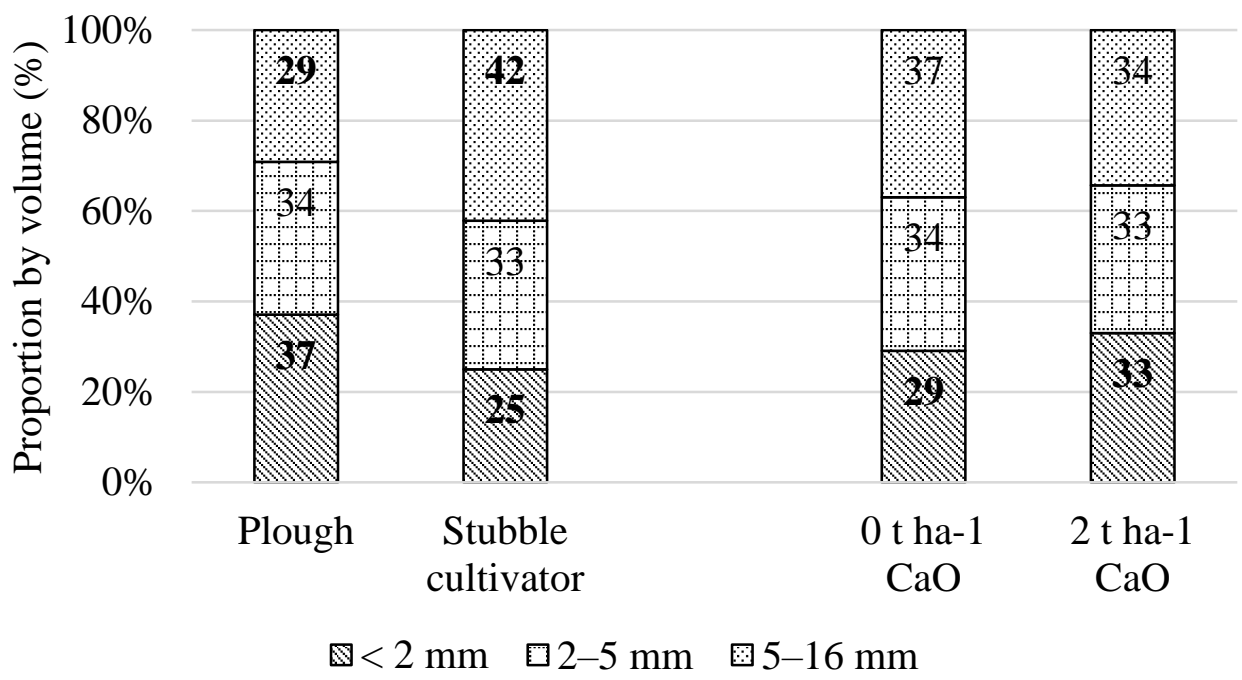
Table 9. Yield response (kg ha⁻¹, 15% water content, and relative (Rel) to control) in trial 8503 in 2011-2014, including four-year average. Significant values compared with the control are indicated in bold. LSDs within brackets indicate a non-statistically significant value.

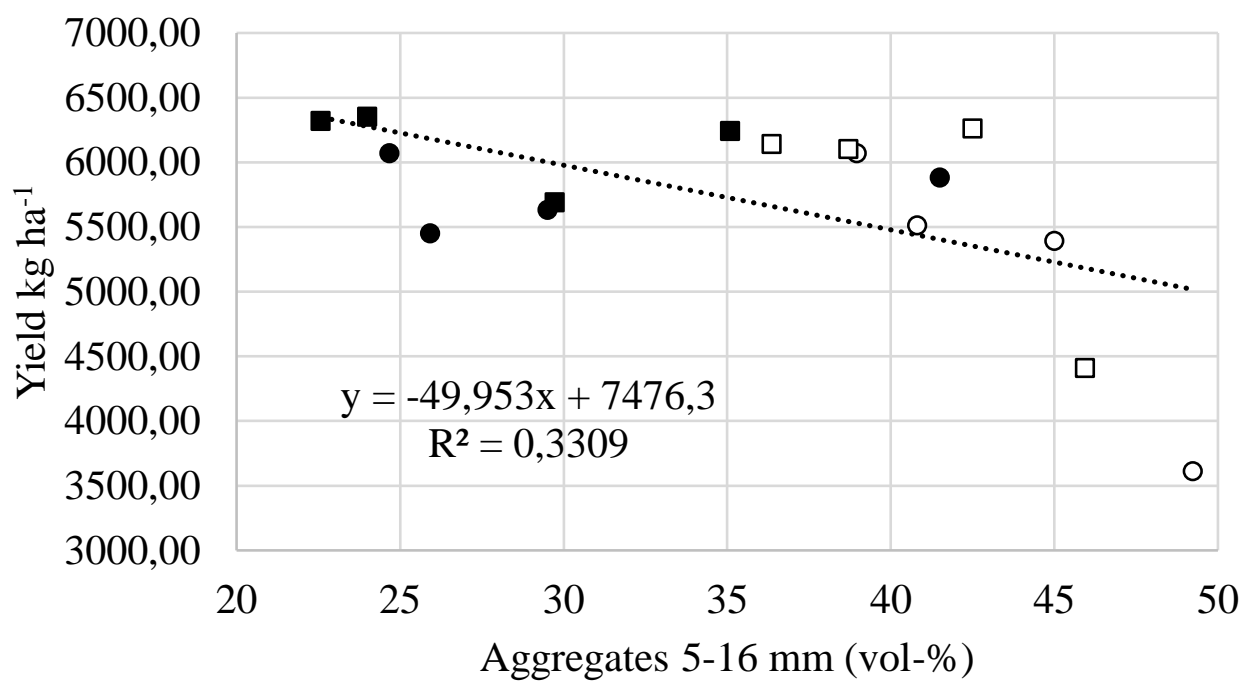
Treatment	2011 (oats)		2012 (oats)		2013 (sp barley)		2014 (sp barley)		2011–2014	
	Yield.	Rel.	Yield.	Rel.	Yield.	Rel.	Yield.	Rel.	Yield.	Rel.
P0. Plough, 0 t ha ⁻¹ CaO	3970	<u>100</u>	5850	<u>100</u>	5760	<u>100</u>	5260	<u>100</u>	5210	<u>100</u>
P2. Plough, 2 t ha ⁻¹ CaO	4110	104	5920	101	6150	107	5170	98	5340	102
S0. Stubble cult., 0 t ha ⁻¹ CaO	4090	103	6300	108	5150	89	4830	92	5090	98
S2. Stubble cult., 2 t ha ⁻¹ CaO	4030	102	6000	103	5730	99	5370	102	5280	101
P. Plough	4040	<u>100</u>	5890	<u>100</u>	5950	<u>100</u>	5210	<u>100</u>	5270	<u>100</u>
S. Stubble cultivator	4060	100	6150	104	5440	91	5100	98	5190	98
0 t ha ⁻¹ CaO as Ca(OH) ₂	4030	<u>100</u>	6080	<u>100</u>	5450	<u>100</u>	5040	<u>100</u>	5150	<u>100</u>
2 t ha ⁻¹ CaO as Ca(OH) ₂	4070	101	5960	98	5940	109	5270	105	5310	103
p F1, Plough/Stubble cult.	0.946		0.248		0.341		0.196		0.707	
p F2, 0/2 ton CaO ha ⁻¹	0.662		0.421		0.007		0.019		0.006	
p F1*F2	0.272		0.205		0.461		0.003		0.566	
LSD F1	(680)		(500)		(1450)		(180)		(530)	
LSD F2	(210)		(320)		290		180		110	

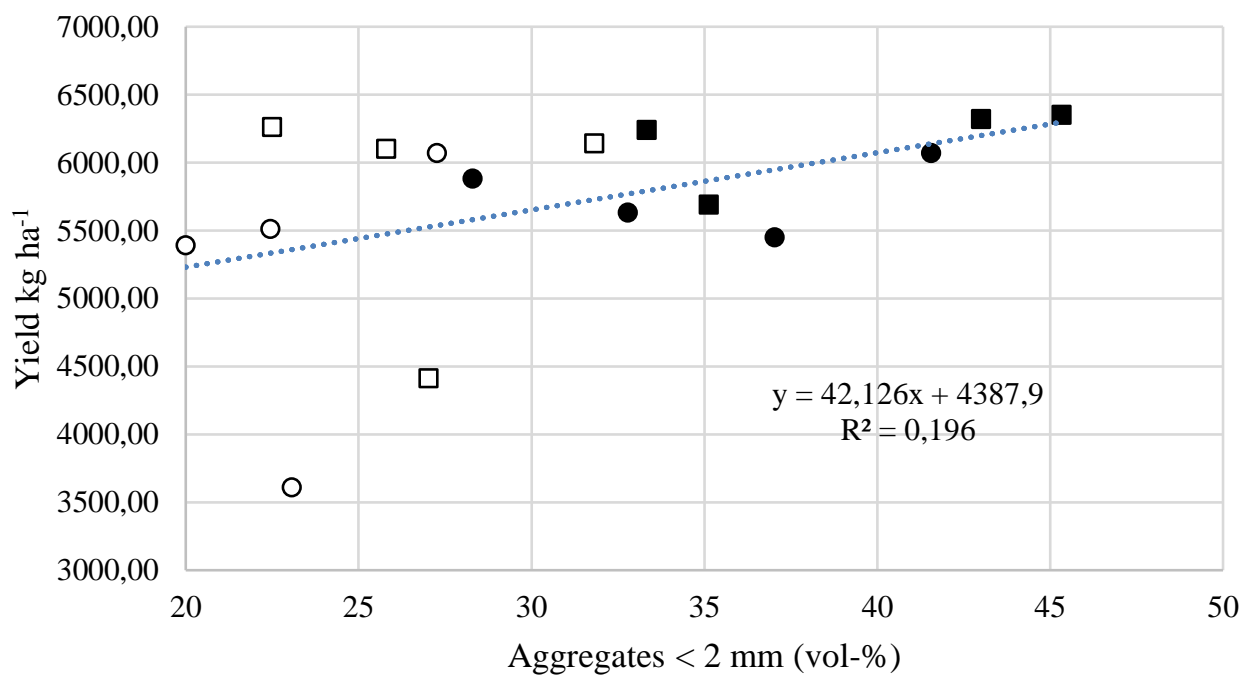
Table 10. Concentration (mg kg⁻¹ dry matter) of Ca, Mg, K, P, S, Zn, Mn and Cu in grain of spring barley in trial 8502 in 2014. Critical concentrations for grain of barley where yield depression of 5-10% can be expected are according to Reuter (1997) (no data for Ca, Mg and K). Significant values compared with the control are indicated in bold.

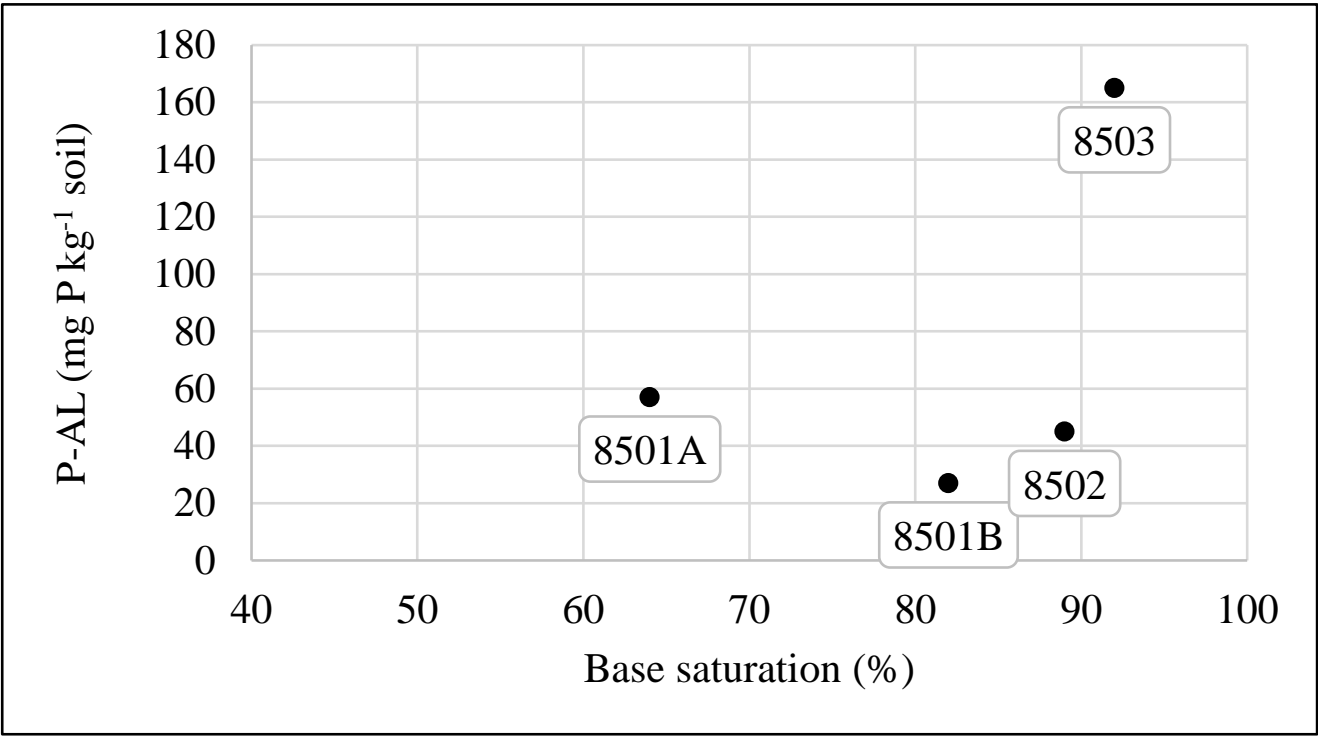
	Tot-Ca	Tot-Mg	Tot-K	Tot-P	Tot-S	Tot-Zn	Tot-Mn	Tot-Cu
Treatment								
A. Control	494	1370	5260	3590	1420	36.6	10.4	4.64
B. Slaked lime 1	495	1340	5210	3510	1260	35.6	9.4	4.51
C. Slaked lime 2	496	1290	5200	3410	1210	34.6	9.8	4.58
D. Slaked lime 6	513	1330	5380	3570	1260	34.6	8.1	4.45
E. Mixed lime 1	500	1320	5150	3390	1370	36.8	9.9	4.64
F. Mixed lime 2	492	1330	5200	3470	1160	35.8	9.6	4.53
G. Mixed lime 6	501	1340	5400	3540	1240	34.2	8.1	4.49
Mean	499	1330	5260	3500	1270	35.5	9.3	4.55
CV %	2.5	3.2	2.4	3.2	13	4.1	7.8	2.1
p	0.281	0.323	0.075	0.139	0.307	0.115	0.001	0.074
LSD	18	63	188	169	238	2.15	1.1	0.14
Critical conc.	–	–	–	1900– 2600	1100–1300	approx. 8	9–10	1–2

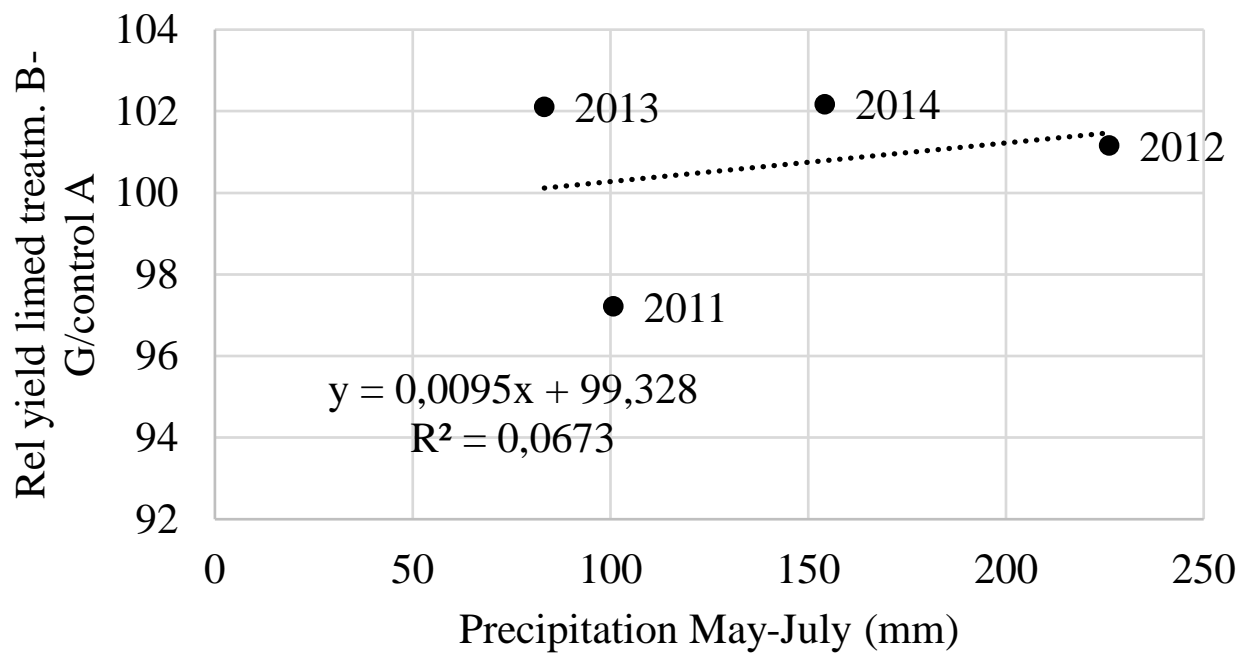




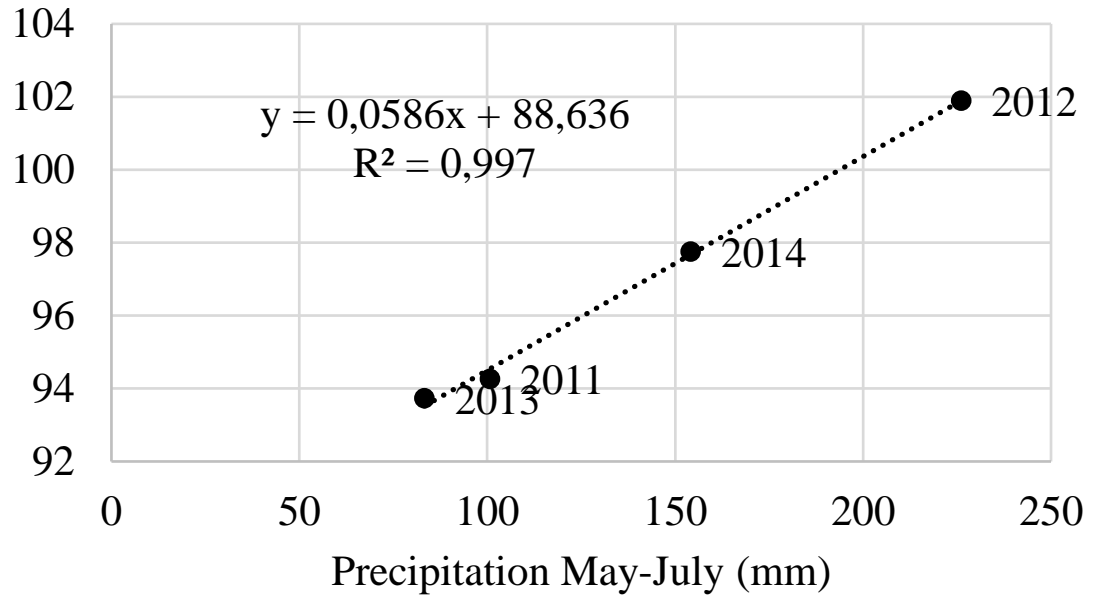








Rel yield limed treatm. B-
G/control A



Rel yield limed treatm. B-
G/control A

