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Cover: Structure liming followed by immediate incorporation, September 2021
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Abstract

Structure lime, comprising 80-85% ground limestone ($CaCO_3$) and 15-20% slaked lime ($Ca(OH)_2$), is applied to clay soils to counteract losses of particulate phosphorus (PP) through aggregate stabilisation. This thesis evaluated the effect of structure lime on soil aggregate stability, aggregate size distribution, draught requirement in tillage and crop yield.

Structure lime at the standard application rate of 8 t ha^{-1} increased aggregate stability at 1-2.5 years after application by 15-35% compared with an unlimed control. On average, structure liming proved to be an effective measure to increase aggregate stability and thereby reduce the risk of PP losses. However, significant trial-treatment interactions indicated different soil reactions in different trials, with clay content, soil organic matter content, initial pH and clay mineralogy being decisive variables. Site-specific application of structure lime is therefore needed. Follow-up studies six years after structure liming showed declining effects on aggregate stability. A tentative recommendation is that clay soils with pH below 7 and clay content above 25% should be given priority in structure liming schemes.

Structure liming resulted in a finer tilth and reduced the draught requirement in cultivator tillage by 7%, thus lowering fuel consumption and reducing associated CO_2 emissions. Crop yield responses were inconsistent, with changes in spring barley grain yield of ±10%. Decreased availability of micronutrients through binding in limed soil can possibly explain the observed yield decreases. Yield increases were likely attributable to a finer tilth.

Keywords: structure lime, particulate phosphorus, aggregate stability, aggregate size distribution, draught requirement, grain yield

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Dedication

I dedicate this piece of work to Swedish farmers, who care about their soil and are striving to minimise the environmental impact that food production inevitably generates. Your efforts deserve recognition.

Contents

List of publications

This thesis is based on the work contained in the following papers, referred to by Roman numerals in the text:

I. Blomquist, J., Simonsson, M., Etana, A. & Berglund, K. (2018). Structure liming enhances aggregate stability and gives varying crop responses on clay soils. *Acta Agriculturae Scandinavica, Section B – Soil & Plant Science* 68 (4), 311-322. https://doi.org/10.1080/09064710.2017.1400096

II. Blomquist, J.E. & Berglund, K. (2021). Timing and conditions modify the effect of structure liming on clay soil. *Agricultural and Food Science 30*(3), 96-107. https://doi.org/10.23986/afsci.103422

III. Blomquist, J., Englund, J.-E. & Berglund, K. (2021). Soil characteristics and tillage can predict the effect of structure liming on soil aggregate stability. *Soil Research*. Accepted for publication.

IV. Gunnarsson, A., Blomquist, J., Persson, L., Olsson, Å., Hamnér, K. & Berglund, K. Liming alkaline clay soils – effects on nutrients, soil structure and barley growth and yield. *Acta Agriculturae Scandinavica*, Section B – Soil & Plant Science. Submitted for publication.

V. Blomquist, J. Englund, J.-E., Sjöberg, C., Kårhammer, J. Svensson, S.-E., Pettersson, E., Keller, T. & Berglund, K.

Structure liming reduces draught requirement on clay soil. Manuscript

VI. Blomquist, J., Englund, J.-E. & Berglund, K. Site characteristics determine the duration of structure liming effects on clay soil. Manuscript

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The contribution of Jens Blomquist to the papers included in this thesis was as follows:

I. Carried out some of the field experimental work. Interpreted the data and wrote the paper in cooperation with the co-authors.

II. Initiated, planned and coordinated the study. Carried out the field experimental work. Performed data analysis, interpreted the data and wrote the paper with some assistance from the co-author.

III. Initiated, planned and coordinated the study. Carried out the field experimental work. Performed data analysis together with the co-authors, interpreted the data and wrote the paper in cooperation with the co-authors.

IV. Carried out the field experimental work. Wrote sections on aggregate stability and aggregate size distribution.

V. Initiated, planned and coordinated the study. Carried out the field experimental work. Performed data analysis together with the co-authors, interpreted the data and wrote the paper with some assistance from the co-authors.

VI. Planned and coordinated the study. Performed data analysis together with the co-authors, interpreted the data and wrote the paper with assistance from the co-authors.

Abbreviations

Al	Aluminium
B	Boron
Ca	Calcium
CaO	Calcium oxide, quick lime, burnt lime, non-hydrated lime
$Ca(OH)_2$	Calcium hydroxide, slaked lime, hydrated lime
$CaCO_3$	Calcium carbonate, limestone, agricultural lime
CEC	Cation Exchange Capacity
DPS	Degree of Phosphorus Saturation
DRP	Dissolved Reactive Phosphorus
DTA	Differential Thermogravimetric Analysis
Fe	Iron
H	Hydrogen
K	Potassium
LOVA	Lokala Vattenvårdsåtgärder (Local water measures)
Mg	Magnesium
Mn	Manganese
N	Nitrogen
P	Phosphorus
PP	Particulate Phosphorus
SOM	Soil organic matter
Structure lime	Mixture of 80-85% ground limestone ($CaCO_3$) and 15-20% slaked lime ($Ca(OH)_2$) in this thesis
XRD	X-ray Diffraction analysis
SmV index	relationship between swelling & non-swelling clay minerals
Zn	Zinc

1. Introduction

Phosphorus is both essential element and environmental burden

Phosphorus (P) is an essential element for all living organisms and vital for plant production. There is no substitute for phosphorus in crop growth, which led Cordell and White (2011) to describe the element as a bottleneck for life, while also citing estimates that phosphate rock reserves are between 30 and 300 years from depletion. Whatever the time frame, it is obvious that the essential element phosphorus is a limited resource

Despite general consensus that remaining reserves are decreasing, the current utilisation of phosphorus is non-circular (Ott & Rechberger 2012). The pronounced one-way flow of P from rock to agricultural soils, and further to freshwater and oceans, in the global phosphorus cycle is reported to be close to the planetary boundary, leaving only a small operating space for humanity (Rockström *et al.* 2009). One of the reasons for this dissipative situation is the global phosphorus imbalance, with 29% of cropland suffering deficits and 71% having an overall phosphorus surplus in 2000 (MacDonald *et al.* 2011). Hence, in parallel to being an essential element, phosphorus is also an environmental burden.

To counteract the effects of phosphorus as an environmental burden at European Union (EU) level, the EU Water Framework Directive was implemented in 2000. To comply with the Directive the Swedish Water Authorities were established and the Water Framework Directive was introduced into Swedish legislation in 2004 (Vattenmyndigheterna 2021), with the aim of securing good ecological quality in inland and coastal waters. Losses of plant nutrients such as phosphorus lead to eutrophication, which is an environmental problem in many parts of the world, including Sweden

(Andersson 2016). At national level in Sweden, agriculture is the largest single source of phosphorus losses to the surrounding seas, accounting for 45% of total anthropogenic net phosphorus loads according to Hansson *et al.* (2019). On clay soils particulate phosphorus (PP) are dominating the losses (Johnsson *et al.* 2019). The easiest way to prevent phosphorus mobilisation from agricultural soil to surface waters is by reducing the losses at source on field level (Bergström *et al.* 2007). This is in line with claims by Alewell *et al.* (2020) that soil erosion must be prevented to slow depletion of global phosphorus reserves, as erosion losses account for more than 50% of total phosphorus losses on a global scale.

'Structure liming' is a measure to mitigate phosphorus losses from agricultural land through improvement and stabilisation of soil structure and is recommended on clay soils by the Swedish Board of Agriculture (Andersson *et al.* 2021). The underlying concept is that particulate phosphorus (PP) bound to aggregate surfaces stays in the field, as the stronger aggregates are not broken down by stresses such as waterlogging. An improving effect on aggregate stability of non-carbonated liming products such as calcium oxide (CaO) and calcium hydroxide ($Ca(OH)_2$) has been demonstrated under laboratory conditions (Berglund 1971; Keiblinger *et al.* 2016), and also under field conditions (Ulén & Etana 2014). However, non-carbonated liming products have also been reported to result in non-significant effects on aggregate stability (Øgaard 2019).

Interest in 'structure liming' of clay soils with a mixed product, normally 80-85% calcium carbonate and 15-20% calcium hydroxide, emerged in Sweden around 2010. The use was driven by national environmental schemes (abbreviated LOVA) under the EU Water Framework Directive that subsidise up to 50% of the costs of liming (HaV 2021). The focus in these environmental schemes is mainly on preventing losses of PP from clay soils and the practice is relatively widespread, with around 65,000 hectares in Sweden being structure-limed between 2010 and 2021. Despite this extensive use, there have been few evaluations of the effects. The work described in this thesis was intended to overcome some knowledge gaps.

Apart from the expected effect on PP losses from 'structure lime', other agronomic characteristics can also be affected, as the calcium ions from lime promote flocculation, thereby making clay soils easier to work and cultivate (Haynes & Naidu 1998). Such improvements could facilitate acceptance of structure liming as a management tool, thereby 'nudging' practical farming in an environmentally friendly direction. A study in Germany found that ‘nudges’ gave behavioural effects and led farmers to comply with water protection rules (Peth *et al.* 2018). Voluntary action through education, inspiration and advice forms the basis for environmental schemes in Swedish agriculture (Olofsson *et al.* 2019). Since the carrot can be a stronger reinforcement tool than the stick, nudging farmers to adopt structure liming may give better compliance with phosphorus mitigation measures than enforcement and legislation, provided that structure liming can prove positive agronomic features for farming. For that reason, studies on agronomic aspects of structure liming, such as tilth and seedbed properties, draught requirement and crop response, were included in this thesis.

2. Aims and objectives

The overall aims of this thesis were to determine the effect of structure liming with mixes of approximately 15-20% calcium hydroxide and 80-85% calcium carbonate on aggregate stability and the risk of particulate phosphorus losses from clay soils, and to identify the associated effects of structure liming on soil chemistry, plant nutrient content, yield response and agronomic characteristics such as aggregate size distribution and soil strength.

Specific objectives of the work described in Papers I-VI were to:

I. Evaluate the effect on aggregate stability of structure lime in comparison with calcium hydroxide and assess the effect of calcium hydroxide in combination with different primary tillage techniques.
II. Investigate whether the timing of structure liming alters the effect on aggregate stability.
III. Quantify the effect of increasing application rates of structure liming on aggregate stability in the short term, and determine the relative importance of the soil properties clay content, initial pH, soil organic matter content and clay mineralogy in combination with soil tillage before and after lime application.
IV. Compare the effect of structure lime and ground limestone on aggregate stability and examine interactive effects between liming and fertilisation strategy on growth and yield in spring barley.
V. Determine the effect of structure liming on soil strength, approximated by horizontal (draught requirement) and vertical (penetrometer resistance) measurements.

VI. Compare the effect of structure liming on aggregate stability one and six years after application, assess the duration of the effect and determine whether different soils react differently to structure lime.

3. Background

3.1 Liming of soil has versatile effects

Liming is a worldwide management practice performed to counteract acidification of soils (Frank *et al.* 2019). The overall effect of liming occurs through changes in soil pH, which in turn affect soil chemistry, soil biology and soil physics. The soil chemical effect of liming indirectly influences the availability of plant nutrients (Goulding 2016). The soil biological effect of liming is also driven by changes in pH (Haynes & Naidu 1998) and can be observed as *e.g*. increased respiration several years after liming (Gustavsson 2021). Changes in pH also have impacts on soil physical properties, as the dissolution of liming materials simultaneously affects cation composition and ionic strength in the soil solution (Holland *et al.* 2018).

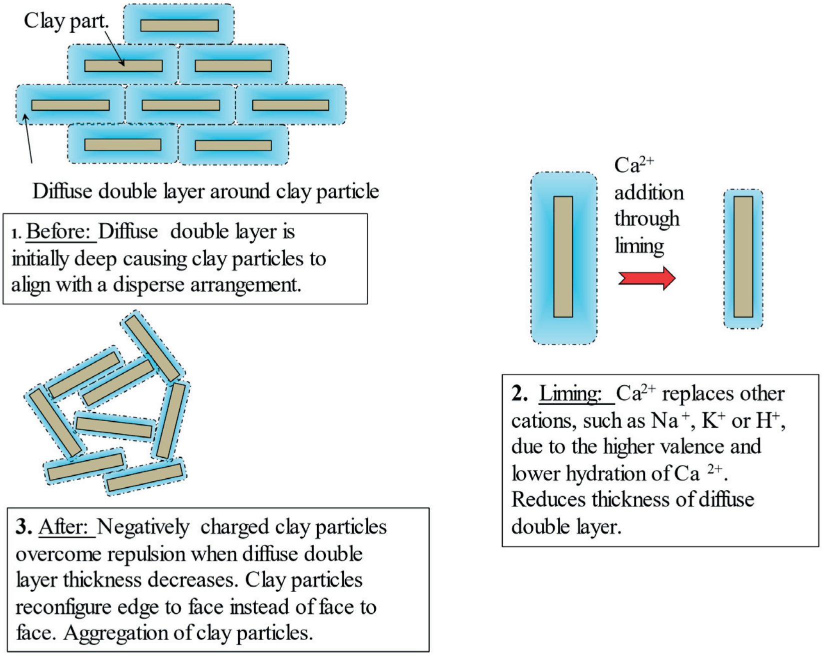
3.2 Structure liming in three reactions

From an agricultural point of view, confusion readily occurs when it comes to the terminology regarding lime, as ‘lime’ commonly refers to calcium oxide/quicklime (CaO) or calcium hydroxide/slaked lime/hydrated lime ($Ca(OH)_2$) in the geotechnical literature (Beetham *et al.* 2015). In agriculture, “lime” refers rather to ground limestone, *i.e*. calcium carbonate ($CaCO_3$). By stating that “limestone is broken down at elevated temperatures to form lime”, Firoozi *et al.* (2017) bring clarity and distinguish between carbonated and non-carbonated forms of lime according to the engineering nomenclature. The use of non-carbonated limed for engineering purposes dates back thousands of years, to the construction of pyramids in China and Egypt and Roman roads (Ballantine & Rossouw 1972). Today ‘lime’ still brings improved engineering properties to subgrades by modification and stabilisation (Little 2000).

'Structure liming' in agriculture is also primarily aimed at influencing soil physical properties in clay soils. The clay content is therefore decisive for the effect of structure liming (Øgaard 2019). The term 'structure liming' previously referred to the use of calcium oxide (CaO) or calcium hydroxide ($Ca(OH)_2$), but is currently used for commercially available mixes of calcium hydroxide ($Ca(OH)_2$) and calcium carbonate ($CaCO_3$) (Aronsson *et al.* 2019), which brings further confusion. The changes in soil structure induced by structure lime are attributable to three mechanisms (Berglund 1971): cation exchange, lime carbonation and pozzolanic reactions.

3.2.1 Cation exchange

When calcium ions (Ca^{2+}) from different types of calcium products (ground limestone, gypsum, quicklime, slaked lime *etc.*) react with soil, the first step involved is cation exchange (Figure 1).



1. Before: Diffuse double layer is initially deep causing clay particles to align with a disperse arrangement.

2. Liming: Ca^{2+} replaces other cations, such as Na^+, K^+ or H^+, due to the higher valence and lower hydration of Ca^{2+}. Reduces thickness of diffuse double layer.

3. After: Negatively charged clay particles overcome repulsion when diffuse double layer thickness decreases. Clay particles reconfigure edge to face instead of face to face. Aggregation of clay particles.

Figure 1. The cation exchange process (modified after Beetham *et al.* (2015)).

Incoming divalent cations such as Ca^{2+} exert a greater attractive force towards the clay particle surface than any monovalent cation present, *e.g.* the sodium (Na^+) or potassium (K^+) ions commonly found in clay soils (Beetham *et al.* 2015). This results in cation exchange, where Ca^{2+} replaces other ions, such as Na^+, K^+ or hydrogen (H^+), due to the higher valence and lower hydration of Ca^{2+}. With a low concentration of Ca^{2+}, the thickness of surrounding water film of the diffuse double layer around clay particles can be 0.01 μm. However, with increasing concentration of Ca^{2+} the thickness of the water film decreases sharply, to 10% of the original value, *i.e.* down to 0.001 μm (Assarson 1977).

Clay particles are negatively charged along their planes. This normally leads to repulsion between the clay lamellae, with increasing electric and osmotic repulsion the closer the clay particles come to each other. However, when the thickness of the double layer water film decreases as the concentration of Ca^{2+} increases, the clay particles overcome this repulsion and electrostatic charges on adjacent clay particles interact. The clay particles reconfigure, to lie edge to face instead of face to face (Figure 1), as short-range attractive forces (London-van der Waals forces) act and combine the clay particles into flocs (Hillel 1982). These processes lead to flocculation and aggregation, as outlined by Choquette *et al.* (1987). Flocculation is a prerequisite for water-stable aggregation (Tisdall & Oades 1982).

The cation exchange reaction can take place with all types of calcium products, including calcium carbonate ($CaCO_3$). However, the reaction time depends on the type of lime, due to differences in solubility. The solubility of $CaCO_3$ in water is low, with a maximum Ca concentration of 6 mg L^{-1} water and with a maximum pH of 8.2 in the soil (Berglund 1971). With the use of non-carbonated types of lime such as quicklime (calcium oxide, CaO) or slaked (hydrated) lime (calcium hydroxide, $Ca(OH)_2$) the opposite situation occurs. Both CaO and $Ca(OH)_2$ are very soluble in water, permitting a maximum Ca concentration of 1,000 mg L^{-1} water and a temporary and momentary maximum pH in the soil exceeding 12 (Berglund 1971). This distinction in solubility between calcium carbonate on the one hand and calcium oxide or calcium hydroxide on the other indicates vast differences in behaviour in contact with clay. The high solubility of quicklime and slaked lime speeds up the process considerably, allowing cation exchange to be observed with the naked eye. Its effects can be seen in less than minutes, as the soil becomes more friable, less sticky, more voluminous and gives the impression of having a lower water content (Ericsson *et al.* 1975).

The next two steps, lime carbonation and the pozzolanic reaction, can only be achieved with calcium oxide or calcium hydroxide.

3.2.2 Carbonation

The lime carbonation step in aggregate stabilisation occurs when calcium hydroxide ($Ca(OH)_2$) reacts with carbon dioxide (CO_2), from the air or dissolved in water, in soil pores or above the soil surface (Akula & Little 2020), according to the reaction:

$$Ca(OH)_2 + CO_2 \rightarrow CaCO_3 + H_2O \qquad (1)$$

This reaction occurs *e.g.* when mortar is applied between bricks during bricklaying. Fine sand and water together with a binding agent, which is normally cement or calcium hydroxide, act as glue between the bricks. As carbon dioxide is picked up from the air, the calcium carbonate ($CaCO_3$) created forms bridges between grains of sand (Berglund 1971).

On studying a heavy clay soil (clay content 65%) in a field trial that had been limed with calcium oxide (CaO) eight years prior to soil sampling, Ledin (1981) detected the presence of calcium carbonate. Scanning electron microscopy (SEM) and X-ray analyses showed that the calcium carbonate was present in several different forms in the soil aggregates, occurring as crystals covering the surface of micro-aggregates as cutans, but also dispersed in the clay matrix and even filling up the pores. All these different forms of calcium carbonate could occur in one single ped. Ledin (1981) concluded that the calcium carbonate could have its origins either in (i) chemical reactions from the CaO that was mixed into the soil or (ii) secondary crystallisation, when calcium carbonate is precipitated from a saturated solution. In that study, limed soil was found to be more rigid than unlimed soil, *i.e.* the limed soil showed lower shrinking and swelling. The explanation suggested was the suppressive effect of Ca^{2+} ions on the diffuse double layer, restricting the movements of particles when wetted and dried.

However, the cementing effects of lime carbonation and the positive effects on soil aggregation are not undisputed. Diamond and Kinter (1965) regard lime carbonation as an undesirable reaction, since it consumes part of the lime that would normally be used to form more resistant cementing products. This view is shared by other authors who describe carbonation as a "deleterious chemical reaction" (Firoozi *et al.* 2017). In a study where the degree of carbonation and pozzolanic reactions were determined in an embankment that had been treated with quicklime (2.5% w/w) during construction of a motorway 34 years prior to sampling (Haas & Ritter 2019), it was concluded that 37% of the quicklime was used in carbonation, 47% in pozzolanic reactions and 16% was still available as CaO. Whether or not these proportions are relevant for agriculture remains to be determined.

3.2.3 Pozzolanic reactions

Clay aggregates can be further stabilised through pozzolanic reactions, often referred to as cementation (Shanmuganathan & Oades 1983). When quicklime is added to soil, it immediately reacts with water (hydrates) under the release of heat (Firoozi *et al.* 2017) in the following reaction:

$$CaO + H_2O \rightarrow Ca(OH)_2 \qquad (2)$$

The slaked lime that is not consumed in cation exchange (see section 3.2.1) is free to react with the silica and alumina in the clay minerals (Åhnberg 2006). Clay minerals are chemically dominated by silicon (Si) and aluminium (Al) in the form of oxides, and these constituents of the clay minerals contribute the pozzolanic materials needed for the reaction. The result is the formation of calcium aluminate silicate hydroxide (CASH), calcium silicate hydroxide (CSH) and/or calcium aluminate hydroxide (CAH) (Beetham *et al.* 2015).

An alkaline environment is a prerequisite for pozzolanic reactions, as silica and alumina become soluble (Kassim & Chern 2004). In the highly alkaline environment (~pH 12.4) that develops when quicklime or slaked lime is added to soil, the silicate tetrahedra and the aluminate octahedra in clay minerals are dissolved and the pozzolanic reactions take place in what has been described as an attack on the clay minerals by the lime (Al-Mukhtar *et al.* 2010). The dissolved clay then forms the new cementitious products described above, *i.e*. CASH, CSH and CAH.

In a study in which four clayey soils were treated with different amounts of quicklime, hydrated lime and ground limestone at different water contents, reaction products of the CSH and CASH types were detected (Choquette *et al.*

1987). The growth of these structures in the soil was found to be progressive over time and was not detected during the first days after treatment, but became abundant after 300 days. The formation of the CSH and CASH products was correlated with a progressive increase in shear strength and also a change in pore size distribution whereby micropores increased at the expense of macropores (Choquette *et al.* 1987).

In another study, Al-Mukhtar *et al.* (2010) conducted laboratory tests with a highly expansive clay soil with a high proportion of smectite, together with increasing amounts of calcium hydroxide (0-20%). The pozzolanic reaction developed over time and the duration of the reaction increased with the amount of lime available, indicating a need for excess lime for the reaction to take place. This led to the conclusion that the pozzolanic reactions are temperature-dependent and take place over a long time.

This time dependency of the pozzolanic reaction was investigated by Kavak and Baykal (2012) in a long-term study of lime-stabilised kaolinite clay. They measured the unconfined compression strength (UCS) at two different contents of calcium hydroxide after long-term curing in a humidity room. After one month, they observed an 8-fold increase, and after 10 years a 21-fold increase, on the initial value.

The microstructure of a calcium hydroxide-treated smectite- and kaolinite-dominated expansive clayey soil was examined by Al-Mukhtar *et al.* (2012). Using X-ray diffraction and SEM, they observed that lime treatments strongly modified the clay texture. The SEM analyses also revealed connected pores in the lime-treated soil, making the structure more permeable.

Bell (1996) concluded that small increases in temperature at liming can improve soil strength significantly, whereas the reaction is retarded below 4°C and ceases at lower temperatures, and that the pozzolanic reaction can remain dormant during periods with low temperatures and regain its potential when the temperature increases.

Akula and Little (2020) treated expansive soils with calcium hydroxide and measured the effect in engineering tests as unconfined compressive strength (UCL) and plasticity index (PI) to show the presence of pozzolanic reactions. They also measured reaction products from pozzolanic reactions with X-ray diffraction (XRD) and differential thermogravimetric analysis (DTA) and, on comparing the data, concluded that XRD and DTA are efficient tools to quantify the degree of pozzolanic reactions.

3.3 New interest in structure liming

Liming with ‘structure lime’ is used in Sweden not primarily to increase pH, but to mitigate the risk of phosphorus losses from clay soils by stabilising aggregates. Structure liming is recommended by the Swedish Board of Agriculture as a possible measure to control losses of phosphorus to surface waters (Andersson *et al.* 2021). The principal driver in liming agricultural soils is pH, and impacts on soil chemistry, soil physics and soil biology occur via pH change (Holland *et al.* 2018). Therefore, structure lime can affect soil in many different respects. The effects of lime and structure lime on soil are outlined in the following sections (3.4-3.7).

3.4 Liming affects soil

The consequences of liming are multifaceted, as pointed out in section 3.1, and in a wide sense liming can have profound impacts on soil (Figure 2). Liming is historically a common management practice to neutralise acidity (Bolan *et al.* 2003). In a meta-analysis of liming covering 175 published studies since 1980, Li *et al.* (2019) showed that the effect on pH of liming was 36% greater in pot conditions (laboratory) than in field conditions.

Figure 2. Liming affects soil physical properties through changes in pH (Holland *et al.* 2018). Photo: Jens Blomquist.

They also found that application of lime always increased soil pH, but that the effect tended to be greater when initial soil pH was lower and that changes in chemical properties were less pronounced on fine-textured soils with a high buffering capacity. In addition, their meta-analysis revealed that lime application increased available nitrogen and available phosphorus by 7% and 9%, respectively (Li *et al.* (2019). This is of relevance also with the use of structure lime.

Another relevant consideration is the general rule that the availability of boron (B), copper (Cu), iron (Fe), manganese (Mn) and zinc (Zn) normally decreases when soil pH increases (Fageria *et al.* 2002). Haynes (1984) cited other studies in which yield depression after liming was associated with decreased concentrations of Fe, Mn, Zn, Cu, cobalt (Co) and B in plants. Such negative effects can also be a consequence of structure liming.

Soil biology is affected by liming, with impacts on almost all types of soil organisms including fungi, bacteria, earthworms and nematodes (Holland *et al.* 2018). A general shift in microbial population from fungi to bacteria occurs as a result of increasing pH (Haynes & Naidu 1998). Lime-induced increases in the abundance of earthworms were observed by McCallum *et al.* (2016) and differences in respiration due to liming by Gustavsson (2021). Liming increased soil nitrogen availability in permanent pasture and perennial ryegrass (Stevens & Laughlin 1996), an effect partly attributable to increasing mineralisation of soil nitrogen through liming effects on soil biology.

Soil physical properties can undergo significant changes with the addition of different types of lime. For example, Berglund (1977) observed increased aggregate mean weight diameter, while increased aggregate stability has also been demonstrated (Bennett *et al.* 2014; Keiblinger *et al.* 2016). Changes in bulk density, plant-available water capacity and pore volume were observed by Frank *et al.* (2019), while Kirkham *et al.* (2007) found decreases in penetrometer resistance due to liming. Similarly, Valzano *et al.* (2001) found decreases in penetrometer resistance together with improvements in infiltration and water availability following liming. It is reasonable to expect that these reported changes in soil physical properties will also occur following application of the mixed structure lime currently used in Sweden. However, the literature reports varying effects that seem to be both time-dependent and affected by soil tillage (Frank *et al.* 2020), as well as site-specific (Bölscher *et al.* 2021). This is important to bear in mind in the context of structure liming.

3.5 Liming affects management

Liming can affect soil management characteristics that are important for practical farming in relation to soil tillage and plant establishment (Fig. 3).

Figure 3. Release of calcium ions from liming favours flocculation, which in turn facilitates soil tillage (Haynes & Naidu 1998). Photo: Jens Blomquist.

Lime application makes soils easier to cultivate and work (Haynes & Naidu 1998), as the slow release of lime maintains high concentrations of calcium ions, which in turn favours flocculation. Ledin (1981) found that limed soil was more friable, fell more readily into smaller aggregates and showed a higher tendency to break up into smaller aggregates than unlimed soil. Blackert (1996) found a pronounced effect of liming, with a higher percentage of aggregates <2 mm and a lower proportion of aggregates >5 mm in seedbeds in limed soil.

Hoyt (1981) observed differences in soil crusting in field trials, where both calcium carbonate and calcium hydroxide improved the resistance to pulverisation by tillage machinery, with increased rapeseed emergence as a consequence. In other field trials, Stenberg *et al.* (2000) found that yield was considerably higher in a treatment with shallow tillage in combination with lime in a year when all yields were relatively low due to crust formation. Lime addition in that particular year improved soil structure in a way that was not accounted for by any of the measured structure variables (Stenberg *et al.* (2000).

Draught requirement is another soil physical trait affecting daily life in farming. It has been observed to decrease with increasing application rates of calcium oxide and calcium carbonate, but with no clear dose-response pattern for calcium carbonate (Siman *et al.* 1984).

These improvements in soil characteristics attributed to different forms of lime can possibly also occur following application of the mixed structure lime products that are currently used in Sweden.

3.6 Liming affects environment

Phosphorus is the growth-limiting nutrient for algae in inland waters and in the Baltic Sea Proper and inputs must be reduced to alleviate eutrophication and repeated cyanobacteria blooms (Boesch *et al.* 2006). Agriculture is the largest single source of phosphorus losses to the seas surrounding Sweden, accounting for 45% of total anthropogenic net phosphorus loads (Hansson *et al.* 2019). An example of a site with a high risk of phosphorus losses from field to water is shown in Figure 4.

Figure 4. Losses of phosphorus from soil to water are episodic. At catchment scale, 90% of phosphorus losses can originate from 10% of the area and occur during only 1% of the time (Bergström *et al.* 2007). Photo: Jens Blomquist.

The mean phosphorus load from Swedish tile-drained agricultural land is approximately 0.4 kg ha^{-1} yr^{-1} (Bergström *et al.* 2007). These phosphorus losses occur as particulate phosphorus (PP) and dissolved reactive phosphorus (DRP) (Ulén *et al.* 2010), via surface runoff or subsurface runoff in tile drainage water (Collin 2010). On average, roughly 50% of phosphorus losses from agricultural land under Swedish conditions are in dissolved form, but the proportion can vary between 10% and 90% (Bergström *et al.* 2008).

Particulate phosphorus normally dominates the total losses from clay soils (Aronsson *et al.* 2019). A study in Finland on clay soils (topsoil clay content 50%) found that 92% of total phosphorus losses to both surface runoff and subsurface drainage waters was in particulate form (Uusitalo *et al.* 2001). This is in line with Svanbäck *et al.* (2014), who found that 87% of total phosphorus leaching losses from a clay soil with 60% clay content occurred as PP. Both surface and subsurface losses are episodic (Johnsson *et al.* 2019). The runoff peaks in phosphorus losses occur in spring, during snowmelt, and in autumn, during periods of rain after harvest (Alakukku & Aura 2006). At these times, the soil water content is high, infiltration capacity is limited, and the soil can even be waterlogged, leading to surface runoff and associated losses of phosphorus.

Phosphorus losses can vary widely between fields and within fields. On catchment scale 90% of phosphorus losses can originate from 10% of the acreage and occur during only 1% of the time (Bergström *et al.* 2007). In other words, phosphorus losses are intermittent.

Phosphorus losses from clay soils could be reduced at source by improving the soil structure (Ulén 2003). Improving soil structure is the basic idea behind structure liming aimed at stabilising aggregates (Aronsson *et al.* 2019). Aggregates that do not disintegrate when waterlogged, but remain intact, are less prone to losing PP bound to clay surfaces. A close relationship between total suspended solids and PP in surface runoff was demonstrated by Puustinen *et al.* (2005) and between clay dispersion (measured as turbidity) and PP by Ulén *et al.* (2012) and is also shown in unpublished data (Berglund *et al.* 2017a; Berglund *et al.* 2017b) (Figure 5). This means that turbidity can be used as a proxy for the risk of PP losses, in spite of not being measured directly.

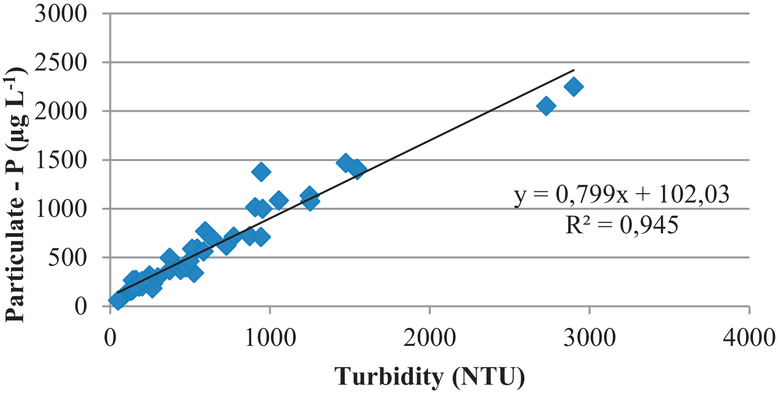


Figure 5. Relationship between turbidity and particulate phosphorus (PP) in leachate from lysimeters (undisturbed soil cores) after one simulated rainfall event. Turbidity measured after sedimentation of material coarser than clay. Data from three field trials reported in Berglund *et al.* (2017a).

The effect of lime in mitigating phosphorus losses has been shown in previous studies in Sweden, where liming with calcium oxide decreased total phosphorus and PP losses (Svanbäck *et al.* 2014) and calcium hydroxide also reduced DRP losses, accompanied by increased aggregate stability (Ulén & Etana 2014). However, a mixed structure liming product containing approximately 80-85% ground limestone and 15-20% slaked lime showed no significant effect on either phosphorus losses in drainage water or aggregate stability (Norberg *et al.* 2021). These contradictory findings regarding the effect of structure liming on phosphorus losses call for further evaluations.

3.7 Liming affects crop and yield

Liming affects the chemistry, biology and physics of soils, and as a consequence of these changes crop yield can often be influenced (Figure 6).

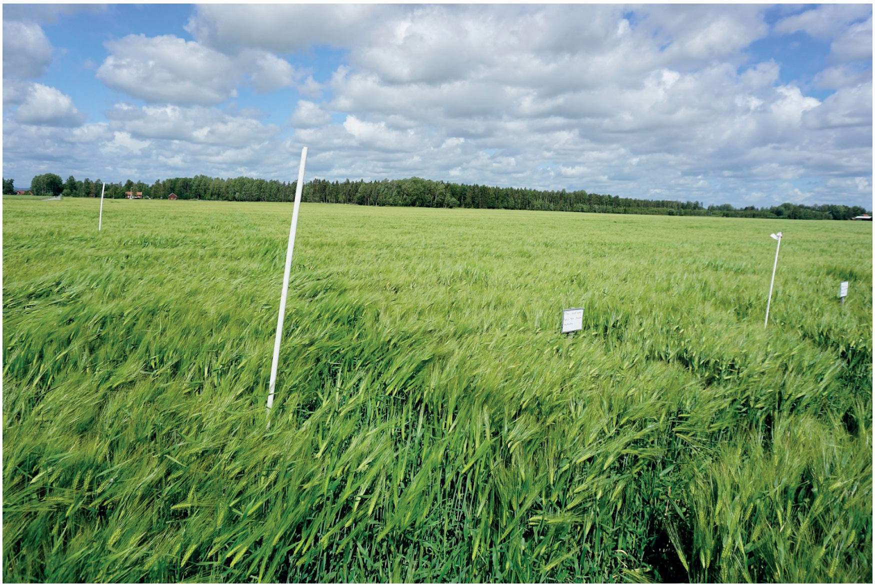


Figure 6. The effect of liming on crops is the net effect of all lime-induced effects on soil chemistry, biology and physics. View of a field trial at Nybble (59.22°N, 15.00°E) with spring barley, July 2019. Photo: Jens Blomquist.

The degree of the yield response to liming depends on the crop tested (Holland *et al.* 2019) and also on soil texture (Li *et al.* 2019). The mechanisms in soils are complex, with interactions between properties, processes and functions. For example, liming influences both water and mineral nutrient uptake through chemical, physical and biological effects on the soil (Holland *et al.* 2018). Therefore, the effect on crop growth and crop yield is the indirect net effect of all the changes that take place in soil after liming. In a recent meta-analysis, it was found that liming significantly increased yield of all crop species with the exception of *e.g.* tuber crops (Li *et al.* 2019). However, yield decreases due to liming can also occur under certain circumstances, often associated with decreased concentrations of Fe, Mn, Zn, Cu, Co and B in plants (Haynes (1984).

Liming under Swedish conditions has been reported to both increase yield (Haak & Simán 1997) and decrease yield (Kirchmann & Eskilsson 2010), with the latter explained by depressed levels of Mn and Cu in grain on coarse textured soils. Recently, Kirchmann *et al.* (2020) found yield increases in most crops at pH 5.5-7.2 in a national survey in Sweden. A declining effect of cereal yields was observed above pH 7.2 in that survey, but yields of winter wheat and spring barley almost doubled in pH range 6 to 7. Taken together, the positive and negative yield responses of crops to liming mean that structure liming can influence yield either way, depending on crop and soil conditions.

4. Materials and Methods

4.1 Study sites

The field investigations described in this thesis were performed at multiple sites in the southern part of Sweden (55.5-60.3°N, 12.7-17.7°E) (Figure 7). The maximum distance between sites in the north-south direction was approx. 600 km. In total, there were 69 trials located at 33 sites (Table 1).

Figure 7. The study sites were located in the southern part of Sweden, in two groups at different latitudes. Map design: Örjan Berglund.

Table 1. Field sites (n=33), lime application year, trial series, number of trials, clay content, coordinates and paper in which results are reported. Sum. = Summarised later in this thesis. Results from 69 trials at these 33 sites are presented in Papers I-VI

Site	Appl. year	Trial series	No. of trials	Clay content (%)	Coordinates	Paper
Säby	2010	SLU I	3	23-40	59.84 °N, 17.71 °E	I
Säby	2010	SLU II	1	25	59.84 °N, 17.71 °E	I
Linelund	2013	SLF	1	18	55.40 °N, 13.30 °E	IV
Hörte-13	2013	SLF	1	18	55.39 °N, 13.55 °E	IV
Krageholm	2014	LOVA-14	4	10-28	55.51 °N, 13.75 °E	III, VI
Lönhult	2014	LOVA-14	4	28-47	56.19 °N, 12.71 °E	III, VI
Vadensjö	2014	LOVA-14	4	21-27	55.92 °N, 12.86 °E	III, VI
Kornheddinge	2014	LOVA-14	4	21-29	55.63 °N, 13.29 °E	III, V, VI
Lindby	2014	SLF	1	18	55.45 °N, 13.48 °E	IV
Kornheddinge	2014	SLF	1	28	55.63 °N, 13.29 °E	IV
Billeberga	2014	SLF	1	24	55.88 °N, 13.03 °E	IV
Hammenhög	2014	SLF	1	28	55.50 °N, 14.10 °E	IV
Hönnedal	2014	SLF	1	16	56.07 °N, 14.24 °E	IV
Krageholm	2015	LOVA-15	1	34	55.49 °N, 13.76°E	II
Krapperup	2015	LOVA-15	1	21	56.18 °N, 12.70°E	II
Råbelöf	2015	LOVA-15	1	41	56.08 °N, 14.18°E	II
Kornheddinge	2015	LOVA-15	1	24	55.63 °N, 13.26°E	II
Västraby	2015	SLF	1	22	56.16 °N, 12.77 °E	IV
Vadensjö	2015	SLF	1	20	55.91 °N, 12.88 °E	IV

Vallby	2015	SLF	1	20	55.40 °N, 13.34 °E	IV
Gislöv	2015	SLF	1	27	55.51 °N, 14.29 °E	IV
Ekeberg	2015	SLF	1	20	56.02 °N, 14.07 °E	IV
Hörte-15	2015	SLF	1	15	55.39 °N, 13.55 °E	IV
Kadesjö	2016	LOVA-16	2	17-33	55.49 °N, 13.66 °E	III
Stureholm	2016	LOVA-16	2	35-38	56.19 °N, 12.76 °E	III, V
Eka	2016	LOVA-16	2	22-33	56.10 °N, 13.98 °E	III
Svinarp	2016	LOVA-16	2	22-33	55.63 °N, 13.33 °E	III
Bjärstad	2017	LOVA-17	1	61	58.52 °N, 16.50 °E	III
Brunnsholm	2017	LOVA-17	1	51	59.55 °N, 16.97 °E	III
Skottlandshus	2017	LOVA-17	2	31-38	56.07 °N, 14.06 °E	III, V
Kadesjö	2017	LOVA-17	2	15-34	55.49 °N, 13.65 °E	III
Wrangelsdal	2018	LOVA-18	2	30-33	56.07 °N, 14.07 °E	Sum.
Hulta	2018	LOVA-18	2	27-29	56.19 °N, 12.66 °E	V, Sum.
Hviderup	2018	LOVA-18	2	22-24	55.78 °N, 13.29 °E	Sum.
Kadesjö	2018	LOVA-18	2	9-17	55.49 °N, 13.64 °E	Sum.
Stäholm	2018	LOVA-18	2	37-48	59.49 °N, 16.08 °E	Sum.
Nybble	2018	LOVA-18	2	35-37	59.22 °N, 15.00 °E	Sum.
Bältarbo	2018	LOVA-18	2	13-17	60.31 °N, 15.96 °E	Sum.
Lilla Bärby	2018	LOVA-18	2	19-23	59.71 °N, 17.38 °E	Sum.
Erikssund	2018	LOVA-18	2	37-43	59.63 °N, 17.58 °E	Sum.

4.2 Experimental design

The five trial series described in this thesis were designed with different aims and objectives. The product used in the majority of the trials was Nordkalk Aktiv/Fostop Struktur. A specially equipped spreader was normally used and the structure lime was incorporated with implements supplied by farmers at the different sites (Figure 8).

a. Soil sampling. b. Clay content approximation.

c. Lime spreading. d. Lime incorporation.

Figure 8. Establishing field trials (a) on soils with different clay contents was difficult and needed approximation of clay content (b) at the time of soil sampling. Liming (c) was followed by incorporation (d) with implements available on the farms where the field trials were located. Photo: Jens Blomquist.

Table 2 summarises the treatments in the different trial series, together with the level of liming product applied. The trial series SLU I compared slaked lime and structure lime at increasing rates equivalent to 1, 2 and 6 t ha^{-1} CaO. The SLU II series had a split-plot design, studying the combined effect of primary tillage and structure liming with slaked lime. The SLF trials compared ground limestone with slaked lime in 2013 and ground limestone with structure lime in 2014-2015. The 48 LOVA trials, established in 2014, 2016, 2017 and 2018, compared structure lime at increasing application rates. In the LOVA-15 trial series, two spreading dates for structure lime were compared.

Table 2. Trial series (n=number of field trials), treatments and level of liming products used in treatments. Slaked lime refers to ($Ca(OH)_2$) and mixed lime refers to Nordkalk Aktiv/Fostop Struktur (Nordkalk Corp. Pargas, Finland) containing approx. 15-20% slaked lime ($Ca(OH)_2$) and 80-85% calcium carbonate ($CaCO_3$)

Trial series	Treatment	Level of liming prod.
SLU I (n=3)	A. Control	-
	B. Slaked lime 1	1.4 t ha^{-1} slaked lime
	C. Slaked lime 2	2.8 t ha^{-1} slaked lime
	D. Slaked lime 6	8.4 t ha^{-1} slaked lime
	E. Mixed lime 1	2 t ha^{-1} mixed lime
	F. Mixed lime 2	4 t ha^{-1} mixed lime
	G. Mixed lime 6	12 t ha^{-1} mixed lime
SLU II (n=1)	P0. Plough 0	-
	P2. Plough 2	2.8 t ha^{-1} slaked lime
	S0. Stubble cult. 0	-
	S2. Stubble cult. 2	2.8 t ha^{-1} slaked lime
SLF (n=13)	L0	-
	GL	8 t ha^{-1} ground limestone
	SL1 (appl. year 2013)	5.6 t ha^{-1} slaked lime
	SL2 (appl. years 2014-15)	7.8 t ha^{-1} mixed lime
LOVA-14, 16-18 (n=48)	SL0	-
	SL0.5 = 0.5 x stand. appl. rate	3.5-4 t ha^{-1} mixed lime
	SL1 = 1 x stand. appl. rate	7-8 t ha^{-1} mixed lime
	SL2 = 2 x stand. appl. rate	15-16 t ha^{-1} mixed lime
LOVA-15 (n=4)	Early application in Aug.	8 t ha^{-1} mixed lime
	Normal application in Sept.	8 t ha^{-1} mixed lime

4.3 Liming product

All trial series except SLU II used the commercially available structure liming product Nordkalk Aktiv/Fostop Struktur (Nordkalk Corp. Pargas, Finland), which is a mixture of approximately 80-85% calcium carbonate ($CaCO_3$) and 15-20% slaked lime ($Ca(OH)_2$). The chemical composition of the product, covering the spreading years 2014-2018, is shown in Table 3. This product is referred to hereafter as 'structure lime' unless otherwise stated.

Table 3. Chemical composition (dry matter basis) of the structure lime product (Nordkalk Aktiv Struktur/Fostop Struktur) used in field experiments 2014-2018. Water content 15-25% depending on storage. Source: Nordkalk Corporation

Macronutrient/ compound	Concentration (%)	Micronutrient/ heavy metal	Concentration (mg kg^{-1})
Total Ca as CaO	50.0-55.0	Cd	0.3-1.8
Mg	0.4-1.0	Co	1-9
SiO_2	1.6-5.4	Cr	9-26
Al_2O_3	0.4-3.4	Cu	3-48
Fe_2O_3	0.2-1.5	Hg	< 0.02
K	0.1-2.5	Ni	3-28
Na_2O	0.5-1.0	Pb	1-59
S	0.1-1.7	Zn	70-290
P	0.07-0.2		

4.4 Soil characteristics

All the LOVA trials were sampled plotwise in the topsoil (0-20 cm) for texture analysis, soil organic matter (SOM) content, pH_{H2O} and ammonium lactate (AL)-extracted soil nutrient concentrations before liming, to obtain initial values as a starting point for each plot. Ammonium lactate extraction (Egnér *et al.* 1960) is a standard analysis in Sweden, aiming at extracting plant-available contents of P, K, magnesium (Mg) and Ca on acid and neutral soils. However, on calcareous soil the acid AL extraction (pH 3.75) also dissolves P bound to Ca, which may affect and overestimate the plant-available P content (Ulén 2006). In 18 LOVA trials limed in 2018, Fe and aluminium (Al) were also analysed in the AL extraction. Approximately one year after liming, a follow-up plotwise sampling was performed for pH_{H2O}

and AL-extracted soil nutrient concentrations. The procedure of sampling both before and after liming provided a database consisting of data from 580 plots in the 48 LOVA trials with trial design of increasing application rates of structure lime (SL0-SL2).

Ten LOVA trials were sampled plotwise in the topsoil (0-20 cm) for extraction of available content of the micronutrients Fe, Mn, Cu and Zn in a CAT extraction (0.01 M $CaCl_2$ + 0.002 M DTPA). This sampling was carried out in the spring prior to start of the growing season.

4.5 Plant nutrient concentrations

Plant nutrient concentrations in barley grain were measured in the study described in Paper I and in barley biomass at the beginning of stem elongation (Zadoks stage (ZS) 31; (Zadoks *et al.* 1974)) in the study in Paper IV. The methods used are described in detail in Papers I and IV.

In eight LOVA trials in 2016, Yara Analytical Services in the UK performed the analyses. Samples of barley grain were analysed to determine their concentrations of macronutrients (N, P, K, S, Ca and Mg) and micronutrients (Cu, Fe, Mn, Zn, B and Mo). Nitrogen concentration was analysed in DUMAS combustion, while the concentration of all other nutrients was analysed by inductively coupled plasma-optical emission spectroscopy (ICP-OES).

4.6 Clay mineralogy

One topsoil sample (0-20 cm) per trial or site, consisting of a pooled sample of equal numbers of subsamples from all plots in the trial, was subjected to X-ray diffraction analysis (XRD) to determine the mineralogy in the clay fraction. To demonstrate this semi-quantitatively, the intensity (=surface) of the three most pronounced clay mineralogy reflections in the X-ray curves, at 14, 10 and 7 Å, was measured. The percentage contribution from each of these three reflection curves was then used to calculate SmV index as: Intensity 14 Å/(Intensity 10 Å + Intensity 7 Å). The SmV index gives an estimate of the relationship between swelling and non-swelling clay minerals. It also indicates the relative proportions of clay minerals with high (smectite and vermiculite, intensity 14 Å) and low (illite, chlorite, kaoline, intensity 10 Å + intensity 7 Å) cation exchange capacity (CEC). A soil with a high proportion of swelling clay minerals is thus characterised by high SmV index.

4.7 Aggregate size distribution

Papers I and IV and Chapter 5 in this thesis present measurements of aggregate size distribution, carried out either in the seedbed immediately after spring drilling or in the autumn. These measurements were performed by sieving loose soil over three different mesh size classes (average diameter <5 mm, 2-5 mm and <2 mm) (Kritz 1983). Figure 9 shows the three size classes of aggregates that were obtained.

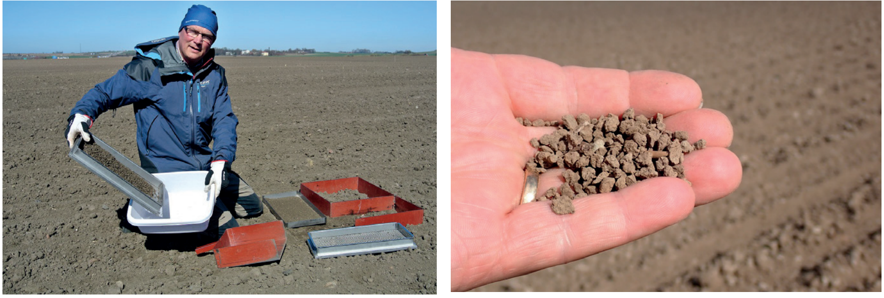
Figure 9. Size classes used in aggregate size distribution measurements. Upper left: >5 mm, upper right: 2-5 mm and left <2 mm. Photo: Jens Blomquist.

4.8 Aggregate stability

The basic concept and the foundation for the work in this thesis was the relationship between aggregate stability and risk of losses of particulate phosphorus (PP), as outlined in section 3.6. Sampling of the soil for aggregate stability measurements was performed 1-6 years after structure liming, depending on the study (Papers I-IV, VI). These stability measurements were carried out on aggregates with average diameter 2-5 mm obtained in autumn after harvesting of a cereal, oilseed or leguminous crop, or in the spring after drilling. In autumn, sampling was performed after shallow tillage down to approximately 6-8 cm and in the spring in the tilled seedbed. Following sieving into the different size classes (Figure 9), the fraction of aggregates with diameter 2-5 mm was collected, stored dry and aerated, and transported to the laboratory at the Swedish University of Agricultural Sciences (SLU) in Uppsala.

In the laboratory, the aggregates were air-dried in plastic jars to equalise differences in water content and thereafter subjected to two simulated rainfall events (denoted A1 and A2) 24 hours apart, with an intensity of 32-39 mm per hour in both events. Each simulated rainfall event lasted for one hour and the irrigation boom moved back and forth continuously without stopping at the ends during irrigation, so the aggregates were subjected to simulated rain for five minutes in the one-hour period. The leachate was collected after each rainfall event, and turbidity and electrical conductivity (EC) were determined (Turbidity A1/A2 and EC A1/A2). For this, the muddy water was shaken for 10 minutes and then particles were allowed to sediment for 4.5 hours. After sedimentation, a supernatant sample was taken at a depth of 5.6 cm and the turbidity was measured with a turbidimeter (Hach TL 2360 Turbidimeter, Hach, Loveland, Co.). Measured turbidity in the supernatant provides an estimate of the concentration of clay in the leachate (Etana et al. 2009) and was used as a proxy for aggregate stability and risk of PP losses (Puustinen et al. 2005; Ulén et al. 2012). Electrical conductivity rises with liming and gives an indication of whether soluble calcium is present in the soil solution. Only turbidity and EC data from the second simulated rainfall event (turbidity A2, EC A2) are reported in this thesis, as differences between treatments were clearer after the second rainfall event. The analytical procedure, from sampling in the field to turbidity measurements, is depicted in Figure 10.

a. Soil sampling by sieving. b. Size class 2-5 mm.



c. Plastic jars for sampling. d. Rain simulator.

e. Leachate collection under aggregates. f. Leachate for turbidity measurements.

Figure 10. After shallow tillage, the loose soil was sieved into three size classes (a). Aggregates 2-5 mm (b) were sampled and transported in plastic jars (c) to the Swedish University of Agricultural Sciences (SLU) in Uppsala. After drying, the aggregates were subjected to two simulated rainfall events 24 hours apart (d). The leachate (in transparent plastic jars below the orange plastic pipes containing the aggregates) was collected after each rainfall event (e). Turbidity was measured in leachate after each simulated rainfall event. Turbidity and electrical conductivity (EC) were determined (f). Turbidity indicates clay dispersion of the aggregates and is therefore an indicator of aggregate stability and a proxy for the risk of particulate phosphorus (PP) losses. Photo: Jens Blomquist.

5. Results and Discussion

5.1 Effects on soil chemical characteristics

Approximately 50% of the global arable acreage consists of acid soils with pH <5.5 (Dai *et al.* 2017). To counteract soil acidity, liming is a well-established management tool (Frank *et al.* 2019) and lime is a common amendment applied to agricultural soils (Haynes & Naidu 1998). With its impact on soil pH, liming also affects the plant nutrient availability in soil, through *e.g.* chemical adsorption, precipitation and uptake (Holland *et al.* 2018). Lime thus brings changes not only in pH, although it primarily counteracts soil acidification caused by natural processes or anthropogenic activities (Holland *et al.* 2018).

The Swedish practice of structure liming, *i.e.* application of calcium oxide/hydroxide or mixes of calcium oxide/hydroxide together with calcium carbonate, is not primarily used to counteract acidification, but to ameliorate soil physical properties, *e.g.* aggregate stability (Paper I). Needless to say, structure lime also increases pH levels in soil, but a recurring question is whether the pH is raised to levels at which plant availability of *e.g.* micronutrients is affected. The following section provides an indication of how soil pH was affected in the studies reported in Papers I-VI.

5.1.1 pH increases and decreases over time

Increasing pH was observed after structure liming in all field trials (Papers I, IV and VI), at initial pH values ranging from 5.8 up to 8.3. In Paper IV, there was an increase of 0.5 pH units following the standard application rate of 8 t ha^{-1} of structure lime, measured approximately 1.5 years after application. This rise was of the same magnitude as in the ground limestone treatment (calcium carbonate) used as reference. It is noteworthy that these increases were achieved on alkaline soils where the untreated control soil had a pH of 7.3.

In Paper VI, there was a distinct dose response in pH with increasing application rates of structure lime, with significant increases of 0.2, 0.4 and 0.6 pH units for treatments supplying 4, 8 and 16 t ha^{-1} of structure lime, respectively. However, by the sixth year after lime application, differences of 0.3 and 0.6 pH units remained only in the treatments with 8 and 16 t ha^{-1}. The soils in Paper VI had initial pH values ranging from 6.2 to 8.2.

Similar time-dependency, with a clear rise and fall in pH, was seen in Paper I, where increasing application rates of both calcium hydroxide and structure lime were compared. There were pH increases in the first and second year after application in that study. In the treatment with 12 t ha^{-1} of structure lime, soil pH increased by approximately 0.8-0-9 units at the most, where pH in the control plots was 5.9-6.3. However, there were no remaining significant differences between any limed treatment and the unlimed control in the third year after structure liming.

Plant nutrient deficiencies depend mainly on crop and soil type, but concerns about elevated pH levels cannot be neglected. However, based on Papers I, III and VI, the increase in pH with the standard application rate of structure lime can be summarised as moderate and temporary. This is in agreement with Ulén and Etana (2014), who found that pH had equilibrated and observed no significant increases in soil pH from six months up to two years after liming with calcium hydroxide and calcium oxide in two different trials. Norberg *et al.* (2021) also observed an initial increase in the first year after structure liming, followed by a decline in the second year.

5.1.2 Soil nutrients also affected

Soil nutrient levels can also be affected by structure liming, as shown in Paper IV (see Table 6 in Paper IV). The AL-extracted Ca and Al concentrations increased in one or both of the two lime treatments in that study, but AL-extracted P, K and Mg were not affected. In contrast to the results in Paper IV, AL-extracted P, K, Mg were affected by structure liming when assessed based on a compilation of results from 48 LOVA trials (Figure 11). In the autumn prior to liming and incorporation, the soil was sampled plotwise in all 48 trials and analysed for pH, AL-extracted P, K, Mg and Ca, in addition to texture and SOM content. In the following autumn soil sampling for analysis of pH and AL-extracted nutrients was repeated. Changes in soil nutrients in the structure lime treatments are shown in Figure 11. The change over time in the unlimed control (SL0) is also shown. The differences in the control were due to the fact that repeated sampling was not carried out in exactly the same positions within each plot, and that soil variables such as pH can change over time during the growing season and between years (Frebourg 2019; Lecourtier 2021). Thus, the net change in the limed treatments was calculated as the difference in treatments applying 3-4, 7-8 and 15-16 t ha^{-1} of structure lime (SL0.5, SL1 and SL2, respectively) minus the difference in the control (SL0).

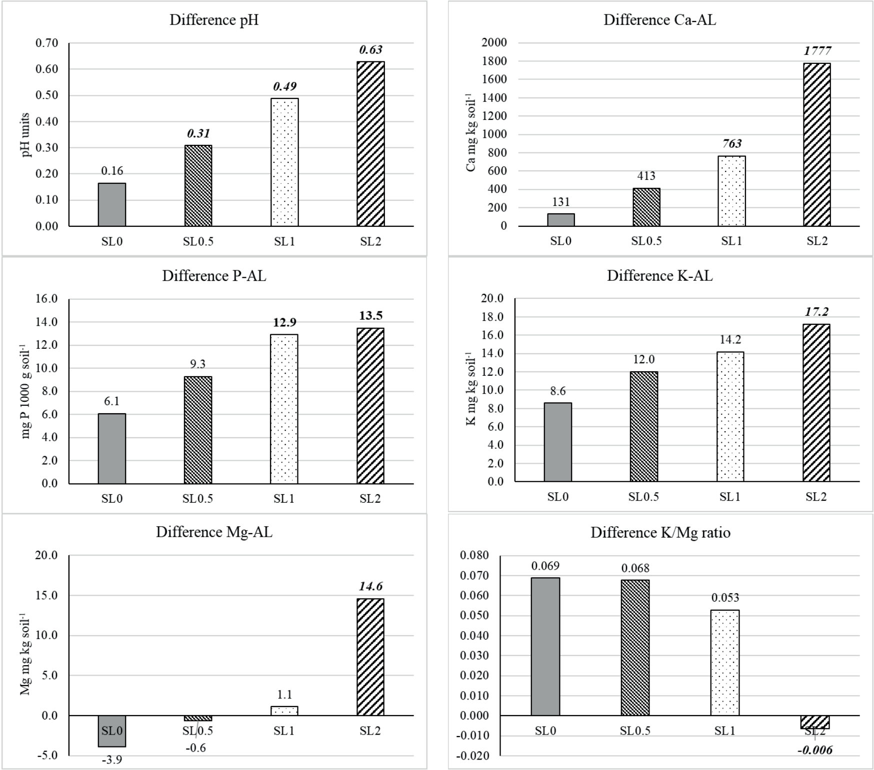


Figure 11. Difference in pH and in AL-extracted Ca, P, K, Mg and K/Mg ratio one year after structure liming compared with before liming in 48 trials, *i.e.* change over time between chemical characterisation prior to and one year after structure liming. Values in bold italics indicate a significant difference from the control (SL0). SL0.5, SL1 and SL2 received 3.5-4, 7-8 and 14-16 t ha^{-1} structure lime, respectively.

The change over time as a result of structure liming in treatments SL0.5- SL2 was significant for pH, P-AL, Mg-AL, K/Mg ratio and Ca-AL. For pH, Mg-AL and Ca-AL, there were also significant interactions between treatment and trial. This indicates that the 48 soils reacted differently to increasing levels of structure lime. This observation fits well with results in Olsson *et al.* (2019), who after treatment with two types of lime found different reactions in the available levels of Mg and Ca in soils when subdivided into three groups with different initial pH. The results of the statistical grouping are summarised in Table 4, together with the p-values for trial, treatment and the interaction between trial and treatment.

Table 4. Statistical grouping of changes in soil chemical variables after liming (absolute changes are shown in Figure 11). Treatments with different letters (a-d) are significantly different. Treatment SL0 = control, SL0.5, SL1 and SL2 received 3.5-4, 7-8 and 14-16 t ha-1 structure lime, respectively

Treatment	pH	P-AL	K-AL	Mg-AL	K/Mg-ratio	Ca-AL
SL0	a	a	a	a	a	a
SL0.5	b	ab	ab	a	a	ab
SL1	c	b	ab	a	a	b
SL2	d	b	b	b	b	c
p Trial	0.001	0.001	0.001	0.001	0.001	0.001
p Treatment	0.001	0.009	0.055	0.001	0.001	0.001
p Trial x Treatm.	0.001	0.280	0.379	0.001	0.073	0.001

The increasing application rate of structure lime in treatments SL0.5, SL1 and SL2 gave a net increase of 0.15, 0.33 and 0.47 pH units, respectively (Figure 11). These expected changes were accompanied by changes in P, K and Mg concentrations. The increases in K and Mg in the soil matrix after liming in treatment SL2 could possibly be explained by cation exchange, *i.e.* with existing K and Mg ions on the clay surfaces displaced by Ca ions after structure liming. The Ca ion has a much greater affinity to clay surfaces compared with both K and Mg, due to its higher valence and also its lower hydration (Eriksson *et al.* 2011). As a consequence of cation exchange, K and Mg are pushed away from the clay surfaces to the surrounding soil matrix.

A second, although far-fetched, explanation for the increased levels of K and Mg may be release from the clay minerals *per se*. The hydroxide $(OH)_2$ contained in structure lime can attack and dissolve the Si and Al layers on clay minerals (Al-Mukhtar *et al.* 2010), with possible release of K and Mg from the clay crystal lattices.

A third and more plausible explanation for the increases in AL-extracted plant nutrients in limed soil is that the structure lime product used in the field trials also contains plant nutrients (see Table 3). The amounts present in topsoil (0-20 cm) before structure liming according to the AL-extraction results and the approximate amounts estimated to be applied with structure lime are summarised in Table 5. The values presented suggest that the structure lime used in the trials was also a fertiliser. In Figure 12, the quantities of P, K, Mg and Ca applied in treatment SL1 are presented as percentages of the existing amounts.

Table 5. Approximate amounts of plant-available P, K, Mg and Ca (extraction with 0.1 M ammonium lactate + 0.4 M acetic acid, pH 3.75) estimated to be present in topsoil (0-20 cm) in 48 LOVA trials before liming (mean of all plots in the trials) and estimated amounts applied with structure lime. Treatments SL0.5, SL1 and SL2 received 3.5-4, 7-8 and 14-16 t ha-1 structure lime, respectively

	Nutrient content in topsoil (kg ha^{-1})			
	P	K	Mg	Ca
Quantity before structure liming (0-20 cm)	253	551	618	11931
SL0.5 – quantity with application	2.7	50	28	1168
SL1 – quantity with application	5.5	100	55	2336
SL2 – quantity with application	11.0	201	111	4672

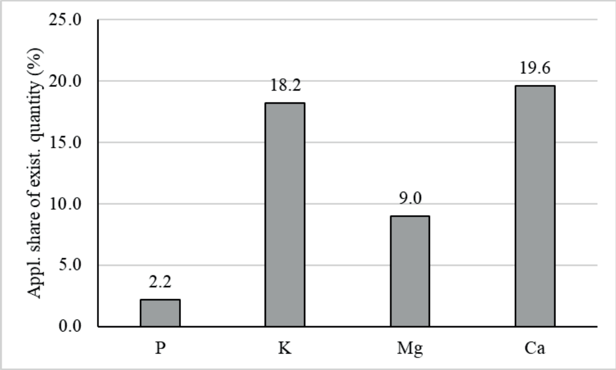


Figure 12. Amount of P, K, Mg and Ca applied with structure lime in treatment SL1 (standard application rate, 7-8 t structure lime ha^{-1}) as a percentage of the amount present in topsoil (0-20 cm) before liming.

As can be seen from Figure 12, the quantities applied in treatment SL1 constituted a substantial share of the existing AL-extracted nutrient pool in the topsoil (0-20 cm), particularly for K (18.2%), Mg (9%) and Ca (19.6%). However, the quantities of K and Mg applied were not fully retrieved in the second sampling of soil nutrients one year after application, using a simple calculation in treatment SL1 with the standard application rate as an example (Figure 13).

Figure 13. Amounts of P, K and Mg (kg ha^{-1}) applied at spreading (1st year) with the standard structure lime application rate of 7-8 t ha^{-1}, and amounts retrieved in approximately one year after liming (2nd year).

For AL-extracted P the opposite occurred (Figure 13), with only 5.5 kg ha^{-1} applied but 21 kg P ha^{-1} retrieved in soil in SL1, as a net change when also taking into account the change in the unlimed SL according to Figure 11. The finest particle size of lime has previously been shown to have a negative effect on soil P availability in the short term, but not coarser fractions of lime (Viade *et al.* 2011). However, in long-term field experiments the solubility of P, measured as AL-extracted P, has been shown to increase with liming to 70% and 100% base saturation, an effect explained by transformation from slightly soluble Fe and Al compounds to more easily soluble Ca compounds (Haak & Simán 1997). Simonsson *et al.* (2018) also observed that liming frequently resulted in higher AL-extracted P content in long-term field experiments, and concluded that lime had a positive effect on the solubility of fertiliser-P applied in the decades following liming. They attributed the effect partly to a shift in desorption curves (dissolved-P concentrations as a function of pH) towards higher P solubility. The time that elapsed between structure lime application and repeated soil sampling in Figure 11 was only approximately one year, in contrast to decades in the study by Simonsson *et al.* (2018). However, the results do not contradict findings in previous studies on Swedish soils, and might therefore suffice as an explanation for the increased levels of AL-extracted P in treatments SL1 and SL2 (see Figure 11), despite the relatively small quantities applied with the structure lime.

5.1.3 Possible P sorption through Al-AL

The AL-extracted Al concentration was significantly affected by the structure lime (see Table 6 in Paper IV). This is in line with results from the 18 LOVA trials performed in 2018, where Al and Fe were AL-extracted before lime application and one year later. For Fe there were no treatment effects ($p=0.460$), but for Al there were significant differences between treatment SL2 and the unlimed control SL0 ($p<0.001$) (Figure 14). However, there was a significant interaction between trial and treatment ($p=0.041$).

Approximations made for Al (comparable to those made for P, K, Mg in Table 5 and Figures 12 and 13) showed that an additional 88 kg ha^{-1} of AL-extracted aluminium (13%) were applied with treatment SL1 to the existing amount of 703 kg ha^{-1}. Of the applied quantity of 88 kg ha^{-1}, only 28 kg ha^{-1} were retrieved in the second soil sampling in the following year. Thus for K, Mg and Al, less of the amounts applied in SL1 were found in the soil one year after liming, whereas for P more was recovered than was applied.

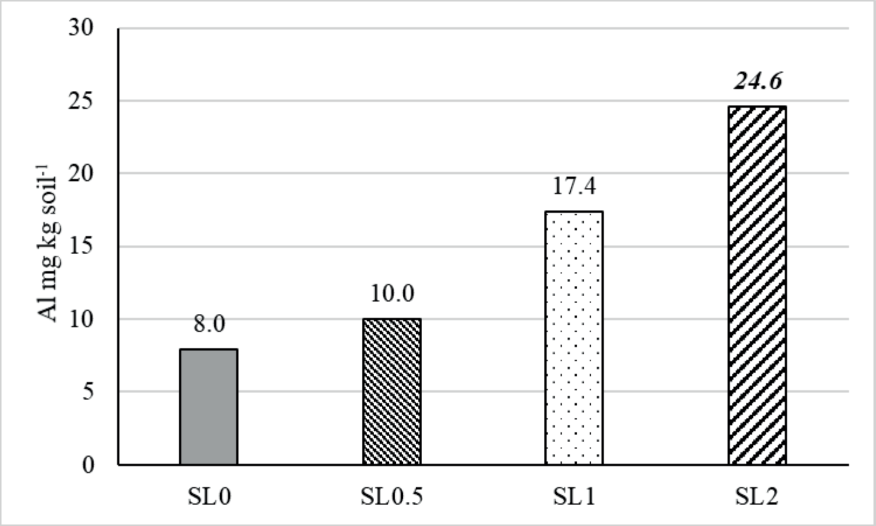


Figure 14. Difference in AL-extracted aluminium one year after structure liming compared with before liming in 18 LOVA trials, *i.e.* change over time between chemical characterisation prior to and one year after structure liming. Values in bold italics indicate a significant difference from the control (SL0). Treatment SL0.5, SL1 and SL2 received 3.5-4, 7-8 and 14-16 t ha^{-1} structure lime, respectively.

The increased AL-extracted Al content as a result of structure liming (Figure 14) could possibly lead to changes in P sorption, as soil extractable Al concentration together with pH have been shown to have a strong influence on sorption of P in Irish soils (Daly *et al.* 2015). In Swedish soils, Börling *et al.* (2001) found acid oxalate-extractable Fe and Al oxides to be important sorbents of P. An increasing level of AL-extractable P leads to an increased risk of P losses from soil (Aronsson *et al.* 2019), but is not the only determinant of P losses. Subsoil properties are more important than topsoil P content according to Djodjic *et al.* (2004), as these determine water transport rate through the soil profile. Andersson *et al.* (2013) also underlined the importance of subsoil properties for P leaching and concluded that topsoil studies can be insufficient for assessing P leaching.

In order to test whether the increased AL-extracted Al due to application of structure lime in the field trials in this thesis had any impact on P sorption, the degree of phosphorus saturation (DPS) was calculated according to Ulén (2006) as: DPS = 100 x P-AL/(Al-AL + Fe-AL), with all soil concentrations on a molar basis. For calcareous soils, the acid AL-extraction process leads to dissolution of Ca-bound P, and can thus overestimate the P-AL results, so DPS-AL as an environmental risk indicator is more valid for acid soils (Ulén 2006). The DPS calculations showed no significant changes as a result of structure liming in this thesis, as the significant increase in Al-AL was counteracted by a simultaneous – but not significant – increase in P-AL in the 18 trials for which this calculation was possible. In this respect, application of structure lime counteracted the environmental objective of the measure by applying P with the liming product and probably also mobilising P, as pointed out above.

5.1.4 pH and calcium interactions by site

In Paper IV, there was a treatment effect on pH of 0.5 for both limed treatments studied (ground limestone (GL) and structure lime (SL)), but with no interaction between treatment and location ($p=0.723$) (Table 6 in Paper IV). The initial pH at the 10 experimental locations used in that study ranged from 6.6 to 8.0 (Table 1 in Paper IV).

Results from the 48 LOVA trials, with a variation in initial pH from 5.8 to 8.3, also showed a treatment effect on pH. However, in the LOVA trials there was a significant interaction between trial and treatment ($p<0.001$) (Table 4). There were also significant interactions between treatment and trial for AL-extracted Mg and Ca (Table 4). In other words, the soil at all trials did not react in the same way to the structure lime with respect to pH, Mg and Ca. As a result of the different reactions in these two sets of trials, follow-up statistical analyses of data on pH and AL-extracted Ca were conducted.

Figures 15 and 16 present examples of the interactions between treatment and trial, shown as the difference in pH and Ca-AL, respectively, as a result of the structure lime treatments SL0-SL2, divided into three groups of trials with different initial pH values.

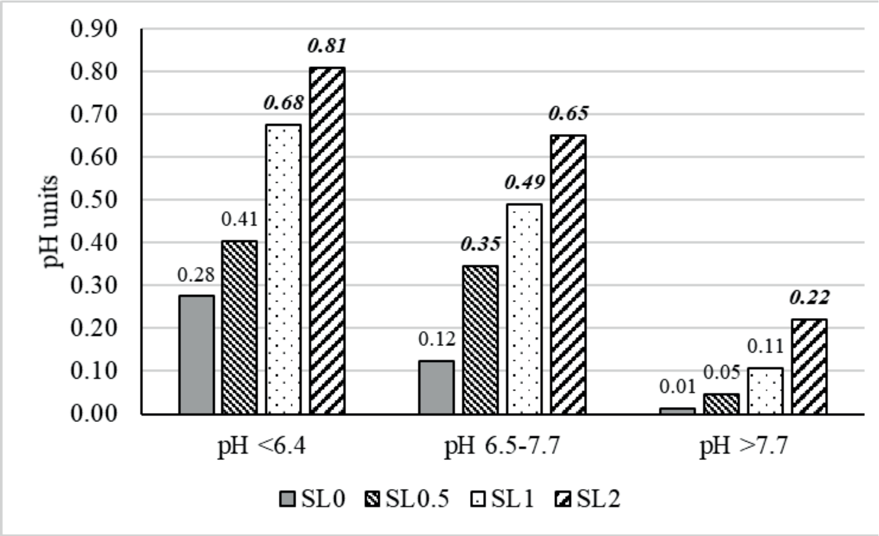


Figure 15. Difference in pH one year after structure liming in trials grouped according to initial soil pH. Mean starting pH (range) in the groups with pH <6.4 (n=20 trials), pH 6.5-7.7 (n=18 trials) and pH >7.7 (n=10 trials) was: 6.2 (5.8-6.4), 7.1 (6.5-7.7) and 8.0 (7.8-8.3), respectively. Values in bold italics indicate a significant difference from the unlimed control (treatment SL0). Treatment SL0.5, SL1 and SL2 received 3.5-4, 7-8 and 14-16 t ha^{-1} structure lime, respectively.

In the group with initial pH <6.4, there were differences between the treatments (p<0.001), where treatments SL1 and SL2 were different from the control (SL0), and there was no significant interaction between treatment and trial (p=0.222). In this group, the pH in treatment SL1 (standard structural lime application rate) increased by 0.4 pH units (net after change also in treatment SL0). In the group with the highest initial pH (pH>7.8) there were also differences (p=0.001), but only the pH of treatment SL2 increased significantly, by approximately 0.2 pH units, and there was no significant interaction between trial and treatment (p=0.642). In the group with initial pH 6.5-7.7, there was a significant treatment effect (p<0.001) and all limed treatments SL0.5-SL2 were different from treatment SL0, but there was a significant interaction between trial and treatment (p<0.001). This meant that general conclusions could not be drawn for that group of soils, so a further division was made into subgroups with initial pH 6.5-7.0 (n=8 trials) and pH 7.0-7.7 (n=10 trials). In the subgroup with pH 7.0-7.7 the significant interaction between treatment and trial disappeared (p=0.109), but in the subgroup with pH 6.5-7.0 the interaction remained (p<0.001). Splitting the subgroup with pH 6.5-7.0 once more into two new subgroups, with pH 6.5-6.7 (n=4 trials) and pH 6.7-7.0 (n=4 trials), revealed a significant interaction in the subgroup with pH 6.5-6.7 (p<0.001). When examining the interaction in detail, the different reactions at the different trials in this subgroup were found to derive from one single trial (Stäholm HP). That trial showed no response in pH for any of the lime treatments, whereas the other three trials in the subgroup were affected. The lack of response to lime in the Stäholm HP trial can probably be explained by a clay content of 48% and a SOM content of 6.4%, providing this soil with high buffering capacity against changes in chemical properties caused by liming, as shown by Li *et al.* (2019).

The analysis of changes in Ca-AL grouped after initial pH showed similar patterns to the change in pH (Figure 16).

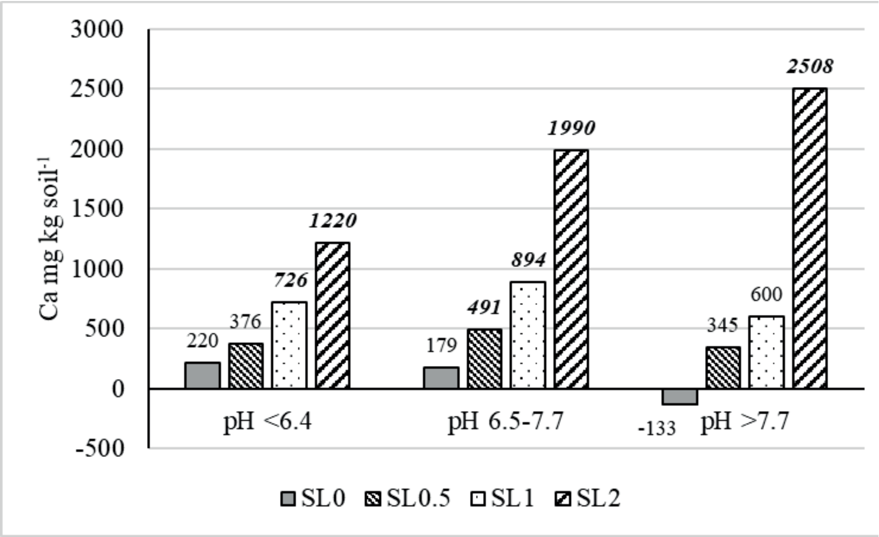


Figure 16. Difference in Ca-AL one year after structure liming in trials grouped according to initial soil pH. Mean starting Ca-AL concentration (range) in the groups with pH <6.4 (n=20 trials), pH 6.5-7.7 (n=18 trials) and pH >7.7 (n=10 trials) was: 2490 (950-3750), 3660 (1850-5770) and 7560 (3690-11630) mg kg^{-1} soil, respectively. Values in bold italics indicate a significant difference from the unlimed control (SL0). Treatment SL0.5, SL1 and SL2 received 3.5-4, 7-8 and 14-16 t ha^{-1} structure lime, respectively.

In the group with initial pH <6.4 there were differences between the treatments ($p<0.001$), where treatments SL1 and SL2 were different from treatment SL0, but with an interaction between treatment and site ($p=0.001$). In this group, the Ca-AL concentration in treatment SL1 (standard structure lime application rate) increased by just over 500 mg Ca kg soil^{-1} (net after change also in treatment SL0). In the group with the highest initial pH (pH>7.7) there were differences ($p=0.001$), but only treatment SL2 showed a significant increase compared with SL0. In this group there was no significant interaction between treatment and site ($p=0.193$). In the group with initial pH 6.5-7.7 there was a significant treatment effect ($p<0.001$), where treatments SL0.5, SL1 and SL2 were significantly different from treatment SL0, but again with a significant interaction between treatment and trial ($p<0.001$). A possible explanation is that at lower pH values (pH<6.4 and pH 6.5-7.7), more cation exchange occurred and therefore less Ca was found in AL-extraction of soil, despite the same amount being applied.

The significant interactions between trial and treatment point to site specific effects for both pH increase and Ca-AL release from the structure lime. This site specificity should be considered when structure liming soils with different initial properties, as it implies that the same application rate of structure lime can give different effects in both pH and AL-extracted Ca content on different soils.

5.1.5 Decreased micronutrient availability

Soil analysis of micronutrients in Paper IV revealed lower concentrations of CAT-extracted Fe and Mn after application of ground limestone (GL) and structure lime (SL) compared with the control treatment (Table 6 in Paper IV). For Cu and Zn, there were no treatment effects. No interactions between trial and treatment were found for any of the micronutrients (Paper IV). CAT-extracted micronutrients were also analysed in 10 of the 48 LOVA trials in 2016 and 2018. This analysis was carried out in the spring before drilling of spring barley in nine of the 10 trials (as done in Paper IV) and in the spring in established winter wheat in the remaining trial.

Results for the two sets of trials (LOVA-16 and LOVA-18) matched relatively well. Overall, the LOVA trials showed an effect of liming on CAT-extracted Fe ($p=0.006$), but only treatment SL2 had significantly lower concentrations compared with SL0 (Table 6).

Table 6. Concentrations of Cu, Fe, Mn and Zn (CAT extraction) at the start of the growing season in spring 2016 and 2018, 1-2 years after liming, in 10 trials. SL0 = unlimed control, treatments SL0.5, SL1 and SL2 received 3.5-4, 7-8 and 14-16 t ha^{-1} structure lime, respectively

Treatment	Cu mg kg soil^{-1}	Fe mg kg soil^{-1}	Mn mg kg soil^{-1}	Zn mg kg soil^{-1}
SL0	2.80^{a}	392^{a}	52.1^{a}	1.62^{a}
SL0.5	2.77^{a}	361^{ab}	52.7^{a}	1.64^{a}
SL1	2.64^{ab}	348^{ab}	48.8^{a}	1.61^{a}
SL2	2.33^{b}	280^{b}	44.9^{a}	1.52^{a}
p Treatment	0.001	0.006	0.071	0.435
p Trial x Treatm.	0.012	0.328	0.026	0.589

No interaction between trial and treatment was observed for Fe. There was no effect of structure liming on CAT-extracted Mn, but there was a slight decrease in concentration compared with the control (p=0.071). For CAT-extracted Cu the treatment effect of liming was significant (p=0.001), but similarly to Fe only SL2 showed a significant decrease compared with SL0. However, for CAT-extracted Cu there was also an interaction between treatment and trial (p=0.012), pointing at different reactions on different soils. The availability of Cu, Fe, Mn and Zn usually decreases as soil pH increases, since the solubility of these ions declines 100-fold for each unit increase in pH (Fageria *et al.* 2002). For this reason, the 10 trials were divided into two groups according to pH after liming (pH post ≤7.0 and >7.0), resulting in five trials in each group. Lee *et al.* (1997) found that total concentration of Cu and Zn was dependent on clay content, so a different division by clay content instead of pH could be justified, but there was only a relatively small difference in clay content between the two pH groups (clay content 31% in pH≤7 and 25% in pH>7). The concentration of CAT-extracted Cu in the soil at the start of the growing season is depicted in Figure 17.

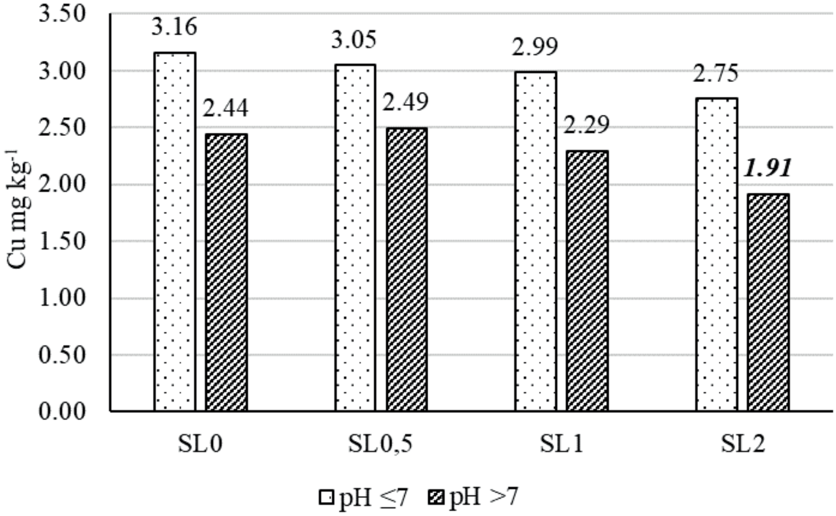


Figure 17. Concentration of CAT-extracted Cu in soil at the beginning of the growing season in 2016 and 2018, approximately 1-2 years after liming, in groups with pH <7.0 and >7.0 after liming. Values in bold italics indicate a significant difference from the unlimed control (SL0). Treatments SL0.5, SL1 and SL2 received 3.5-4, 7-8 and 14-16 t ha^{-1} structure lime, respectively.

In the group with pH <7.0, none of the differences in Cu-CAT concentrations were statistically significant. However, in the group with pH >7.0 after liming there was a significant treatment effect, where the Cu-CAT concentration in SL2 differed significantly compared with SL0, with no remaining interaction between trial and treatment. In a study on field liming by Kirchmann and Eskilsson (2010), crop yield declined on average by 7%, and this yield decrease was attributed to low concentrations of Cu and Mn in the grain caused by liming. However, in the set of 15 trials examined in that study only five showed actual yield losses and four of those five were on sandy soils, so Kirchmann and Eskilsson (2010) concluded that soil texture was the most plausible explanation for the results.

As structure lime application in Sweden is targeted at clay soils, and not sandy soils, the risk of Cu deficiency as a result of structure liming is probably limited. The soil concentrations of Cu in Figure 17 are within the recommended range of 1.2-2.5 for soils with pH>7.5 (Eurofins 2021). It is also worth pointing out that with the standard application rate (treatment SL1), no significant decrease in Cu content from structure liming was observed. The only significant decrease was in treatment SL2, which applied double the standard structure lime rate.

5.2 Effects on plant nutrient concentrations

Availability of all plant nutrients is influenced by liming through the impact on pH, which in turn affects soil processes such as mineralisation, adsorption, precipitation and nutrient uptake (Holland *et al.* 2018). Plant availability of all micronutrients except molybdenum (Mo) has been found to decrease with liming, as concentrations of these elements decrease in the soil solution (Bolan *et al.* 2003). According to Goulding (2016), the optimum soil pH for Fe is <6, for Mn 5-6.5, for B, Cu and Zn 5-7 and for Mo >7. However, availability is not only an effect of pH but also of time since liming was carried out, *e.g.* according to Shorrocks (1997), B is more affected by recent liming than by the actual increase in pH.

5.2.1 Mn grain concentration decreased

Concentrations of the macronutrients P, K, Mg, Ca and S and the micronutrients Mn and Zn were analysed in spring barley grain in one of the trials reported in Paper I. None of the macronutrients was affected by liming with calcium hydroxide or the mixed structure lime product, irrespective of application rate. The concentration of Zn in grain was also unaffected, but Mn showed a decreased concentration at the highest application rate (6 t CaO ha^{-1}) of both products. The level of Mn was below the reported critical level (Reuter & Robinson 1997), but no yield decreases were observed in the two treatments (data not shown in Paper I), indicating that Mn level did not restrict crop yields in that trial. However, the observed decrease in grain Mn concentration provides a general reminder of one of the unwanted side-effects of structure liming, especially since the measurements were performed four years after structure lime application. Both treatments with the highest application rates of lime showed decreases in grain Mn content and significantly higher pH levels (pH 7.5-7.9) compared with the control treatment (pH 6.8) approximately one year after lime application. However, no significant differences in pH were observed after three years, when pH values had decreased to 6.9-7.0. Karimian and Ahangar (1998) observed that Mn added to calcareous soils swiftly disappeared and concluded that SOM and calcium carbonate were sites of Mn retention. The lingering effect of the two lime treatments on Mn grain content in Paper I could possibly be related to such retention processes, despite the pH not being significantly elevated three years after lime application.

5.2.2 K and Mo increased

In Paper IV, lime treatment effects on plant nutrient concentrations were observed. Regarding Mn, there were similarities with findings in Paper I, although there was only a tendency ($p=0.051$) for treatment effects from lime in Paper IV, based on measurements at beginning of stem elongation in ZS 31 (Zadoks *et al.* 1974), *i.e.* earlier than in Paper I. A finding worth further reflection was the lower concentration of Mn in treatment SL (structure lime) compared with GL (ground limestone) (Figure 3 in Paper IV), possibly indicating a greater effect on plant nutrient uptake despite similar effects on pH as described in section 5.1.1. Both limed treatments also resulted in increased concentrations of Mo, which is in accordance with the claim by Fageria *et al.* (2002) that Mo is the only micronutrient for which availability normally increases with a rise in soil pH.

The content of K in spring barley biomass was elevated in the structure lime treatment SL compared with both the unlimed control (L0) and GL (Paper IV). The basis for that study was 13 field trials where treatment SL actually consisted of two different forms of structure lime: SL1 (calcium hydroxide) was applied in two trials in 2013 and SL2 (mixed structure lime) in 11 trials in 2014-2015. The amount of Ca applied was the same in the two treatments, corresponding to 4 t CaO ha^{-1}, but the content of K in the liming products differed considerably (Table 3 in Paper IV), as did the amounts applied. The K content was 0.3% in GL, 0.1% in SL1 and 1.5% in SL2. The plant nutrient contents shown in Figure 3 in Paper IV are based on 10 of the 13 trials in which spring barley was grown during the study period. Of these 10 trials, two were treated with calcium hydroxide (SL1) containing 0.1% K as treatment SL, and eight were treated with mixed structure lime (SL2) containing 1.5% of K as treatment SL. As a weighted average, the K content in treatment SL was four-fold the K content in GL. This considerable difference can possibly explain the observed higher K content in spring barley biomass in treatment SL, although AL-extracted K in topsoil showed no differences between the limed treatments (Table 6 in Paper IV). Thus the structure lime product used in Paper IV also acted as a fertiliser, an effect previously mentioned in section 5.1.2 of this thesis.

5.2.3 Final remarks regarding nutrient effects in crop

Plant analysis of nutrients was performed in the eight LOVA trials at two of the sites (Krageholm and Vadensjö) studied in 2016. Analysed together, the results showed decreases in Mn ($p=0.041$) and Zn ($p=0.002$) content in barley grain, together with increasing Mo ($p<0.001$) content, with increasing application rates of structure lime. These findings match the results in Papers I and IV described above. However, micronutrient content in barley grain differed between the Krageholm and Vadensjö sites. The differences in barley grain nutrient concentrations, the associated differences in CAT-extracted micronutrients in soil and the possible link to discrepancies in grain yield are discussed in detail in sections 5.6.4 and 5.6.5, with initial soil pH as the discriminating variable and possible explanation.

Overall, the results in this thesis show that structure lime, through bringing about an increase in soil pH, can decrease the concentration of the micronutrients Mn and Zn, and increase the content of Mo, in plant tissues. This confirms previous findings, and the effect of structure liming in this respect is not any different from that of other liming treatments aimed at counteracting acidification and increasing pH in soil. Depressed micronutrient levels in barley grain were pronounced at initial $pH>7$, whereas no significant effects were observed at $pH<7$, pointing at risks with structure liming on calcareous soils. The structure lime used in this thesis (see Table 3) also contained other nutrients such as K, which increased the K content in plant biomass of spring barley at stem elongation.

5.3 Effects on aggregate size distribution

Kirkham *et al*. (2007) performed aggregate size distribution measurements in a field trial 28 years after the first application of lime (in total 15 t ha^{-1} of calcium carbonate, in six separate applications of 2.5 t ha^{-1} in six separate years), and found an increased percentage of coarser aggregates (>4 mm and >8 mm) in the top 0-5 cm. This increase occurred at the expense of the four aggregate sizes <0.25, >0.25, >0.5 and >1 mm. Contrasting effects have been observed, however, when studying aggregates <2 mm diameter, with mean weight aggregate diameter increasing with increasing application rates of calcium oxide, but not calcium carbonate, in laboratory experiments (Siman *et al.* 1984). However, no increase in mean weight aggregate diameter was observed in soil from field trials with corresponding lime application rates

(Siman *et al.* 1984). Similar discrepancies between laboratory and field liming studies have also been reported for pH (Li *et al.* 2019).

Under Swedish field conditions, Ledin (1981) found that a heavy clay soil (65% clay content) limed with calcium oxide eight years prior to sampling was more friable and fell into smaller aggregates at 10-20 cm depth. Another study in Sweden on soils with clay content 38-56% found a higher proportion of aggregates <2 mm and 2-5 mm, and a lower proportion of aggregates >5 mm, giving a finer tilth in the seedbed, in a field trial limed with calcium oxide eight years prior to sampling (Blackert 1996). Thus, under Swedish conditions liming seems to lead to an increased percentage of aggregates <2 mm, at the expense of aggregates with larger diameter.

5.3.1 Slaked lime probably reduced evaporation

The results on aggregate size distribution obtained in Paper I were contradictory. On the one hand, no effect on aggregate size distribution was noted in the three trials with increasing application rates of either calcium hydroxide or mixed structure lime, when studied individually or as a group. Further, no effects on cultivation depth or gravimetric water content were observed. On the other hand, clear effects emerged in the trial combining primary tillage and structure liming, based on measurements of aggregates in the seedbed in May 2013. Replacing mouldboard ploughing with non-inversion tillage during previous autumns 2010-2012 led to a higher proportion of coarse aggregates (5-16 mm) and a lower proportion of fine aggregates (<2 mm), meaning that the seedbed became coarser. On the other hand, application of calcium hydroxide in October 2010, 2.5 years prior to the seedbed studies, led to a finer tilth in the seedbed, with a higher proportion of fine aggregates and a tendency for a lower proportion of coarse aggregates (Paper I). To summarise, this meant that both autumn ploughing in October 2012 and calcium hydroxide application in October 2010 gave a better barrier against evaporation in May 2013. These seedbed properties imparted advantages to the spring barley under the prevailing dry conditions in May 2013, with precipitation of only 15 mm, as indicated in the correlations between aggregate size and yield found in Paper I. The combined effects of primary tillage and application of calcium hydroxide on spring barley yield in 2013 are discussed further in section 5.6.2. The overall conclusion from measurements of aggregate size distribution and yield under the dry conditions in 2013 was that omitting mouldboard ploughing impaired the evaporation barrier, but calcium hydroxide counteracted the coarser seedbed and helped to alleviate the yield reduction.

5.3.2 Both limed treatments gave a finer tilth

Investigations of aggregate size distribution were also performed in the seedbed prepared for spring barley and in the tops of potato ridges in 2015-2017 (Figure 2 in Paper IV). The two limed treatments gave similar effects, with a lower proportion of coarse aggregates (>5 mm) compared with the unlimed control L0. In addition, structure lime (SL), but not ground limestone (GL), resulted in an increased proportion of fine aggregates (<2 mm) compared with the control. There were no differences with respect to fine aggregates between the liming treatments. The aggregate size distribution was not linked to any differences in yield performance, but both limed treatments gave agronomic advantages. Thus, the findings on aggregate size distribution in Paper I were confirmed in Paper IV.

The results in Paper IV were based on measurements in the first crop rotation in a set of 13 trials where liming was carried out in autumn 2013-2015, followed by sugar beet in the first year after liming. The second crop rotation is currently being studied in terms of many different liming effects on plant and soil, *e.g*. follow-up measurements of aggregate size distribution in the sugar beet crop after establishment in the spring. Data available in 2022 will show whether the promising effects of liming in terms of creating a finer tilth persist over time or not.

5.3.3 Dose-response also in seedbed tilth

The effect of structure lime on seedbed tilth was also investigated in selected LOVA trials with increasing application rates of structure lime. Figure 18 shows the effect on aggregate size distribution in nine trials in the LOVA series. As Figure 18 shows, the fraction of coarse aggregates (>5 mm) was reduced in SL2 compared with SL0, whereas the shift among the finest aggregates (<2 mm) was not significant. The decrease in the proportion of coarse aggregates only appeared with the highest rate of structure lime, indicating a dose-response reaction in this set of trials. However, treatment SL in Paper IV received the same amount of structure lime as treatment SL1 in Figure 18 (8 t ha^{-1}), making the results comparable. The tendency (non-significant) for an effect in treatment SL1 in Figure 18 points in the same direction as the significant effect in Paper IV.

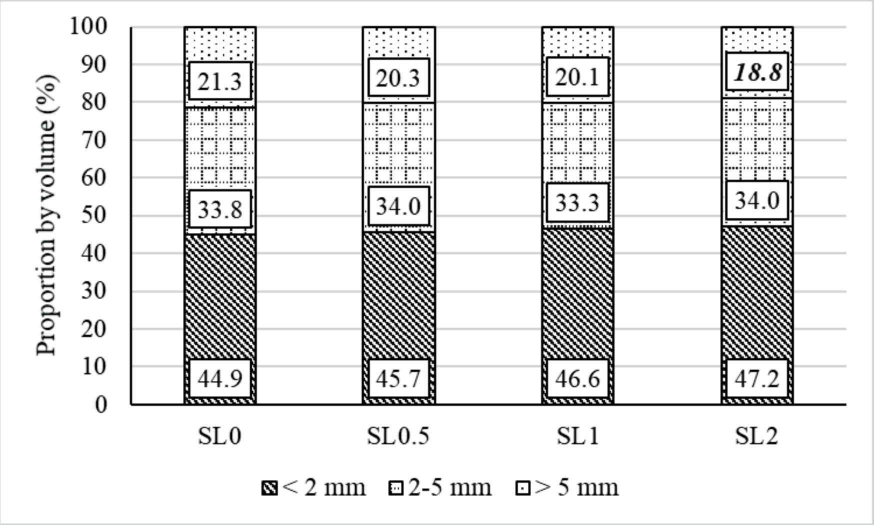


Figure 18. Aggregate size distribution in the seedbed after drilling in spring and in the tilled top layer in autumn. Sampling was performed in nine LOVA trials one year after structure liming in autumns 2017 and 2018. Value in bold italics indicate a significant difference from the unlimed control (SL0). Treatment SL0.5, SL1 and SL2 received 4, 8 and 16 t ha^{-1} structure lime respectively.

5.3.4 Significant and not insignificant

Overall, Figure 18 gives further support to the findings in Papers I and IV that the proportion of coarse aggregates can be decreased with structure liming. The shift in aggregate size distribution by a few percent towards a finer tilth was significant in the statistical sense, but can seem insignificant in practical agriculture. However, from a farm management perspective, the finer seedbed tilth in structure-limed soils means that seedbed preparation is facilitated, as the number of passes required to create a suitable seedbed is lower. It also improves crop security under dry conditions by protecting the seedbed from evaporation. Moreover, a coarse seedbed gives deeper and more variable seed placement (Guerif *et al.* 2001) and decreasing aggregate size has been shown to increase emergence (Håkansson *et al.* 2002). Altogether, the finer tilth as a result of structure liming can be considered an agronomic advantage.

5.4 Effects on draught requirement

Apart from aggregate stability, structure liming also affects other soil physical conditions, in the short term (Frank *et al.* 2019; Frank *et al.* 2020) and in the longer term (Bennett *et al.* 2014). A soil physical property affecting tillage operations in practical farming is soil strength, often quantified as draught requirement, which has been observed to decrease with increasing application rate of calcium oxide and calcium carbonate (Siman *et al.* 1984).

There is episodic and anecdotal evidence of decreased draught requirement following application of structure liming products currently used in Sweden. Prior to this thesis the impact had not been tested in detailed studies, however, and this lack of quantitative measurements was the driving force for the study reported in Paper V. The aim in that study was to quantify the effect of increasing application rates of structure lime on the draught requirement in clay soils. The work was enabled through financial support from The Royal Swedish Agricultural Academy and SLU Partnerskap Alnarp, together with technical support from Väderstad AB.

5.4.1 Force measurements in three directions

In eight trials (four sites with two trials per site), structure lime was spread and incorporated in summer/autumn 2014, 2016, 2017 and 2018. Measurements of draught requirement were carried out in August and September 2020, *i.e.* two, three, four and six years after application of structure lime.

Draught requirement was measured in untilled soil after harvest in stubble of the preceding crop, using a Väderstad TopDown 400 tine cultivator (4 m working width) equipped with points (80 mm width) pulled by a John Deere 6215R tractor (Figure 19a). The cultivator towing eye (Figure 19b) was equipped with a built-in traction meter connected to a computer, enabling force measurements in three directions using strain gauges. The tractor and cultivator forward speed was 8 km h^{-1}. The tine working depth was set at 12 cm (Figure 19c), with cultivator discs lifted, so that only the tines worked the soil (Figure 19d). The packer roller was kept floating without pressing the soil.

a. Draught requirement measurements.

b. Towing eye.

c. Working depth measurement.

d. Disc lifted on the cultivator.

Figures 19. Tractor and cultivator at work (a) with specially equipped towing eye (b) at working depth of 12 cm (c) with cultivator discs lifted (d). Photo: Jens Blomquist.

5.4.2 Draught requirement reduced

Analysis of data in Paper V included other soil variables, such as soil organic matter and clay content, that can be expected to affect draught requirement according to Watts *et al.* (2006). However, only clay content as a covariate affected the results. With clay content included, draught requirement was significantly reduced by liming ($p=0.002$) and there was no interaction between trial and treatment, indicating the same reaction to structure lime in all trials. Pairwise comparison showed a significant decrease of 11% in treatment SL2, and non-significant decreases of 6% and 4% in treatments SL0.5 and SL1, respectively, compared with the unlimed control (SL0).

5.4.3 No obvious dose response

There was a clear treatment effect from structure lime, but an unclear dose-response effect (Paper V). The structure lime product used consisted of approximately 80-85% ground limestone and 15-20% slaked lime, so the main component was calcium carbonate. Therefore the results were in agreement with Siman *et al.* (1984), who found no clear linear relationship between lime application rate and draught requirement with calcium carbonate, but observed a dose-response effect with calcium oxide. This called for an analysis of the general effect of structure lime on draught requirement, and for this reason the average value obtained for all limed treatments was compared with that in the unlimed control (SL0) (Figure 20). The general effect of structure liming on draught requirement was a 7% decrease (p=0.002) (Paper V).

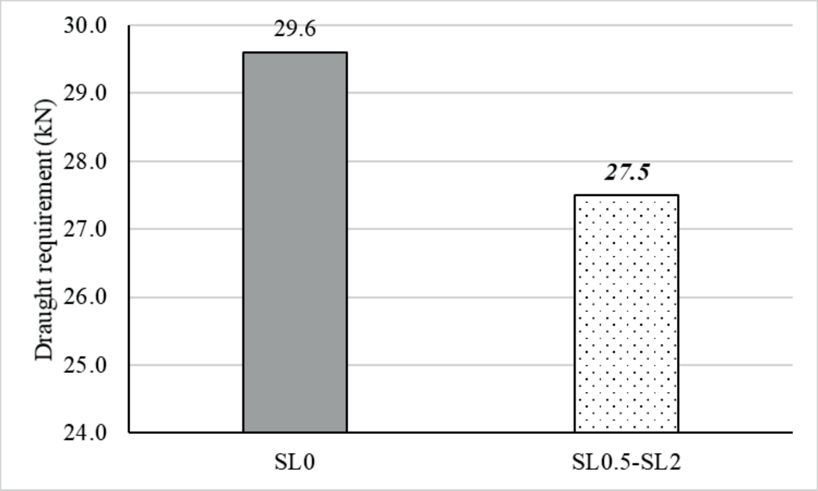


Figure 20. Draught requirement in unlimed (SL0) and structure-limed treatments (SL0.5-SL2) measured in August-September 2020. The value for SL0-SL2 is the average draught requirement in all three structure-limed treatments. Values in bold italics indicate a significant difference from the unlimed control (SL0). Treatment SL0.5, SL1 and SL2 received 4, 8 and 16 t ha^{-1} structure lime, respectively.

5.4.4 Signs of time-dependency

On analysing the four sites separately in Paper V, it was found that the two sites where structure lime was applied six and four years prior to measurements showed significant results on draught requirement, whereas no significant results were observed at the two sites where structure lime was applied more recently, only three and two years prior to measurements in 2020. No analysis was performed on whether any pozzolanic reactions

(Choquette *et al.* 1987; Firoozi *et al.* 2017) had occurred at the four sites. Such reactions are functions of *e.g.* curing time (Kassim & Chern 2004), as demonstrated for periods of up to 10 years when measuring unconfined compression strength on a kaolinite clay treated with calcium hydroxide (Kavak & Baykal 2012). The apparent time-dependent effect on draught requirement in Paper V could possibly be interpreted as a time-dependent contribution from the calcium hydroxide component in the structure lime, but this cannot be proven based on the existing data.

5.4.5 Added value for practical farming

The significantly reduced draught requirement of 11% in treatment SL2 (equivalent to 3.2 kN) compared with the unlimed control (SL0) corresponded to reduced fuel consumption of approximately 1.2-1.4 litre diesel ha^{-1} and a lowering in CO_2 emissions of 3.1-3.7 kg ha^{-1} for one single pass with the cultivator. For all tillage operations over the working year, the total effect on fuel and CO_2 emissions would be even larger. Similarly, to the observed effects of liming on aggregate size distribution (see section 5.3), this effect on draught requirement can be considered a bonus for both practical farm management and the environment. The reduced draught requirement in Paper V provided added value to structure liming and represented an agronomic advantage.

5.5 Effects on aggregate stability and risk of PP losses

The EU Water Framework Directive came into force in December 2000 (EU-Commission 2021) and was adopted nationally in Sweden in 2004. In environmental programmes implemented in Sweden since then (HaV 2021), structure liming as a measure to mitigate losses of particulate phosphorus (PP) has been given priority. For that reason, the main focus of this thesis, and also the main orientation of the bulk of field trials presented in Papers I-VI, was the effect of structure liming on the risk of PP losses from arable soil.

Phosphorus losses from clay soils are dominated by PP losses, according to Aronsson *et al.* (2019). Losses of PP and other phosphorus species were not measured directly in individual tile-drained plots in the field trials in this thesis, but this was done in studies by Ulén and Etana (2014) and Norberg *et al.* (2021), where exact data on *e.g.* drain discharge together with losses of total phosphorus (TP), PP and dissolved reactive phosphorus (DRP) in different liming treatments were obtained. In this thesis, these phosphorus fractions were only occasionally measured in leachate from soil cores (0-15 cm) from field trials in lysimeter studies (Paper II). Instead, the standard method employed was to measure turbidity in leachate after exposure of aggregates to simulated rainfall events, as a proxy for aggregate stability and thereby the risk of PP losses. This estimation/assumption is based on turbidity as a function of suspended clay (Etana *et al.* 2009), the correlation between total suspended solids and PP (Puustinen *et al.* 2005), and the relationship between turbidity and TP (Ulén & Etana 2014) and between turbidity and PP (Ulén *et al.* 2012). In a previous study, colloidal P was shown to comprise predominantly inorganic Fe- and Al-associated P in two Chinese soils cropped with rice and vegetables (Liu *et al.* 2014). In a study on two fractions of leached clay-sized particles (>0.45 and <0.45 μm) from tile-drained agricultural soils in Sweden, Adediran *et al.* (2021) found organic P and P adsorbed to aluminium-bearing particles to be the most common forms of leached P. In these leachates Ca-P was also prominent, but Fe-P was less abundant. Together, these relationships formed the basis for using turbidity as a proxy for the risk of PP losses in this thesis. Such approximations will never give exact and absolute values of PP losses, but represent a relatively inexpensive and cost-effective shortcut to estimating the relevant risk. Thereby using turbidity as a proxy provides the possibility to assess the risk of PP losses from many field trials on different soil types, instead of in only a few trials where more detailed information can be compiled. It thereby represents a way forward to screen soil types with a greater variation in soil properties.

In the following sections, turbidity is used interchangeably and synonymously with aggregate stability.

5.5.1 Effect of application rate – short term

Turbidity decreased significantly, by 13%, with the standard application rate of 8 t ha^{-1} of structure lime, referred to in the short-term study as SL8 (Figure 2 in Paper III). This was the overall effect in 30 field trials where sampling was performed approximately one year after application of the structure lime. With the doubled application rate of 16 t ha^{-1} of structure lime, the decrease in turbidity was 20%, whereas the halved application rate of 4 t ha^{-1} gave a decrease of 10%, which was not significantly different from the unlimed control treatment. Altogether, in Paper III there was a clear dose-response reaction to structure lime in the experimental soils. In Paper I, there was also a dose-response reaction in the experimental soils from application of calcium hydroxide and structure lime in increasing application rates (equivalent to 1, 2 and 6 t ha^{-1} of CaO) (see Figure 1 in Paper I). Those results were derived from three field trials in which sampling was performed approximately 2.5 years after lime application. In all those trials, the turbidity in leachate was only significantly reduced with the highest application rate of both products, with a 26% reduction with calcium hydroxide and a 21% reduction with structure lime.

In Paper IV, different application rates of structure lime were not examined, so no dose-response effect could be evaluated. Instead, structure lime was compared with ground limestone (calcium carbonate) based on equal applications of calcium ions. Structure lime at the standard application rate of 8 t ha^{-1} reduced the turbidity by 35% compared with the unlimed control, as an average for the 13 field trials examined (Figure 1c in Paper IV), where 11 trials used the mixed structure lime and two trials used slaked lime. Sampling in that set of trials was performed approximately 1.5 years after application.

The short-term effect of the standard application rate of 8 t ha^{-1} of structure lime can thus be summarised as a reduction in turbidity of approximately 15-35% when measured approximately 1-2.5 years after application (Papers I, III and IV). Increased aggregate stability from applying calcium carbonate is in accordance with findings by *e.g.* Bennett *et al.* (2014). An overview and comparison of the structure lime treatments with increasing application rates and the relative turbidity decrease in different studies in this thesis are provided in Table 7.

Table 7. Relative turbidity of seedbed aggregates 2-5 mm in leachate after a second simulated rainfall event (A2) (data compiled from Papers I, III and IV). Values in bold italics indicate a significant difference from the unlimed control (SL0=100). Treatment SL0.25, SL0.5, SL1, SL1.5 and SL2 received 2, 4, 8, 12 and 16 t ha-1 structure lime, respectively

	Paper I	Paper III	Paper IV
	n=3 trials	n=30 trials	n=13 trials[*]
	Rel. turbidity A2	Rel. turbidity A2	Rel. turbidity A2
Treatment			
SL0	<u>100</u>	<u>100</u>	<u>100</u>
SL0.25	93	-	-
SL0.5	104	90	-
SL1	-	***87***	***65***
SL1.5	***79***	-	-
SL2	-	***80***	-

[*] 11 trials with mixed structure lime, two trials with slaked lime.

5.5.2 Effect of application rate – longer term

An effect on aggregate stability following structure lime application was also seen in the slightly longer term in Paper VI, where the effect on turbidity was compared in the first and sixth year after application of structure lime (Figure 21). In the first year after structure liming, turbidity in treatments SL1 and SL2 decreased, but SL0.5 showed no significant effect. In the sixth year, no significant effects remained when the three limed treatments were analysed separately.

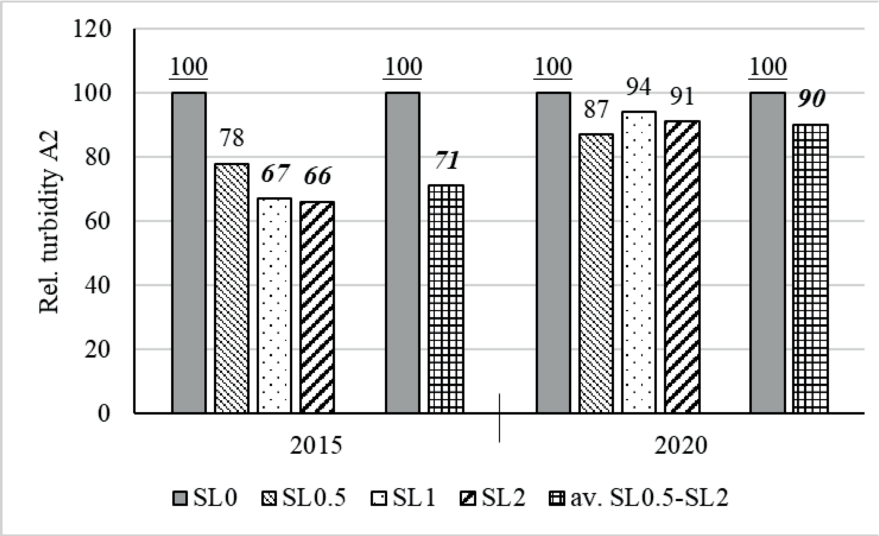


Figure 21. Relative turbidity after a second simulated rainfall event on 2-5 mm aggregates of tilled soil collected one year (2015) and six years (2020) after structure liming. Results for eight trials with increasing application rates of structure lime analysed separately (left) and grouped in a contrast of limed treatments SL0.5-SL2 (right) and compared with the unlimed control SL0. Treatment SL0 = 100. Values in bold italics indicate a significant difference from treatment SL0. Treatment SL0.5, SL1 and SL2 received 4, 8 and 16 t ha^{-1} structure lime, respectively. Treatment av. SL0.5-SL2 is the mean of treatments SL0.5-SL2, corresponding to 9.33 t ha^{-1} structure lime.

However, with the limed treatments grouped together in a statistical contrast to show the general effect of structure liming compared with the unlimed control, the decrease in turbidity was 29% (p=0.0002) in the first year after application and was still significant (p=0.0318) in the sixth year, but had declined to 10%. Thus, the initial effect of the structure lime treatments was transient, but still remained and was detectable after six years. Decreasing effects of structure lime over time on aggregate mean weight diameter were observed by Berglund (1977). Diminishing effects over time was also offered as a possible explanation by Hellner *et al.* (2018) for a lack of significant effects of liming on macropore network characteristics.

The results reported in Paper IV are currently being complemented with measurements of aggregate stability in the second crop rotation after structure liming, *i.e.* follow-up measurements are now being carried out 5-6 years after liming. Those results will be compiled in 2022, so new data on the effect of structure lime and ground limestone on aggregate stability in the slightly longer term will then be available and can be compared with the results in Paper VI. Preliminary data from some of the ongoing field trials show a persisting structure lime effect on turbidity.

5.5.3 Effect of liming products

Paper IV compared the effect of two liming products, *i.e*. ground limestone (GL) and structure lime (SL). One of two starting hypotheses in that study was that structure lime improves soil structure more than ground limestone, but the data obtained did not support this hypothesis. The results showed that overall aggregate stability increased with liming ($p<0.001$), with turbidity decreases of on average 43% and 35% with application of GL and SL, respectively, compared with the unlimed control. However, there were no significant differences in effects between the two liming products.

One possible reason for this is that limestone was the main constituent of both products (GL consisted of 100% ground limestone and SL of 80% ground limestone plus 20% slaked lime). The finer particle size seen for GL (0-0.2 mm) compared with SL (0-0.5 mm) gave the GL treatment an advantage, as the dissolution velocity depends on soil particle surface area (Erstad 1992), as pointed out in previous studies (Mattsson 2010; Conyers *et al.* 2020). The expected additional effect on soil structure from application of SL, as outlined in the starting hypothesis, did not materialise. Such an additional effect could theoretically have been achieved with the 20% of slaked lime contained in the SL product, allowing carbonation and pozzolanic reactions to occur (Choquette *et al.* 1987). The results obtained in Paper IV therefore suggest that the increased aggregate stability was achieved as a result of cation exchange. Complementary follow-up measurements of aggregate stability are currently being performed in the second crop rotation, 5-6 years after liming. Data available in 2022 can indicate whether carbonation or pozzolanic reactions have developed over time in treatment SL.

5.5.4 Effect of application conditions

In Paper II, two structure lime application dates (early in August, normal in September) were compared, to test whether prevailing conditions with respect to tilth and temperature at the time of lime application are decisive for the outcome in terms of aggregate stability.

Measurements of aggregate size distribution after spreading and incorporation showed a considerably finer tilth at the early application date compared with the normal liming date. There were significantly lower proportions of clods (>64 mm average diameter) and higher proportions of smaller aggregates (<2 mm average diameter), enabling closer contact between soil and lime, at the early application date. These findings are in line with those in previous studies examining the effect of liming with regard to soil tillage (Valzano *et al.* 2001; Conyers *et al.* 2003; Joris *et al.* 2016). The finer tilth was possibly the reason why turbidity decreased by 11% (p=0.026) at the early liming compared with the normal date when measured on seedbed aggregates (2-5 mm) (Paper II).

Contrary to results on aggregate stability in the seedbed, no significant differences were found on structure stability in topsoil lysimeters (0-15 cm) between the two application dates (Paper II). An interaction between liming date and experimental site was found, with contradictory patterns for turbidity in leachate from the lysimeters. This discrepancy in results was possibly attributable to different prevailing conditions in the trials at the two lime application dates. Therefore, the results in Paper II suggest that early liming date in combination with a finer tilth can give better aggregate and structure stability, but only if accompanied by favourable soil conditions. The importance of incorporation and soil tillage before and after lime application was also revealed in discriminant analysis in Paper III (see below). In short, liming needs timing!

5.5.5 Interactions are fundamental

Effects of structure lime on turbidity will probably vary with application rate, sampling time, liming product and conditions at application as described above, and new studies will fill existing and future knowledge gaps. The fundamental finding in this thesis was the significant interaction between structure lime treatment and trial. Such significant, or near-significant, interactions were found in Paper III (p=0.056), Paper IV (p=0.049) and Paper VI in the first year after application (p=0.049), and were even stronger in Paper VI in the sixth year after application (p=0.003). The results in Paper I were actually the only exception in terms of trial- treatment interaction p-values. The implication of these interactions between trial and treatment is that different soils react differently to application of structure lime. To exemplify and clarify this interaction between treatment and trial, Figure 22 illustrates the different reactions for structure lime application in the two neighbouring trials Krageholm LC and Krageholm HC in 2015 (Paper VI).

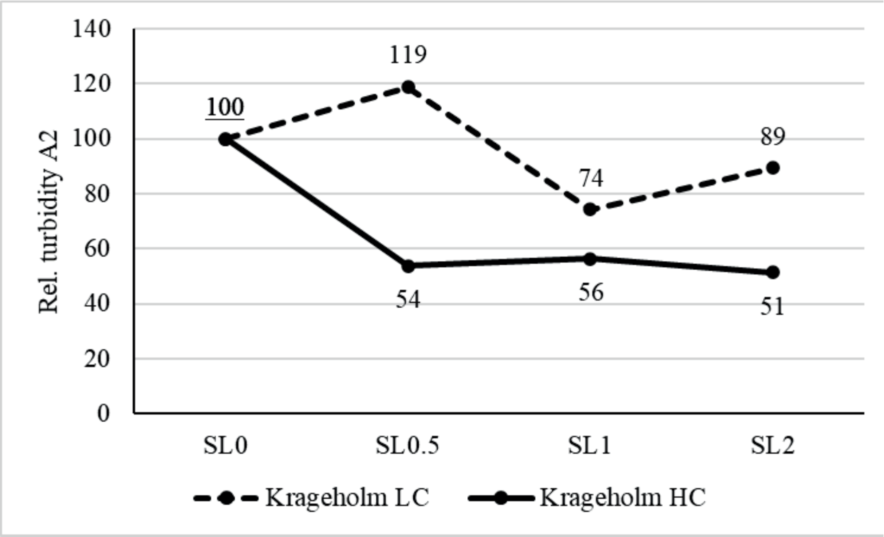


Figure 22. Relative turbidity A2 in 2015 at neighbouring trials Krageholm lower clay (LC) and Krageholm higher clay (HC), situated 200 m apart. Sampling performed approximately one year after structure liming. Treatment SL0 (unlimed control) = 100. Treatment SL0.5, SL1 and SL2 received 4, 8 and 16 t ha^{-1} structure lime, respectively.

None of the trials showed significant differences between treatments SL0, SL0.5, SL1 and SL2 in pairwise comparisons in 2015, one year after application. However, in t-tests of the contrast (difference between unlimed control and the average of the three limed treatments), there was a significant difference for Krageholm HC (p=0.012), but not Krageholm LC (p=0.756). Thus, these two neighbouring trials reacted very differently to structure lime application, despite being located at the same site (only 200 m apart) (Figure 22).

Similar varying effects from lime treatments on different soils have been observed in previous studies, although not explicitly termed interactions between lime treatment and soil. In laboratory studies, Berglund (1971) observed different reactions in terms of soil physical properties (aggregate mean weight diameter, bearing capacity, tensile strength, shrinkage, pore size distribution and water permeability) to application of different types of lime to soils with differing clay content. Similarly, Keiblinger *et al.* (2016)

found that aggregate stability after application of quicklime was strongly dependent on clay content, pH and CEC on three soils in a greenhouse pot experiment. In field trials, Berglund (1977) observed and discussed varying effects on aggregate mean weight diameter in soils in different trials after application of both calcium oxide and calcium carbonate, but did not analyse the varying effects statistically. Using data from the same field trials, Siman *et al.* (1984) found significant effects on aggregate mean weight diameter and draught requirement from quicklime treatment in 11 trials, but did not report a possible interaction between trial site and treatment.

Ulén and Etana (2014) found significant decreases in turbidity following structure liming in two trials with calcium oxide (trial Bornsjön) and calcium hydroxide (trial Wiad), but as both lime treatments were not included at both sites, any trial-treatment interaction could not be examined. However, it is worth pointing out that the two trials showed different patterns regarding losses of PP and DRP when analysed individually. This could possibly be attributable to different clay and P contents in the topsoil. Norberg *et al.* (2021) applied the mixed structure lime used in this thesis in a trial at a site in south-west Sweden (Lilla Böslid) and observed no significant effects on aggregate stability or on phosphorus leaching, but could not assess any trial-treatment interaction as the study comprised only one trial. Unequal responses in turbidity to gypsum treatments were reported separately for two fields by Uusitalo *et al.* (2012) and different responses in easily extractable P to liming treatments were reported for two field trials by Øgaard (2019). Together, this suggests that the effect of liming on soil variables can vary widely and therefore generalisations are rarely possible.

5.5.6 Predictions are desirable

The varying effects of lime treatments seen in the laboratory and field studies cited above can possibly be attributable to a significant trial- treatment interaction (as seen in Papers III, IV and VI), but this has seldom been assessed. Such interactions, as illustrated in Figure 22, render discussions on average effects of structure liming pointless and meaningless. As underlined in Paper VI, the great variation in aggregate stability means that structure liming cannot be used as a general remedy for all clay soils to reduce the risk of phosphorus losses. On the contrary, the observed significant trial-treatment interactions call for a site-specific application strategy for structure liming. Such a strategy should take into consideration decisive soil properties. In Paper III, the trial-treatment interaction was ‘deconstructed’ by splitting the 30 trials into subgroups based on clay content, initial pH, SOM content and the proportion of swelling *vs* non-welling clay minerals (SmV index). The ‘deconstructed’ trial x treatment interaction obtained as the outcome of subdivision based on soil characteristics was in line with Bölscher *et al.* (2021), who observed that changes induced by structure liming are site-specific.

Knowledge of the trial-treatment interactions in Papers III, IV and VI led to the conclusion that structure liming should not be recommended for all clay soils. While it is evident that structure liming is not a one-size-fits-all prescription for clay soils, questions arise regarding the type of clay soil on which structure liming should be recommended if the desired outcome is an increase in aggregate stability. The discriminant analysis in Paper III was a preliminary attempt to predict the effects of structure lime application based on four soil properties (variables) of soils for which significant aggregate stabilisation can be expected. In the discriminant analysis. observed values of turbidity were classified into two groups, comprising: i) trials with a significantly higher value of turbidity in the unlimed control (SL0) compared with the mean of the limed treatments (SL0.5, SL1 and SL2), and ii) trials that did not have significant differences between the control and liming treatments. Following classification into these two non-overlapping groups, a discriminant component was calculated based on the four selected predictor variables, which were: initial pH, clay content, SOM content and mineralogy properties condensed in the SmV index. The discriminant analysis performed on the four independent soil variables was not sufficiently accurate to predict whether structure liming would have a favourable effect or not. However, combining these variables with four more variables describing how the soil was tilled before and after lime application gave better accuracy. With eight predictor variables, the discriminant analysis correctly predicted all trials with a significant aggregate stability increase, where structure liming could be recommended. Tillage before and after liming seemed to be important for the effect on aggregate stability, just as timing of lime incorporation was found to be in Paper II. The discriminant analysis represented a leap forward in the possibility to predict the effect of structure lime based on soil variables. It also revealed the relative importance of the soil variables, as summarised in Figure 23 using data from Table 1 in Paper III.

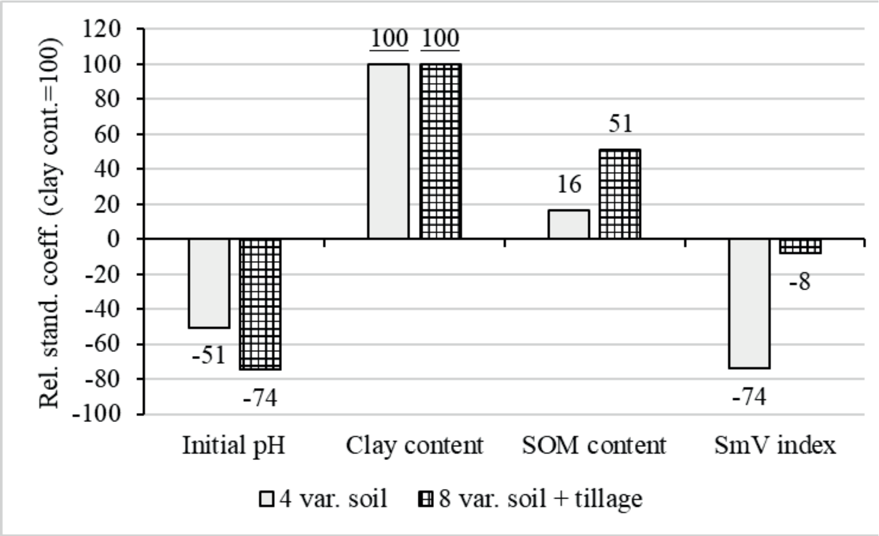


Figure 23. Relative standardised coefficient (clay content=100) of soil variables, indicating their relative importance for the effect of structure liming on aggregate stability. Calculated using data from discriminant analysis taken from Table 1 in Paper III, either with four soil variables or with four soil variables and four tillage variables.

There was a difference in the relative importance of the soil variables when using four soil variables or eight soil and tillage variables, but in essence both analyses pointed in the same direction as regards the relative importance of the soil variables (Figure 23). Clay content was the most important soil variable in both analyses. Taken together, the results from Paper III suggests that structure liming is a more effective measure to stabilise aggregates, and mitigate phosphorus losses, on soils with high clay and SOM content, low SmV index and low initial pH.

Further support for the importance of clay content was provided in Paper VI, where aggregate stability was analysed in the first and sixth year after lime application. Subdivision according to clay content into a group with lower clay content (LC) and a group with higher clay content (HC) showed significant treatment effects of structure liming in the LC group in the first year, but not in the sixth year. For the HC group, however, the treatment effects were significant in both the first and sixth year. Paper VI also indicated that initial pH may be a decisive soil property. Of the eight trials examined in that study, only one showed a persistent aggregate stability increase six years after liming as a proposed consequence of the combination of low initial pH and sufficiently high clay content. This led to the tentative suggestion in Paper VI that structure liming with the mixed product used in this thesis is most effective to reduce the risk of PP losses on soils with initial pH <7 and clay content >25%.

5.6 Effects on crop yield

Liming is a common management practice on agricultural soils (Haynes & Naidu 1998) and is the dominant practice used for reducing soil acidity and improving yield of annual crops (Fageria *et al.* 2010). However, liming as an amendment measure for agricultural soils is decreasing in *e.g.* the UK (Holland *et al.* 2018). In Germany, more than 40% of arable soils are classified as lying in the low pH range, with yield losses as one of the consequences (Frank *et al.* 2020), and could benefit from liming.

Yield response to liming differs between crops, as they vary in their tolerance to acidity, so critical soil pH values vary with crop species and soil texture (Goulding 2016). The different yield responses to liming were recently demonstrated in a global meta-analysis by Li *et al.* (2019) showing a significant increase in yield of all crop species tested except for sorghum, tuber crops and tobacco. Differences in yield response to liming under UK conditions were found by Holland *et al.* (2019), who observed weak responses to lime in potatoes and oats, but positive yield responses in other cereal crops and also in winter oilseed rape.

Under Swedish conditions, a general positive effect on crop yield of liming up to 70% base saturation was observed by Haak and Simán (1997), although they also observed varying responses to liming for different soils and crops. In a set of 15 field trials in Sweden, liming to 70-85% and 100% base saturation was observed to give a yield decrease of 6% and 8%, respectively, which was mainly attributed to a pronounced effect on sandy soils and depressed levels of Mn and Cu in grain (Kirchmann & Eskilsson 2010).

For soils with SOM <6%, a target pH_{H2O} of 6.3-6.5 depending on clay content is the official recommendation in Sweden (Andersson *et al.* 2021), with an additional 0.5 pH unit if sugar beet is part of the crop rotation. However, according to Kirchmann *et al.* (2020), the current recommendation should be raised to pH 7. In a comprehensive national survey, those authors found a strong yield response to most crops in the pH range 5.5-7.2. Yields of winter wheat and spring barley almost doubled in the range 6 to 7, but with a declining effect of cereal yields above pH 7.2 (Kirchmann *et al.* (2020). For sugar beet, Olsson *et al.* (2019) found significant increases in yield on soils with initial pH values >7 and without a liming requirement, but lower sugar yield responses on soils with initial pH 6.5-7.0 and with a liming requirement. Such enigmatic yield responses probably fall within the framework of what Li *et al.* (2019) refer to as limited knowledge on quantitative relations between liming management and crop yield.

5.6.1 Early inspiration in sugar beet project

My own first contact with structure liming was when I coordinated Project 4T – a sugar beet yield enhancement programme run by the sugar industry and the Swedish Sugar Beet Growers' Association (NBR_Betförsök 2021). On alkaline clay soils (pH variation 7.1-7.9 and CEC variation 12.2-23.5 meq. 100 g soil^{-1}), 12 field trials were carried out with different types of lime for sugar beet crops harvested during 1998-2000. The first beet harvest (1998) revealed significant yield increases in treatments with slaked lime ($Ca(OH)_2$), leading the official organisation for field trials in southern Sweden to investigate whether the effect of structure lime persisted as a yield increase in the following year. To this end, cereals were harvested in 10 of the 12 trials during 1999-2001. The sugar and cereal yields recorded in the project are summarised in Table 8.

Table 8. Extractable sugar yield in first year after liming (12 trials, 1998-2000) and cereal yields in the second and third year after liming (10 trials 1999-2000) in Project 4T. Significantly different yield increases compared with the unlimed control are indicated by asterisks

Treatment	Extract. sugar yield (t ha^{-1})	Rel.	Cereal yield (kg ha^{-1})	Rel.
Control	8.76	100	7380	100
$Ca(OH)_2$, 3 t ha^{-1}	9.09*	104	7455	101
Ground limestone, 4 t ha^{-1}	8.93	102	7514	102
Sugar factory lime, 8 t ha^{-1}	9.00	103	7653*	104
$Ca(OH)_2$, 9 t ha^{-1}	9.51*	109	7632*	103
CV	3.7		2.3	
LSD, 5%	0.27		157	

In the sugar beet crop, both levels of slaked lime tested increased the extractable sugar yield significantly, by 4% and 9% respectively. In cereals, yields increased significantly with sugar factory lime and with the highest level of slaked lime. As soon as the sugar beet had been harvested in the first year, a discussion arose among sugar beet growers as to whether the yield increase was an effect of modified soil structure or a plant effect in the form of reduced attacks of root rot (*Aphanomyces cochlioides*), or both. Whatever the causes of the positive yield increases, they fuelled my own interest in the practice of structure liming.

5.6.2 Varying effects on crop yield

The positive effect of structure lime on crop yield in Project 4T was partly contradicted by the results from Paper I, for trials performed at SLU in Uppsala over the years 2011-2014. That study examined the effect on crop yield of structure lime in trials with different designs, with the objective of addressing two different research questions: dose responses of structure lime and the combined effect of structure lime and primary soil tillage.

In three trials, two structure liming products (slaked lime *vs* a mix of calcium carbonate and slaked lime) were compared at increasing application rates, but based on supplying equal amounts of calcium, irrespective of differences in solubility of the calcium compounds. The overarching results showed no positive yield response over a four-year period. The different crops grown (oats, spring barley and winter wheat) did not react differently to the structure lime treatments (interaction lime-year p=0.208), but there was a significant interaction between trial and treatment (p=0.025) indicating different reactions to structure lime in different soils. Two trials were unaffected by structure liming, whereas the third trial (8501B) showed significant yield reductions in two of four years during 2011-2014. Those two years (2011, 2013) were characterised by low precipitation from spring drilling until May-July. Over the four-year period, the mean effect of the six limed treatments compared with the unlimed control was a negative yield response, of -170 kg ha^{-1}, in 8501B. The three trials were situated next to each other (within 400 m), so the different reactions to the structure lime treatments were ambiguous. The discriminating soil variable in trial 8501B with its negative yield response was a low AL-extracted P level (50-60% of the levels in neighbouring trials). The causality of the yield reduction could not be unravelled, but the combination of low precipitation and initially low available P levels aggravated by liming is a possible explanation. Such combined effects of water stress and P deficiency were examined by Brown *et al.* (2012), who found that the impact on barley biomass of increasing water availability or P availability separately was similar, but providing water and P in combination gave a greater effect. Reduced uptake of phosphate with increasing soil pH was also reported by Barrow (2017), with the explanation that roots take up phosphate as the monovalent ion $H_2PO_4^-$, dominating the balance between $H_2PO_4^-$ and divalent HPO_4^{2-} up to pK_a 7.21, where the ions occur in equal proportions. Barrow (2021) reiterated this explanation, arguing that the dominating precipitate-particulate theory, where maximum phosphate availability is reached at near-neutral pH, lacks supporting solubility data. In this context, the observed yield decline in trial 8501B can perhaps be explained by decreased P availability following liming and increasing pH, as outlined above.

The second research question explored in Paper I was structure liming combined with different primary tillage (mouldboard plough or stubble cultivator). In this single split-plot trial, the results were clear-cut over the period 2011-2014: primary tillage had no effect on yield, but application of structure lime (2 t ha^{-1} CaO as slaked lime) increased yield significantly. This yield increase, as an average of the two primary tillage methods, did not materialise until the last two years of the four-year period. In the last year there was an interaction between tillage and lime, *i.e.* structure lime only increased yield in the stubble-cultivated treatment. The seedbed aggregate size distribution in the dry spring of 2013, characterised by only 15 mm of precipitation in May, revealed differences both as a consequence of primary tillage and of structure lime application. Ploughing instead of stubble cultivation, and structure liming instead of no structure liming, created seedbeds with a finer tilth, with a lower proportion of coarse aggregates (5-16 mm) and higher proportion of very fine aggregates (<2 mm). The finer tilth deriving from both ploughing and structure liming may have acted as an evaporation barrier (Håkansson *et al.* 2002) under the dry conditions in 2013. Structure liming increased yield by 9% in 2013 on average for both primary tillage methods, but more strongly when ploughing was replaced by stubble cultivation. Thus, applying structure lime in the dry spring of 2013 may have counteracted the otherwise coarser seedbed resulting from non-inversion tillage. This conclusion is logical, as the structure lime was concentrated in the upper part of the topsoil, instead of being diluted by inversion of the soil with mouldboard ploughing.

Taken together, the results from both sets of trials showed that the crop response to structure lime varied, with yield decreases and increases of approximately 10%. The conflicting treatment effects led to rejection of the hypothesis that structure liming significantly improves crop yield. However, structure liming was also shown to increase aggregate stability (see section 5.6), with the inconsistent effects on yield indicated in the title of Paper I: "*Structure liming enhances aggregate stability and gives varying crop response on clayey soils*."

5.6.3 Early effect on plant growth, but not on grain yield

The detailed studies in Paper IV can possibly cast light on the general effect of lime on early growth of spring barley. Lime treatments (ground limestone (GL) and structure lime (SL)) increased the number of shoots, nitrogen uptake (indicated by SN-values derived from canopy reflectance) and biomass. However, the early positive effects on growth were not reflected later in positive grain yield increases at harvest, where no differences were observed between the limed treatments and the unlimed control, or between the two limed treatments. This discrepancy between the increases in early growth variables and the lack of effect on yield was possibly caused by low Mg levels and high Ca levels in the plants resulting from depressed Mg/Ca ratio in the limed treatments, although there were no obvious differences in Mg/Ca ratio between the three liming treatments (ratio 0.167-0.169).

The trials in Paper IV were established to study the combined effects of liming and fertilisation in a split-plot design. Beyond the scope of those studies, and in contrast to the lack of liming effects on yield, there was a significant effect on spring barley yield from fertilisation. One of the starting hypotheses was an expected interactive effect on growth and nutrient content in spring barley between liming treatment and fertilisation strategy. No significant interactions between lime and fertilisation treatments (apart from SN-value) regarding shoot numbers, biomass and grain yield were found, however, so the starting hypothesis could not be validated.

There were no significant interactions between lime treatment and location regarding the plant variables shoot number, SN-value, biomass and grain yield (expressed as P Lime x Location in Table 3 in Paper IV). This can be interpreted as a consistent reaction to liming in the spring barley crop at all locations, which was a sharp contrast to the significant interaction between lime treatment and location regarding the soil variable turbidity, as outlined in section 5.5.

5.6.4 Varying yield response on different soils

Apart from the crop yield responses to ground limestone, slaked lime and the mixed structure lime described in Papers I and IV, a number of trials were harvested in the different LOVA projects in 2015, 2016, 2018 and 2019. For example, in 2015 11 trials with winter wheat were harvested in the second year after structure liming at increasing application rates (see Table 2). On average, no yield increase was recorded in that year except at the site with the highest clay content, where yield increased by 5% in treatment SL2.

The yield responses in the eight trials in 2016 were the most intriguing and they are therefore summarised in this section. At two sites (Krageholm and Vadensjö), eight trials (four trials at each site with different clay contents) were studied. In all trials at both sites, structure lime was applied in August-September 2014 in increasing application rates according to Table 2. In the year following liming, winter wheat was grown at Krageholm and sugar beet at Vadensjö, followed by spring barley at both sites in 2016. In that year, the structure lime plots were split in half and each plot was either left untreated or sprayed with a foliar fertiliser (YaraVita® Gramitrel®, containing (g L^{-1}) 64 N, 150 Mg, 50 Cu, 150 Mn and 80 Zn) on two occasions, with 2 L ha^{-1} at ZS21-23 (tillering) and 1 L ha^{-1} at ZS 37-39 (stem elongation stage) (Zadoks *et al.* (1974).

As an average for the eight trials at both sites grouped together, there were no differences in yield, either as an effect of structure liming (F1) or from the foliar application of nutrients (F2). No interaction between structure liming and foliar application was observed.

There was no statistically significant interaction between lime treatment and trial, so the results could be presented as an average for the eight trials. Nonetheless, yields of spring barley are presented separately for the two sites in Table 9, as a way to explore the results further and develop structure liming recommendations.

No differences due to structure lime (F1) or foliar application (F2) were observed at Krageholm as an average for the four trials (Table 9). However, the responses were different in the four trials at that site, and in the trial with the highest clay content there was a lime treatment effect ($p=0.005$), and all limed treatments increased yield of spring barley by 17-19%. At the Vadensjö site no treatment effect from lime was observed, but the treatment effect from foliar application of nutrients (F2) was significant ($p=0.035$) and yield increased by 5% as an average for the four trials (Table 9). There was no interaction between liming and foliar application of nutrients, *i.e.* the yield increase from the foliar application was independent of the structure liming treatment at Vadensjö.

To further clarify and illustrate the effect of structure liming at the two sites, the data in Table 9 are presented graphically in Figure 24.

Table 9. Yield of spring barley (15% water content) in 2016 at the sites Krageholm and Vadensjö. Four trials at each site. Significant differences are indicated by different letters. LSDs within brackets indicate a non-statistically significant value compared with the unlimed control (SL0). Treatment SL0.5, SL1 and SL2 received 4, 8 and 16 t ha-1 structure lime, respectively

	Krageholm		Vadensjö	
	Yield kg ha^{-1}	Yield relative	Yield kg ha^{-1}	Yield relative
Treatment F1, lime				
SL0	5282^{a}	100	5613^{a}	100
SL0.5	5727^{a}	108	5477^{a}	98
SL1	5628	107	5317^{a}	95
SL2	5828^{a}	110	5090^{a}	91
Treatment F2, micronutrients				
No foliar fertiliser	5660^{a}	100	5242^{a}	100
With foliar fertiliser	5574^{a}	98	5506^{b}	105
p Treatment F1	0.223		0.423	
p Treatment F2	0.290		0.035	
p F1 x F2	0.210		0.826	
LSD F1	(553)		(666)	
LSD F2	(163)		245	

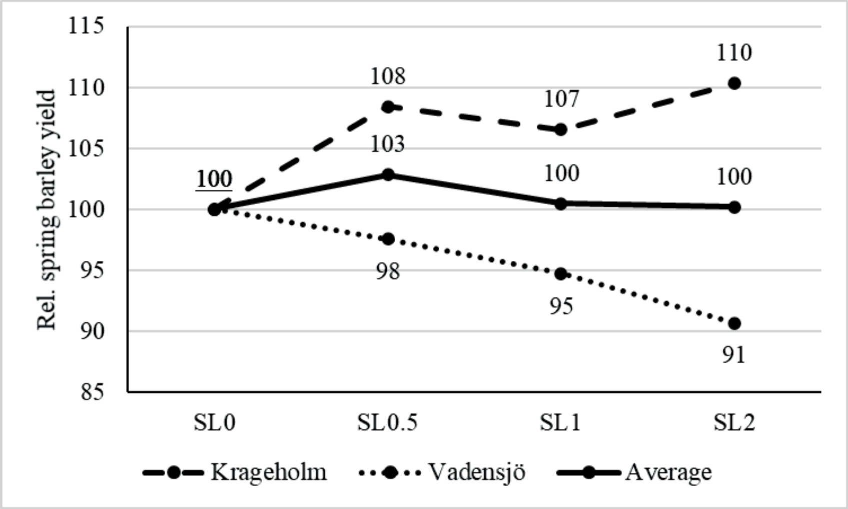


Figure 24. Yield of spring barley (15% water content) in 2016 at the sites Krageholm and Vadensjö. Four trials at each site. SL0 = unlimed control, treatment SL0.5, SL1 and SL2 received 4, 8 and 16 t ha^{-1} structure lime, respectively. Treatment SL0=100.

It appeared as though the spring barley reacted differently to structure lime at the Krageholm and Vadensjö sites, despite the lack of significant interaction between lime treatment and trial. When presenting the eight trials in a group, no sign of structure lime effect on yield could be noted. However, when split between the two sites the response curves were mirror images of each other, with opposing effects of structure lime (Figure 24).

The causes of the apparent different reactions were not unravelled, but CAT-extracted analyses of Cu, Fe, Mn and Zn performed in topsoil (0-20 cm) at the start of the growing season at both sites provided some indications (see section 5.1.4). At Krageholm, there were no effects of liming on any of the micronutrients analysed. In contrast, at Vadensjö lime affected Fe concentration (p=0.009) with a decrease in SL2, and also affected Cu concentration (p=0.010), with decreases in both SL1 and SL2 compared with SL0. This is in line with Fageria *et al.* (2002), who point out that Cu is adsorbed and becomes less available when pH increases. In addition, there was a tendency (p=0.061) for a lime treatment effect on Mn at Vadensjö. Lower Mn content with increasing pH fits well with Karimian and Ahangar (1998), who found that organic matter and calcium carbonate were sites of retention for Mn in calcareous soils (such as that at Vadensjö).

At harvest, the concentrations of six macronutrients and six micronutrients in barley grain were analysed (see sections 4.5 and 5.2.3). As an average for the eight trials, the content of Mn ($p=0.041$) and Zn ($p=0.002$) decreased, and that of Mo ($p<0.001$) increased, in treatments SL1 and SL2 compared with SL0, without an interaction between lime treatment and trial. Divided into the two sites, there were no treatment effects of structure lime on micronutrient content in barley grain at Krageholm, but at Vadensjö lime increased the grain Mo content ($p=0.002$) and decreased the Zn content ($p<0.001$) in treatment SL2 compared with SL0. Uptake of Zn can be inhibited by high concentrations of divalent cations such as Ca (Marschner 1986). In light of the decreased CAT-extracted levels of micronutrients and the depressed Zn content in barley grain, the significant yield increase caused by foliar fertiliser application at the Vadensjö site appears logical. The analyses of soil and grain might also supply a clue as to why there were non-significant yield decreases with increasing application rates of structure lime.

The question remains why different sites reacted differently with respect to crop yield, CAT-extracted micronutrients and micronutrient concentration in the barley grain. A plausible explanation can be found in the pH values at the different sites. At Krageholm, the four trials had initial pH values ranging from 6.2 to 6.6 before liming in 2014. After liming, pH varied between 6.4 to 7.0 with an average of 6.8. At Vadensjö, pH was 7.0-8.2 before liming and increased to 7.4-8.3 with an average of 7.8 after liming. The difference of 1 pH unit between the two sites can possibly explain the depressed levels of CAT-extracted micronutrients in the soil and in barley grain at Vadensjö, in contrast to Krageholm, where no such declines were observed. The reason for the apparent, but not significant, yield increase at Krageholm remains obscure and cannot have derived from any lime-induced changes in micronutrient status in soil or barley grain. No other soil or plant measurements were performed in the growing season 2016 that could have further explained the crop response. However, only 24 mm of rain fell during the first month after drilling on 23 March 2016 at Krageholm, so a finer tilth from liming, giving security in crop establishment (Håkansson *et al.* 2002), as outlined in section 5.3, could possibly explain the yield increase in the limed treatments. The yield increase was perhaps also an effect of increased pH due to structure liming, as pH values at Krageholm were still below the level at which yield increases in spring barley could be expected (Kirchmann *et al.* 2020).

5.6.5 Varying yield response in different crops

The negative yield response in spring barley at Vadensjö in 2016 was in contrast to the positive yield response in sugar beet in 2015 following structure liming in 2014 (Figure 25). The concentrations of B and Mn in sugar beet leaves decreased below critical levels with increasing application rate of lime and increasing pH, especially in the trial with the highest pH. Foliar fertiliser application (YaraVita® Brassitrel®, containing (g L^{-1}) 69 N, 71 Mg, 89 Ca, 60 B, 70 Mn and 4 Mo) did not affect the content of B and Mn, but resulted in a significant yield increase in the trial with the highest pH (Olsson 2016). There were no differences in sugar yield between the limed treatments SL0-SL2 in 2015 and, as mentioned, no differences in spring barley in 2016.

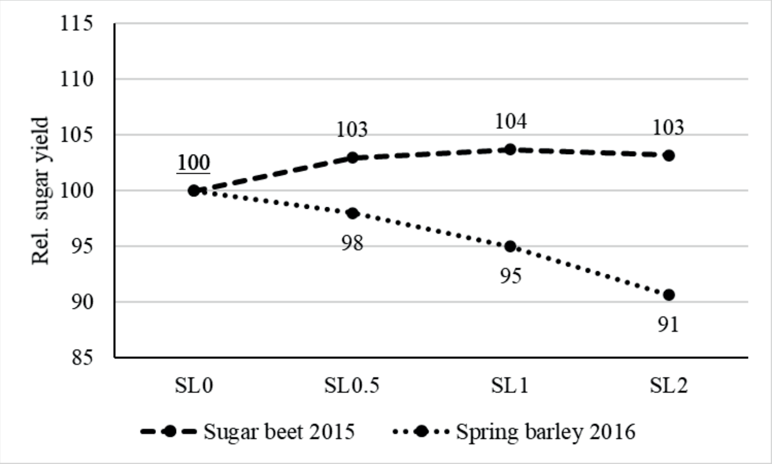


Figure 25. Rel. sugar yield (2015) and rel. spring barley yield (2016) after structure liming in 2014 at Vadensjö site. Average of four trials. SL0=unlimed control=100, treatm. SL0.5, SL1 and SL2 received 4, 8 and 16 t ha^{-1} structure lime respectively.

Nonetheless, the apparent positive and negative reactions by different crops to the structure lime treatment call for an explanation from a farming perspective. Roots of sugar beet have been shown to acidify the rhizosphere continuously, possibly as a strategy to facilitate and enable uptake of *e.g.* P, Fe, Mn and Zn (Hellgren 2003). The release of H^+ to overcome micronutrient deficiencies aggravated by liming can possibly explain why sugar beet in 2015 did not suffer after structure liming, as spring barley did in 2016 in the same plots with the same soil.

6. Conclusions, agronomic implications & future perspectives

Structure lime, in this thesis referring to a mixture of approximately 80-85% calcium carbonate ($CaCO_3$) and 15-20% slaked lime ($Ca(OH)_2$), is used to stabilise aggregates on clay soils, as a measure to prevent particulate phosphorus (PP) losses to surface waters.

6.1 Structure liming reduced risk of PP losses

A standard application rate of 8 t ha^{-1} of structure lime reduced turbidity (increased aggregate stability) by approximately 15-35% compared with the unlimed control 1-2.5 years after application (Papers I, III, IV). There was a clear dose-response effect between application rate and aggregate stability (Papers I, IV, VI), with an even better response with 16 t ha^{-1} compared with the standard application rate. On average for all clay soils tested, structure liming proved to be an effective measure in practical agriculture to reduce the risk of PP losses.

6.2 Treatment-site interactions call for site-specific application strategies

The average values obtained masked the variation between sites and trials. Different soils reacted differently to structure liming, as shown by significant interactions between trial (soil) and treatment (structure lime) (Papers III, IV and VI). The soil variables clay content, initial pH, soil organic content and type of clay minerals (SmV index) proved to be decisive for the structure liming effect on aggregate stability (Papers III, VI). This implies that structure liming is not a cost-effective measure to control losses of PP from all clay soils, and application should instead be site-specific. Structure liming is not a universal environmental countermeasure, so future studies must identify where structure liming gives the greatest environmental benefits. More data on aggregate stability at Swedish sites will be available in 2022, and should be included in a new discriminant analysis similar to that performed in Paper III.

6.3 Management can fine-tune the outcome

The effect of structure liming on aggregate stability was not only a function of inherent soil properties, but was also affected by management at farm level. Structure liming in August significantly decreased aggregate stability compared with application in September, probably due to a finer tilth in August than in September. Thus, early application is recommended, provided that conditions for application and incorporation are favourable (Paper II). The effect of structure liming can thus be fine-tuned at farm level.

The importance of tillage for the outcome of structure liming was demonstrated, with calcium hydroxide giving a more positive yield response in non-inversion primary tillage than with mouldboard ploughing (Paper I). Tillage before and after liming also affected aggregate stability in a discriminant analysis (Paper III). However, the relative importance of tillage variables on the outcome of structure liming on aggregate stability needs further investigation.

6.4 Calcium ions governed the effect

Structure lime and calcium hydroxide affected structure stability equally (Paper I), as did structure lime in comparison with ground limestone (Paper IV). These similarities between the three liming products indicate that it was the Ca ion *per se*, rather than the chemical form (compound), that governed the effect on aggregate stability in these studies. This preliminary conclusion was further strengthened by findings on the duration of aggregate stability in follow-up measurements one and six years after lime application (Paper VI). There was a significant increase in aggregate stability from structure lime compared with the unlimed control of approximately 30% after one year. After six years structure liming still significantly improved aggregate stability, but the effect declined over time to 10%. There was also an interaction between trial and treatment (Paper VI). Six years after structure liming, a significant effect only persisted at one of eight field trials where initial pH was sufficiently low and clay content sufficiently high. This led to a tentative recommendation that structure liming should be targeted at soils with pH below 7 and clay content above 25%, but further studies are needed to validate this recommendation.

6.5 Cation exchange was the dominant stabilisation mechanism

The focus of the work in this thesis was on if, when and where structure liming is an effective measure to stabilise soil aggregates, and not on the type of mechanisms involved in the stabilisation process. For this reason, no detailed mineralogical studies (*e.g.* X-ray diffraction, XRD), were performed. However, the similar results on aggregate stability from different liming products (Papers I, IV) and the declining effect over time (Paper VI) indicate that cation exchange was the dominant mechanism behind aggregate stabilisation. Modification and stabilisation of clay soil also involves carbonation and pozzolanic reactions. For the latter, non-carbonated lime and an alkaline environment are required to dissolve clay aluminosilicates and produce new cementitious products. Whether any such processes actually occurred in the studies presented in this thesis cannot be verified. Ongoing studies (continuation of the work in Paper IV) will however indicate whether similarities between different liming products regarding aggregate stability change over time or not. The current conclusion, based on the results available, is that calcium ions must be replenished to maintain an effect on aggregate stability. Future studies using XRD or differential thermogravimetric analysis (DTA) to scrutinise the processes involved can bridge the knowledge gap.

6.6 Agronomic properties improved

The knowledge gap on the stabilisation processes involved is mainly of academic interest, but the effects of structure lime on agronomic properties are of high practical interest. Structure lime gave a finer tilth, measured as a higher proportion of aggregates <2 mm and a lower proportion of aggregates >5 mm (Papers I, IV). A finer tilth means that fewer passes are needed at seedbed preparation and that crops can establish more easily. It also provides crop security under dry conditions, when small aggregates act as a barrier to evaporation. This effect can probably explain the results obtained in this thesis.

Draught requirement was reduced as a general consequence of structure lime application (Paper V). Lower draught requirement is equally important at farm and environment level as it means lower diesel consumption, which in turn means decreased emissions of CO_2, and therefore benefits both the farmer and the environment. Together, a finer tilth and reduced draught requirement as a consequence of structure lime application make clay soils easier to till and cultivate, bringing added value at farm level.

6.7 Rise and fall of pH

Structure liming increased pH by 0.3-0.5 units when measured approximately 1-1.5 years after liming (Papers I, IV, VI). This pH increase has an economic value if the structure-limed soil has a liming requirement according to target pH values. The pH increase lasted for different periods of time in different studies when measured 3-6 years after liming, but generally the pH increase was moderate and temporary. Nevertheless, micronutrient availability was decreased in CAT-extractions in soil (Paper IV, section 5.1.5). This decrease was reflected in lower levels of *e.g.* Mn in biomass of spring barley (Paper IV) and in barley grain (Paper I, section 5.1.5). Decreased content of Mn in barley grain was observed despite pH not being significantly affected four years after liming (Paper I), which was a lingering and unwanted side-effect.

6.8 Crop responses were inconsistent

Crop responses to structure lime were inconsistent. Both increases and decreases in cereal yields of 10% were recorded (Paper I), along with no significant yield increase in spring barley despite early increases in shoot number, N uptake and biomass (Paper IV).

Soil is a complex system and links between soil and crop response are seldom clear-cut, so explanations for yield increases or decreases following structure liming can vary depending on soil properties. Two such contrasting examples were demonstrated in this thesis. At one site where initial pH was

7.0-8.2 before liming, decreased availability of micronutrients in soil and decreased plant nutrient content in barley grain possibly explained observed tendencies for yield decreases. This indicates risks with structure liming on calcareous soils. At another site with initial pH 6.2-6.6, yields of spring barley tended to increase (17-19%) with application of structure lime. A conceivable explanation was a finer tilth protecting the soil from evaporation. Future studies should clarify the causal links between structure lime, aggregate size distribution and crop water balances.

The overall conclusions obtained in this thesis regarding the effect of structure lime are summarised graphically in Figure 26.

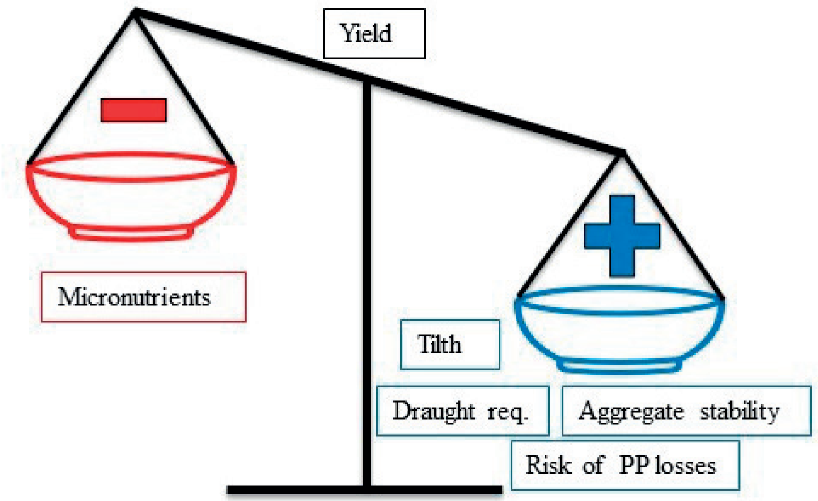


Figure 26. Advantages/disadvantages of structure liming identified in this thesis: Decreased micronutrient availability on calcareous soils (left), but well outweighed by stabilisation of aggregates and decreased risk of particulate phosphorus losses, plus agronomic improvements as a finer tilth and reduced draught requirement (right).

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Popular science summary

Losses of phosphorus (P) from Swedish agricultural land amount to approximately 0.4 kg per hectare and year. These losses can contribute to eutrophication in many inland surface waters in Sweden and in the Baltic Sea, so mitigating measures are needed. Losses of P from clay soils are dominated by so-called particulate P (PP), *i.e.* P associated to clay particles. To counteract losses of PP from clay soils, structure lime (80-85% ground limestone ($CaCO_3$) and 15-20% slaked lime ($Ca(OH)_2$) is applied. When clay and the calcium ions in structure lime react, different processes take place, resulting in aggregate stabilisation. Stabilised clay aggregates do not break down when exposed to *e.g.* rain, and are less prone to lose associated PP. In the period 2010-2021 approximately 65,000 hectares of Swedish clay soils were structure-limed.

This thesis evaluated the effect of structure lime, primarily on aggregate stability but also on crop response and on important agronomic features, such as soil tilth and draught requirement (mechanical tillage resistance).

Soil aggregates (mean diameter 2-5 mm) were sampled 1-2.5 years after structure lime application and subjected to rainfall events in a rain simulator. To quantify aggregate stability, the turbidity (cloudiness) in leachate from the aggregates was measured, where high turbidity meant that aggregates were broken down and low turbidity meant that aggregates remained intact. Turbidity was therefore used as a proxy for aggregate stability and the risk of PP losses. Aggregate stability increased by approximately 15-35% with a standard application rate of 8 t per hectare of structure lime, so on average for all clay soils, structure liming proved to be an effective measure for reducing the risk of PP losses. However, different soils reacted differently to structure lime. Structure lime proved more effective in stabilising aggregates in soils with high clay and organic matter content, low initial pH and a low proportion of swelling clay minerals. Follow-up studies six years after structure liming showed declining effects on aggregate stability, leading to a tentative recommendation that clay soils with pH below 7 and a clay content above 25% should be given priority.

Structure liming gave better aggregate stability when performed in August, compared with September, as the soil had a higher proportion of small aggregates in August, permitting closer contact between soil and lime. This means that management of structure liming (timing and incorporation) is of great importance for the outcome.

Application of structure lime needed a fine tilth to get a good outcome in terms of aggregate stability, but also improved the tilth, measured as a higher proportion of small aggregates and a lower proportion of coarse aggregates. In addition, structure lime reduced the draught requirement by 7% for a tractor pulling a cultivator with 4 m working width through clay soil at 12 cm working depth. On farm level, this effect of structure lime means fewer passes are needed to create a seedbed with a favourable tilth, lowering diesel consumption. From an environmental point of view, this lower draught requirement means reduced CO_2 emissions.

Crop response to structure lime was inconsistent, resulting in both increases and decreases in spring barley yields of 10%. Decreased availability of micronutrients due to lime-induced increases in pH can possibly explain the yield decreases, while the yield increases can be attributed to a finer tilth as an effect of structure liming. They can also be attributed to many other effects of liming on soil, such as changes in pH, nutrient availability and water-holding properties.

Populärvetenskaplig sammanfattning

Förlusterna av fosfor (P) från svensk jordbruksmark uppgår till cirka 0,4 kg per hektar och år. Dessa förluster kan bidra till övergödning eftersom P är ett tillväxtbegränsande ämne i många ytvatten i Sverige och i Östersjön. Av det skälet behövs motåtgärder. Förluster av P från lerjord domineras av s.k. partikulär fosfor (PP) d.v.s. av P som binds till jordens lerpartiklar. För att motverka förluster av PP sprids strukturkalk – blandningar av 80-85 % kalkstensmjöl ($CaCO_3$) och 15-20 % släckt kalk ($Ca(OH)_2$) – på lerjordar. När ler och kalciumjoner i strukturkalken reagerar sker olika processer som resulterar i aggregatstabilisering. Stabiliserade leraggregat bryts inte ner av t.ex. regn och blir mindre benägna att förlora den partikulära fosforn. Under perioden 2010-2021 strukturkalkades cirka 65 000 hektar svenska lerjordar.

Denna avhandling utvärderade i första hand effekten av strukturkalk på aggregatstabilitet. Dessutom undersöktes också effekten på avkastning samt på viktiga agronomiska egenskaper som aggregatstorleksfördelning och dragkraftsbehov.

Leraggregat (medeldiameter 2-5 mm) provtogs 1-2,5 år efter kalkspridningen, och aggregaten utsattes för bevattningar i en regnsimulator. För att kvantifiera aggregatstabiliteten mättes turbiditeten (grumligheten) i lakvattnet från aggregaten. Hög grumlighet innebär att aggregat brutits ner, medan låg grumlighet innebär att aggregat behållits intakta. Grumlighet är därför en uppskattning av aggregatstabiliteten och därmed risken för PP-förluster. Aggregatstabiliteten ökade med ca 15-35% med en normalgiva av 8 ton strukturkalk per hektar. I genomsnitt för alla lerjordar visade sig alltså strukturkalkning vara en effektiv åtgärd för att minska risken för PP-förluster. De olika jordarna reagerade dock olika. Bäst aggregatstabiliserande effekt hade strukturkalkningen på jordar med hög ler- och mullhalt, lågt start-pH och med låg andel svällande lermineral. En uppföljande studie sex år efter strukturkalkning visade minskande aggregatstabilitet med tiden, vilket leder till en preliminär rekommendation att lerjord med ett pH under 7 och ett lerinnehåll över 25% bör prioriteras för åtgärderna.

Strukturkalk gav bättre aggregatstabilitet när den utfördes i augusti jämfört med september, eftersom jorden i augusti var mer finbrukad. Fler små aggregat tillät en större kontaktyta mellan jord och kalk. Det visar att själva utförandet (tidpunkt och nedbrukning) av strukturkalkningen är av stor betydelse för slutresultatet.

Strukturkalk behövde inte bara en finbrukad jord för att öka aggregatstabiliteten. Strukturkalken gjorde också att jorden fick en högre andel fina och en lägre andel grova aggregat. Dessutom minskade strukturkalk dragkraftsbehovet med 7% för en traktor som drog en 4 m bred kultivator genom en lerjord på 12 cm arbetsdjup. På gårdsnivå innebär effekten av strukturkalk färre överfarter för att skapa en såbädd med gynnsamt bruk. Det innebär också lägre dieselförbrukning. Ur miljösynpunkt innebär lägre dragkraftsbehov minskade koldioxidutsläpp.

Grödans svar på strukturkalk var motsägelsefullt, vilket visade sig som både ökade och minskade vårkornsskördar med 10 %. Minskad tillgänglighet av mikronäring på grund av strukturkalkningens pH-höjning kan möjligen förklara skördesänkningarna. Skördeökningarna å andra sidan kan hänga samman med ett finare bruk, eller andra egenskaper som förändras vid strukturkalkning såsom t.ex. pH, växtnäringstillgång och vattenhållande egenskaper.

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

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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 ($Ca(OH)_2$) and a mixed product of calcium carbonate ($CaCO_3$) and slaked lime ($Ca(OH)_2$), were applied at three different rates in field trials on clayey soils (23%–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.

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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).

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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).

Treatments

Three of the trials (8501A, 8501B and 8502) had four replicates in a randomised block design in which different levels of slaked lime ($Ca(OH)_2$) and a mixed product named Nordkalk Aktiv Struktur (NKAS) consisting of $Ca(OH)_2$ 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).

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

Table 1. Soil organic matter (SOM) and soil texture (% of all material <2 mm) in the topsoil at the four trial sites.

Trial	SOM	Sand (>2000µm)	Silt (200–2000µm)	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

Note: Texture analysis by laser scanning, which generally gives lower levels of clay than conventional sedimentation analysis.

Table 2. Nutritional status in topsoil of untreated control plots at the four trial sites.

Trial	CEC (pH7) me kg^{-1}	Base sat. %	pH H$_2$O	P-AL[a] (class) mg kg^{-1}	P-HCl[b] (class) mg kg^{-1}	K-AL[a] (class) mg kg^{-1}	K-HCl[b] (class) mg kg^{-1}	Mg-AL[a] mg kg^{-1}	Ca-AL[a] mg kg^{-1}	K/Mg quota	Cu-HCl[b] 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

Note: Sampling in October 2013 in two of four replicate plots.

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

[b] Extraction 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.

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
Normal	*− 4.4*	*− 4.6*	*− 1.1*	*3.9*	*10.2*	*15.0*	*16.3*	*15.1*	*10.8*	*6.4*	*1.2*	*− 2.8*
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
Normal	*34.0*	*25.0*	*26.0*	*29.0*	*33.0*	*46.0*	*70.0*	*66.0*	*57.0*	*50.0*	*51.0*	*41.0*

Note: Normal refers to period 1961–1990 with data from Karlsson and Fagerberg (1995).

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 drilling 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 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).

Treatment	Levels of liming product[a,b]
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)$_2$

Note: Numbers 1, 2 and 6 in Treatment designation refers to liming level (CaO t ha^{-1}).

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

[b] The mixed lime NKAS consisted of 82% CaCO$_3$ and 18% Ca(OH)$_2$ by weight.

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 h at 20°C and then the procedure was repeated. The turbidity of the

Table 5. Crops and levels of fertiliser (kg ha^{-1}) in the field trials 2011–2014.

	2011				2012				2013				2014			
Trial	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	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

Note: 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.

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 and 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 (5–15 cm in accordance with indication above) 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 (HNO_3) 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.

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.

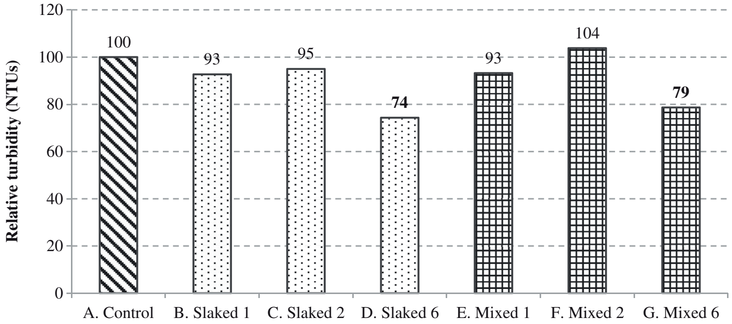

Figure 1. Relative turbidity of 2–5 mm aggregates from the drilled seedbed in May 2013 in treatments applying CaO as calcium hydroxide ($Ca(OH)_2$) (Slaked) or as a mixture of calcium carbonate ($CaCO_3$) and calcium hydroxide ($Ca(OH)_2$) (Mixed) in trials 8501A, 8501B and 8502. Control treatment (A) = 100. Significant reductions in turbidity in comparison with the control are indicated in bold.

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.

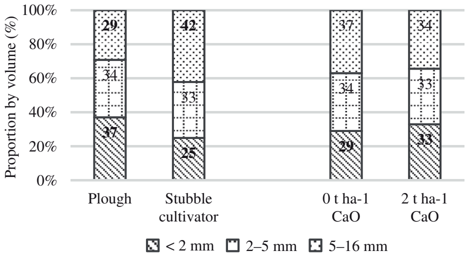

Figure 2. Seedbed aggregate size distribution in trial 8503, May 2013. Plough and stubble cultivator (factor 1) refer to primary tillage conducted in autumn 2010, 2011 and 2012. Structure lime with CaO levels of 0 and 2 t ha^{-1} (factor 2) refers to application in October 2010. Results are grand means 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.

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

Table 6. pH (H_2O) in December 2011 and September 2012 and pH (H_2O) and electrical conductivity (EC) in October 2013 in trials 8501A, 8501B and 8502.

	8501A				8501B			8502		
Treatment	pH Apr – 11	pH Sept – 12	pH Oct – 13	EC Oct – 13 (µS/cm)	pH Sept – 12	pH Oct – 13	EC Oct – 13 (µS/cm)	pH Dec – 11	pH Oct – 13	EC Oct – 13 (µS/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	6.30	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

Note: Significant differences compared with the control are indicated in bold.

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.

Table 7. pH (H_2O) in September 2012 and pH (H_2O) and electrical conductivity (EC) in October 2013 in trial 8503.

Treatment	pH Sept -12	pH Oct -13	EC Oct -13 (µS/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 cult., 0 t ha^{-1} CaO as $Ca(OH)_2$	7.28	6.76	146
S2. Stubble cult., 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

Note: Significant differences are indicated in bold.

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.

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 t 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.

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.

	2011 (oats)		2012 (oats)		2013 (sp barley)		2014 (sp barley)		2011–2014	
Treatment	Yield.	Rel.	Yield.	Rel.	Yield.	Rel.	Yield.	Rel.	Yield.	Rel.
A. Control	5310	100	5310	100	5810	100	5020	100	5360	100
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)	

Note: Significant values compared with the control are indicated in bold. LSDs within brackets indicate a non-statistically significant value.

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.

	2011 (oats)		2012 (oats)		2013 (sp barley)		2014 (sp barley)		2011–2014	
Treatment	Yield.	Rel.	Yield.	Rel.	Yield.	Rel.	Yield.	Rel.	Yield.	Rel.
P0. Plough, 0 t ha^{-1} CaO	3970	100	5850	100	5760	100	5260	100	5210	100
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	100	5890	100	5950	100	5210	100	5270	100
S. Stubble cultivator	4060	100	6150	104	5440	91	5100	98	5190	98
0 t ha^{-1} CaO as $Ca(OH)_2$	4030	100	6080	100	5450	100	5040	100	5150	100
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	

Note: Significant values compared with the control are indicated in bold. LSDs within brackets indicate a non-statistically significant value.

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.

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

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.

	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

Note: 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.

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.

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 t ha^{-1} 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 t ha^{-1} 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 ($Ca(OH)_2$) 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 ($Ca(OH)_2$). 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).

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.

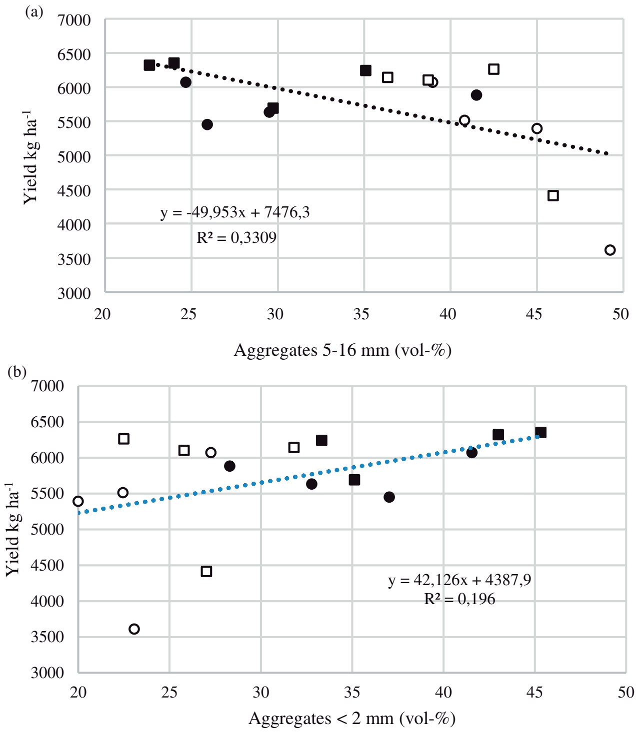

Figure 3. Correlation between aggregate size in seedbed and yield in 2013 in trial 8503. a) aggregates 5–16 mm ($R^2 = 0.33$; $p = 0.020$) and b) aggregates <2 mm ($R^2 = 0.20$; $p = 0.086$). Black circle = plough, 0 t ha^{-1}, black box = plough, 2 t ha^{-1}, white circle = tine, 0 t ha^{-1}, white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

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).

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

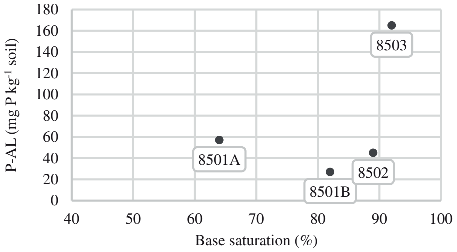

Figure 4. Degree of base saturation and available phosphorus (P-AL) in two of four untreated plots at the trial sites in October 2013.

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.

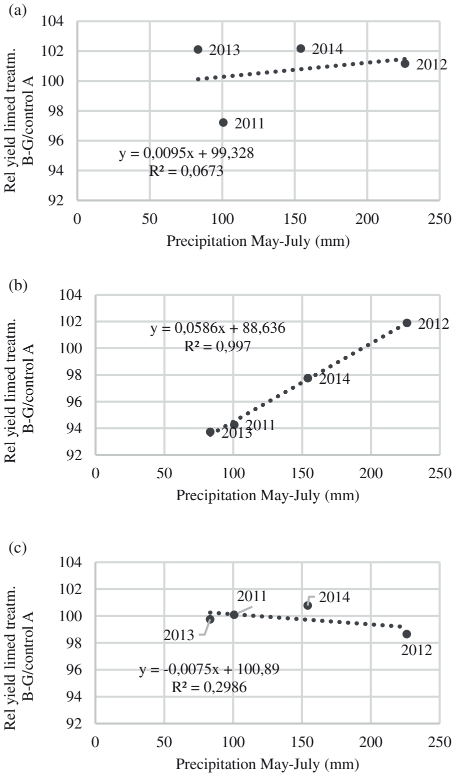

Figure 5. Mean relative yield in structure-limed treatments (B-G) relative to the untreated control (A = 100) in relation to yearly precipitation 2011–2014 in May-July in trials a) 8501A ($R^2 = 0.07$; $p = 0.741$), b) 8501B ($R^2 = 1.0$; $p = 0.002$) and c) 8502 ($R^2 = 0.30$; $p = 0.454$).

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.

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II

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Timing and conditions modify the effect of structure liming on clay soil

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Two dates (early, normal) for application and incorporation of structure lime to clay soil were examined at four field sites, to test whether early liming had more favourable effects on aggregate stability. Aggregate size distribution measurements revealed a finer tilth at the early liming date (20 August) than the normal date (14 September). Aggregate stability estimated one year later, using as a proxy turbidity in leachate from 2–5 mm aggregates subjected to two simulated rainfall events, was significantly improved (11% lower turbidity) with early compared with normal liming date. Three years after structure liming, soil structural stability measurements on lysimeters (15 cm high, inner diameter 18 cm) subjected to repeated simulated rainfall events showed no significant differences in turbidity in leachate between the early and normal liming dates. However, there was a strong interaction between liming date and site indicating different reactions at different sites. Our results suggest that early spreading and incorporation can improve the success of structure liming, but only if soil conditions are favourable.

Key words: structure lime, aggregate stability, structural stability, turbidity, phosphorus, timing

Introduction

Under the EU Water Framework Directive as implemented in Swedish legislation, structure liming qualifies for an environmental subsidy of up to 50% of the cost, in order to reduce phosphorus losses to surface waters through increased soil aggregate stability. In the period 2010–2020, approximately 60000 hectares of clay soil in Sweden were structure-limed with blends of $CaCO_3$ and $Ca(OH)_2$. In the coming six years it is recommended by the Swedish Water Authorities that close to 500000 hectares of clay soils in Sweden should be structure limed in order to fulfil the commitment of the EU Water Directive (VISS 2021). It is very important that these liming measures are carried out in an appropriate way.

Liming has multiple impacts on soils, affecting chemical, biological and physical properties (Holland et al. 2018). Soil aggregate stability can be influenced by applying different forms of lime, e.g. calcium carbonate (limestone, agricultural lime, $CaCO_3$), calcium oxide (quicklime, burnt lime, CaO) or calcium hydroxide (hydrated lime, slaked lime, $Ca(OH)_2$). The mode of action is probably a result of both chemical form and the calcium ion per se. The speed at which liming alters soil structure is dependent on the solubility and particle size of the added lime, and also on the buffering capacity of the soil (Holland et al. 2018). When structure lime, i.e. CaO or $Ca(OH)_2$, either in pure form or in mixtures with $CaCO_3$, encounters clay, different reactions take place on microaggregate level. These include cation exchange, flocculation and agglomeration, carbonation (where lime and carbon dioxide from air form calcium carbonate) and pozzolanic reactions/cementation (where lime, silicon and aluminium form new cementing products) (Choquette et al. 1987). Adding $CaCO_3$ can also influence aggregate stability, probably through cation exchange and flocculation, but not through carbonation and pozzolanic reactions (Berglund 1971). Cation exchange is a relatively rapid reaction that typically takes place within a day (Al-Mukhtar et al. 2012). Pozzolanic reactions are very slow at normal soil temperatures, with reaction times from a week up to years at low temperatures (Al-Mukhtar et al. 2012). If the temperature falls below around 4 ˚C, pozzolanic reactions can cease until the temperature increases again (Bell 1996).

The reactions between structure lime (pure $Ca(OH)_2$ or in mixtures with $CaCO_3$) and clay have been shown to improve aggregate stability, and thereby reduce clay soil erosion (Alakukku and Aura 2006). This leads to decreases in the associated risk of phosphorus losses from soils (Blomquist et al. 2018, Eslamian et al. 2018, Eslamian et al. 2020). A phosphorus leaching mitigating effect of structure lime (CaO) on clay soil of marine origin (permanent cracks in the subsoil) has been demonstrated by Ulén and Etana (2014) and Svanbäck et al. (2014). Gypsum ($CaSO_4$) also has the capacity to bring about substantial decreases in turbidity and phosphorus losses (Uusitalo et al. 2012). Quicklime (CaO) application has been shown to improve clay soil structure in laboratory experiments (Berglund 1971) and to increase soil aggregate stability in greenhouse pot experiments with silty/clayey soils

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(Keiblinger et al. 2016). Structure lime ($CaCO_3$ mixed with $Ca(OH)_2$) can also result in finer aggregate size distribution in the seedbed (Blomquist et al. 2018).

Results from 30 field trials in southern Sweden (manuscript submitted) showed a significant increase in aggregate stability measured one year after liming, with increasing structure lime application rate. However, the results also revealed that reactions to structure liming differed between soils, with the outcome depending on soil variables, clay content in particular, but also clay mineralogy, soil organic matter content and initial pH. Management factors at application, such as tillage and timing, also played important roles. These management factors are the subject of the present study.

Under Swedish conditions, soils are often most friable and workable in early autumn, resulting in a finer tilth and facilitating contact between structure lime and soil. Compared with surface spreading or combined liming-direct drilling, liming followed by tillage has been shown to have greater effects on aggregate stability (Valzano et al. 2001) and pH (Joris et al. 2016). Field mixing, compared to more thorough mixing of lime into the soil, has been shown to significantly reduce the incidence of clubroot (*Plasmodiophora brassicae*) (Dobson et al. 1983). This indicates the importance of close contact between soil and lime to achieve the desired soil physical, chemical and biological effects. Soil temperatures are also higher in early (August) than late (September) autumn, providing better conditions for the temperature-dependent pozzolanic reactions (Bell 1996).

The aim of this study was to investigate whether timing of structure liming alters the effect on aggregate stability. The hypothesis tested was that spreading and incorporating structure lime in early autumn results in better aggregation and soil structure stability than structure liming later in autumn.

Materials and methods

Sites and trial design

Four field sites with clay soils were selected in different parts of Scania, southern Sweden, in order to cover different soil conditions. The trial at all sites had a randomised block design with four replicates and compared two dates for spreading and incorporation of structure lime: early and normal. Both involved incorporation of a standard dose of 8 t ha^{-1} Nordkalk Aktiv Struktur (NKAS), a mixture of approximately 80–85% ground limestone and 15–20% slaked lime (Table 1).

Table 1. Chemical composition of the liming product Nordkalk Aktiv Struktur (NKAS) used in the trial. Nutrients and compounds are expressed as concentrations of dry matter. Water content 15–25% depending on storage. Bulk density 1 g cm^{-3}. Source: Nordkalk Corp

Macronutrient	Concentration (%)	Micronutrient	Concentration (mg kg^{-1})
CaO	50.0	Cd	1.8
Mg	1.0	Co	9
SiO_2	5.4	Cr	26
Al_2O_3	3.4	Cu	44
Fe_2O_3	1.5	Hg	< 0.02
K	2.5	Ni	28
Na_2O	0.6	Pb	59
S	1.7	Zn	290
P	0.07		

Plots without lime were not included in these trials, both for practical reasons and since application rates (0, 4, 8, 16 t ha^{-1}) were tested in parallel studies. Sites, site coordinates and the dates of early and normal liming at the different sites are shown in Table 2.

The pre-crop at all four sites was winter oilseed rape, an early-maturing crop, to enable early and normal liming dates with a reasonable number of days in between under Swedish conditions. On average for the four sites, the early liming date was 20 August, the normal liming date was 14 September and there were 25 days between the dates (Table 2).

Table 2. Trial site coordinates, dates of spreading and incorporation in autumn 2015, type of tillage equipment used and number of passes. Disc cultivator (Väderstad Carrier), tine cultivators (Väderstad Cultus, Väderstad Opus, Väderstad Swift, Lemken Thorit), combination cultivator with discs and tines (SMS Finisher)

Site	Coordinates	Early date	Early incorporation/ tillage	Normal date	Normal incorporation/ tillage
Krageholm	55.49˚N, 13.76˚E	26 August	2 x Väderstad Carrier + 2 x Väderstad Cultus	15 September	3 x Väderstad Cultus
Krapperup	56.18˚N, 12.70˚E	10 August	2 x Lemken Thorit	11 September	2 x Lemken Thorit
Råbelöf	56.08˚N, 14.18˚E	19 August	2 x Väderstad Cultus	7 September	2 x Väderstad Opus
Kornheddinge	55.63˚N, 13.26˚E	24 August	2 x SMS Finisher	21 September	2 x Väderstad Swift

The structure lime was incorporated within one day after application, with equipment available at the time on the farms at the trial sites (Table 2). Mouldboard ploughing was not carried out after incorporation, and all sites were drilled with winter wheat after the second (normal) spreading and incorporation. All sites were harvested in 2016 for yield measurements, including protein, starch and specific grain weight (data not shown but commented in the Result section)

Soil texture and chemical properties

Before the start of the study, soil samples were taken from all plots for analysis of soil characteristics (Table 3). The soils at the four sites had pH values, clay and soil organic matter contents representing normal ranges on agricultural soil in Scania. Soil at three of the sites had normal levels of plant-available phosphorus, while the Råbelöf soil had a very low level of soil phosphorus (Table 3).

Weather data from spreading and sampling years (2015, 2016 and 2018) including mean monthly air temperature and precipitation for the 30-year average period (1991–2020) at official meteorological stations nearest the sites are summarised in Supplementary Tables 1 and 2.

Table 3. Texture and soil nutritional status in topsoil (0–20 cm) at the four trial sites in August 2015, prior to structure liming.

Site	SOM[a]	Sand[b] > 60 µm	Silt[c] 2–60 µm	Clay[d] < 2 µm	pH H_2O	P-AL[e] mg kg^{-1}	K-AL[e] mg kg^{-1}	Mg-AL[e] mg kg^{-1}	K/Mg quota	Ca-AL[e] mg kg^{-1}
Krageholm	3.2	16.3	50.1	33.6	6.3	69	139	150	0.9	2660
Krapperup	3.7	58.8	19.9	21.3	7.4	66	151	148	1.0	3310
Råbelöf	4.1	9.1	50.4	40.5	6.6	20	169	286	0.6	3610
Kornheddinge	3.0	42.0	33.7	24.3	7.8	71	138	159	0.9	4200

[a] Soil organic matter, measured as loss on ignition; [b] Wet sieving; [c] Calculated as difference between the sand and clay fractions; [d] Hydrometer sedimentation; [e] Extraction with 0.1 M ammonium lactate + 0.4 M acetic acid, pH 3.75 (Egnér et al. 1960).

Tillage depth and aggregate size distribution after liming

Tillage depth and aggregate size distribution were measured within three days after lime spreading and incorporation in 2015. Aggregate size distribution was categorised using a total of eight different size classes. First, the tilled soil passed through sieves with coarse mesh in five different size classes (average diameter >64 mm, 32–64 mm, 16–32 mm, 8–16 mm and <8 mm). The finest fraction (<8 mm) was passed through sieves with finer mesh in three different size classes (average diameter >5 mm, 2–5 mm and <2 mm). Unfortunately, the Krapperup site was hit by a heavy thunderstorm (rainfall not measured) shortly after spreading and incorporation at the early date (10 August). As a result, tillage depth could not be measured three days later, on 13 August, and aggregate size distribution could only be measured to shallow depth, and with great difficulty, at the very top of the tilled soil.

Sampling of soil for aggregate stability one year after liming

Measurements of aggregate size distribution were repeated after harvest in August 2016 approximately one year after spreading and incorporation of the structure lime. Soil samples for aggregate stability testing were taken at the same occasion. Sampling was carried out after two passes with implements resulting in shallow tillage to 6–8 cm depth. The loose soil samples were passed through sieves in three different size classes (>5 mm, 2–5 mm, <2 mm), as described above. Aggregates with diameter 2–5 mm were placed in dry, aerated containers and stored for rainfall simulations and turbidity measurements.

Sampling of soil for structure stability three years after liming

Lysimeters consisting of PVC pipes (height 15 cm, inner diameter 18 cm) were centrally placed in the trial plots (one lysimeter per plot) after removal of crop residues in 2018. The lysimeters were forced perpendicularly into the soil using a loader mounted on a tractor. The surrounding soil was then removed with a shovel and the lysimeters were extracted with a margin of undisturbed soil underneath. The top and bottom of the lysimeters were protected with plastic lids and styrofoam, and they were placed in plastic bags and stored at 4 ^{o}C until measurements were performed. At all trial sites, shallow tillage had been performed before sampling, meaning that the top of the soil columns was disturbed. At Krapperup 20 t ha^{-1} of pig slurry was incorporated on 29 August 2018 seven days before lysimeter extraction.

Aggregate and structure stability and associated risk of phosphorus losses

Aggregate stability was determined in the laboratory by applying simulated rainfall to air-dried aggregates (average diameter 2–5 mm) (Almajmaie et al. 2017). Irrigation (representing artificial rainwater) was applied at an intensity of 32–39 mm per hour on two occasions 24 hours apart (aggregate irrigations A1 and A2). The irrigation boom moved back and forth continuously without stopping at the ends during irrigation, so the aggregates were subjected to simulated rain for five minutes in the one-hour period. The leachate was collected after each event, and turbidity and electrical conductivity (EC) in the leachate were determined (Turb. A1/A2, EC A1/A2). Before the turbidity measurements, the soil-water suspension was agitated in a shaker for 10 minutes and allowed to sediment for 4.5 hours. A sample of the suspension was then taken at 5.6 cm depth and the turbidity was measured using a Hach TL 2360 Turbidimeter (Hach, Loveland, Co.). Turbidity in leachate indicates the concentration of clay in the suspension, and is thereby a proxy for aggregate stability and particulate phosphorus losses (Puustinen et al. 2005, Ulén et al. 2012).

The lysimeters taken at the four sites three years after liming (2018) were subjected to two simulated rainfall events (lysimeter irrigations L1 and L2), as described above for soil aggregates, but at an intensity of only 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. L2) and also for concentrations of total phosphorus (Tot-P) and dissolved phosphorus (PO_4-P). Tot-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 phosphorus (Part-P) was estimated as the difference between Tot-P before and after filtration of leachate with the same filters. Only turbidity and EC data from the second simulated rainfall event (Turb. A2, Turb. L2, EC A2) are reported, as differences between treatments were clearer after the second rainfall event.

Statistical analyses

Analysis of variance (ANOVA) was performed on aggregate size distribution (General Linear Model in Minitab 18, Minitab Inc.) and on log-transformed data on turbidity, EC and concentrations of different phosphorus fractions. 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 absolute and relative values.

Results

pH and yield effects

Liming significantly increased pH (p=0.000), plant-available phosphorus (p=0.000) and calcium content (p=0.000) when comparing soil nutritional status before (2015) and after (2016) liming. Mean pH increased by 0.7 units (range 0.4–0.9), from 7.0 to 7.7. In 2016 there were no significant differences between the two treatments (early and normal spreading date). Yield of winter wheat after early liming exceeded that after the normal liming date by 3%, or 0.24 t ha^{-1}. However, this difference in yield, and differences in wheat quality parameters such as protein, starch and specific grain weight, were not significant. There were no significant interactions between treatment and site regarding yield of winter wheat in the year following liming.

Tillage depth and aggregate size distribution at liming

At the Krapperup site, tillage depth could not be measured at early liming due to rainfall shortly afterwards, which caused the tilled aggregates to integrate with the underlying untilled soil. Tillage depth on average for the four sites was approximately 12 cm at both liming dates, with consideration of missing values from Krapperup at early liming, and with no significant differences between the dates (Table 4).

Table 4. Average tillage depth (cm) and variation between replicates (range) at the four sites at the early and normal dates for lime spreading and incorporation

Trial site	Early spreading	Normal spreading
Krageholm	11.5 (10.0–12.5)	11.3 (10.0–12.5)
Krapperup	Not measured	15.0 (12.5–18.0)
Råbelöf	15.0 (14.0–18.0)	14.6 (13.5–16.5)
Kornheddinge	7.0 (6.5–7.8)	8.3 (6.3–9.5)

Aggregate size distribution showed significant differences between the dates, with a finer tilth at the early liming date compared with the normal date (Fig. 1). There were significant differences in the proportions of size classes >64 mm (*p*=0.000), 32–64 mm (*p*=0.043), 16–32 mm (*p*=0.000), 8–16 mm (*p*=0.002) and <8 mm (*p*=0.000) between the liming dates.

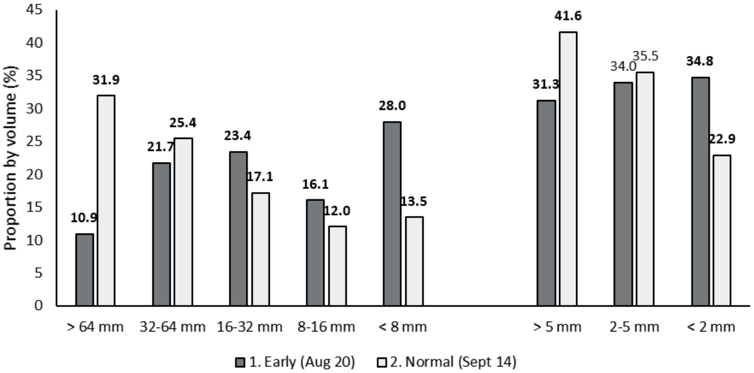

Fig. 1. Aggregate size distribution after spreading and incorporation of structure lime at the early (average 20 August) and normal (average 14 September) dates in 2015. Results of sieving over (left) coarse sieves in five different size classes and (right) fine sieves in three different size classes. Significant differences between treatments (dates) and size classes are indicated in bold. Results and dates are averages for four sites.

However, there were also significant interactions between liming date and site for size fractions >64 mm (*p*=0.036), 8–16 mm (*p*=0.019) and <8 mm (*p*=0.000) meaning that the tillage effects were different at the four trials sites. When the finest fraction (<8 mm) was passed once again over sieves with a finer mesh (>5 mm, 2–5 mm, <2 mm), there were significant differences in the fraction >5 mm (*p*=0.001), with no interaction between site and treatment (*p*=0.070). For the fraction <2 mm, there were significant differences (*p*=0.000) and an interaction between liming date and site (*p*=0.000). For the size fraction 2–5 mm, the same size fraction that was also used in aggregate stability testing in the following year, there was no significant difference between the two liming dates (*p*=0.363).

Aggregate size distribution and aggregate stability one year after liming

Aggregate size distribution was measured again approximately one year later, in August 2016. The results showed a significantly increased proportion of aggregates in size fraction <8 mm (*p*=0.007), and a significantly decreased proportion of aggregates in size fraction >5 mm (*p*=0.007) at the normal liming date compared with early liming.

Turbidity and EC results for all sites combined, and for the four separate sites, are shown in Figure 2. Average turbidity, and therefore loss of soil from aggregates with diameter 2–5 mm, after the second simulated rainfall event (Turb. A2) was significantly lower (*p*=0.026) with early liming than with the normal liming date, with no statistically significant interaction between site and liming date (*p*=0.414). Aggregate soil losses (measured as turbidity) decreased by 11% with early liming, accompanied by a 12% increase (*p*=0.000) in EC (EC A2), again with no significant interaction between site and liming date (*p*=0.256).

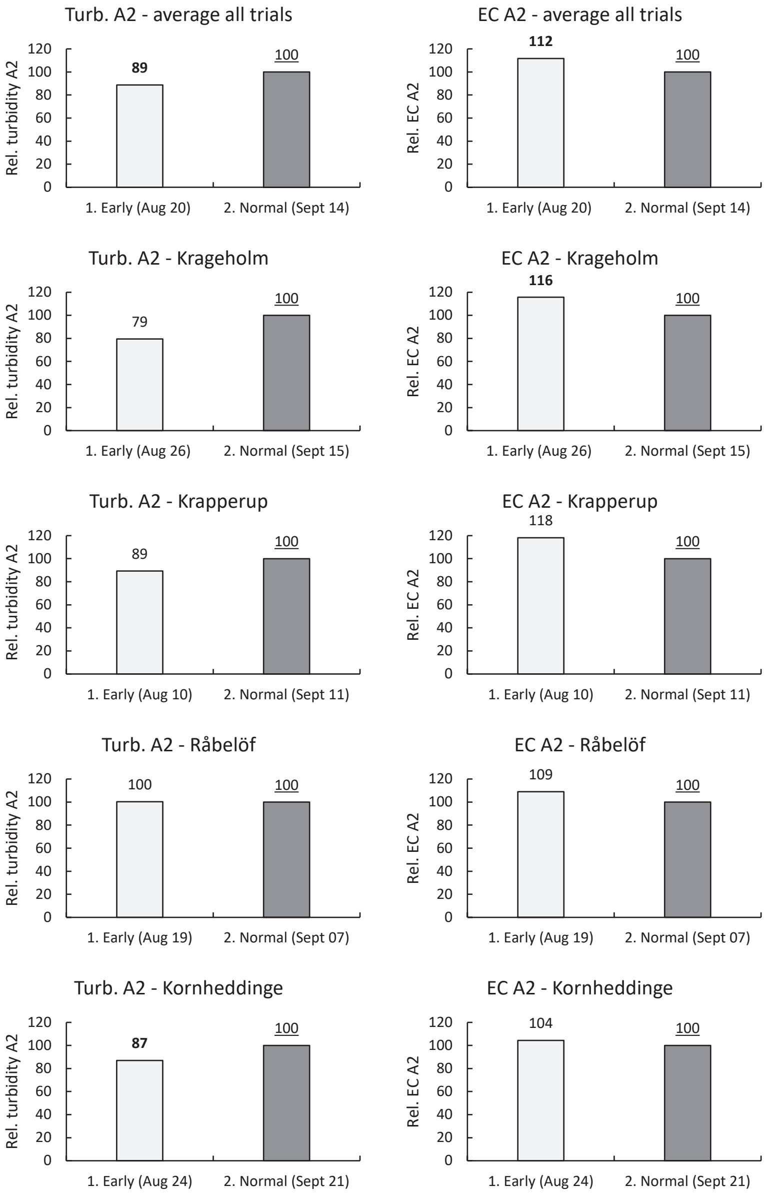

Fig. 2. (Left) Relative turbidity (Turb. A2) values and (right) relative electric conductivity (EC A2) values in leachate from aggregates with diameter 2–5 mm after a second simulated rainfall event, for all sites and for each individual site. Aggregates sampled in August 2016 after two passes with tine or disc cultivator in plots with early and normal spreading and incorporation of lime in August/September 2015 (normal liming date = 100). Significant differences between treatments are indicated in bold.

At the Krageholm site, there was a tendency (*p*-value < 0.1) for differences between the two liming dates in terms of turbidity (*p*=0.061) and a significant difference for EC (*p*=0.022). The Kornheddinge site showed a similar pattern for early and normal liming, with a significant difference between the liming dates for turbidity (*p*=0.035) and a tendency for differences for EC (*p*=0.055) (Fig. 2).

Structure stability and phosphorus concentrations after three years

There were no significant differences between the two liming dates in terms of turbidity L2 (*p*=0.247) or EC L2 (*p*=0.602) in leachate from the undisturbed lysimeters taken three years after liming. There was a significant interaction (*p*=0.010) between site and liming date regarding turbidity L2, making generalisations impossible. Leachate from the lysimeters contained significantly higher concentrations of Tot-P (*p*=0.002) and Part-P (*p*=0.008) with the early liming date. However, there was again a significant interaction between site and liming date (*p*=0.009 for Tot-P; *p*=0.011 for Part-P), as seen in the turbidity results for the lysimeters, so no general conclusions could be drawn. For PO_4-P (dissolved P), there were no significant differences or interactions between site and liming date.

Site-specific differences in structure stability and phosphorus concentrations

Due to the significant interactions between liming date and site, the data on turbidity and phosphorus concentrations in leachate from the lysimeters had to be analysed by site (Table 5). The results for turbidity (structure stability, Turb. L2) were significant for only two of the four sites (Kornheddinge and Krapperup).

Table 5. Turbidity L2, EC L2 and concentrations of total phosphorus (Tot-P), dissolved phosphorus (PO4-P) and particulate phosphorus (Part-P) in leachate from undisturbed lysimeters of soil from the four sites. Significant differences are indicated by different letters. See Table 2 for dates for lime spreading and incorporation.

Site	Treatment	Turb. L2 NTU	EC L2 µS cm^{-1}	Tot-P µg l^{-1}	PO4-P µg l^{-1}	Part-P µg l^{-1}
Krageholm	Early	147	400	320	30	270
Krageholm	Normal	146	367	281	21	244
Krapperup	Early	115a	393	678a	305	312a
Krapperup	Normal	74b	462	315b	111	167b
Råbelöv	Early	968	240	463a	8	448
Råbelöv	Normal	430	290	281b	10	247
Kornheddinge	Early	17b	457	114	48	40
Kornheddinge	Normal	33a	426	128	54	51

For Kornheddinge, the turbidity in leachate from lysimeters was significantly lower (*p*=0.033) at the early liming date, whereas for Krapperup it was significantly higher (*p*=0.012) at the early liming date. The concentrations of the different phosphorus fractions followed the turbidity values reasonably well at Krapperup. For Kornheddinge soil, there were no significant differences between the two liming dates for any phosphorus fraction, whereas for Krapperup the Tot-P and Part-P concentration were significantly higher at the early liming date (Table 5). Råbelöv site also showed significantly increased Tot-P concentrations at early liming date, without turbidity showing significant differences between the treatments.

Aggregate size distribution directly after liming at Kornheddinge and Krapperup

As pointed out earlier there were interactions between the effect of liming date on aggregate size distribution and site. At Kornheddinge, there were clear differences between the two dates in aggregate size distribution directly after liming (Fig. 3).

For the coarser aggregate classes (Fig.3, left), at the early liming date there was a significantly lower proportion of aggregates >64 mm (*p*=0.013) and a higher proportion of aggregates <8 mm (*p*=0.008) at Kornheddinge.

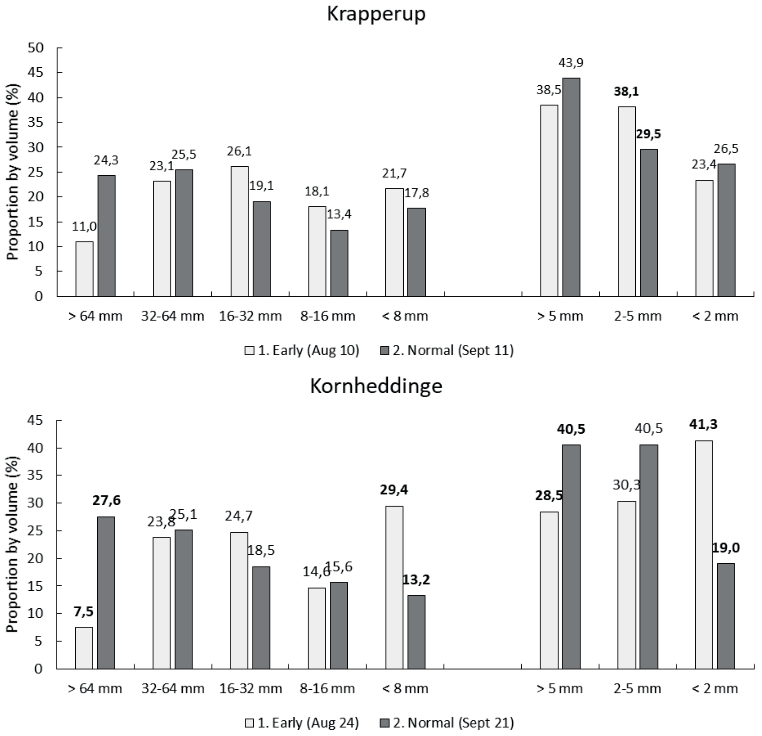

Fig. 3. Aggregate size distribution directly after early and normal spreading and incorporation of structure lime at (upper panel) Krapperup and (lower panel) Kornheddinge, based on sieving over (left) coarse sieves in five different size classes and (right) finer sieves in three different size classes. Significant differences between treatments (dates) and within size classes are indicated in bold.

For the finer aggregate classes (Fig. 3, right), at the early liming date there was a smaller proportion of aggregates >5 mm (*p*=0.017) and a larger proportion of aggregates <2 mm (*p*=0.001). Thus, there was a distinctly finer tilth after early liming compared with liming at the normal date at this site. The tillage implement used for early incorporation at Kornheddinge was a combination cultivator with discs, tines and a reconsolidating packer. For practical reasons, this implement was not available at the normal date, so a tine cultivator was used (Table 2). The less intensive work carried out by the tine cultivator was most probably reflected in the coarser tilth at the normal date.

At Krapperup, there were only significant differences in the aggregate fraction 2–5 mm, with a higher proportion (*p*=0.030) at the normal liming date. The same combination cultivator with the same adjustments was used at both dates at this site, apparently leaving the tilled soil with approximately the same tilth on both occasions.

Discussion

Finer tilth at early liming

This study examined whether timing of structure lime spreading and incorporation influences the effect. In Sweden, an early date (August) normally provides a more workable soil with a finer tilth, and a higher temperature. The solubility of lime would be improved under moist conditions, however the soil must be sufficiently dry to permit tillage with minimised damage to soil structure. The specific hypothesis tested in this study was that spreading and incorporating structure lime in early autumn results in better aggregation and soil structure stability than structure liming later in autumn.

Measurements of aggregate size distribution immediately after spreading and incorporation of structure lime verified that conditions were more favourable at the early liming date (mean 20 August) than at the normal date (mean 14 September). On average for all four sites, there were significant differences in all aggregate size classes except 2–5 mm diameter, with a distinct shift towards a finer tilth at the early compared with the normal liming date.

Particle size of the lime is a factor that determines the dissolution and the effect on soil properties. A study comparing different particle sizes of magnesium limestone found that the finest fraction (<0.25 mm) was best for increasing soil pH (Álvarez et al. 2009). This fraction also had a significant negative effect on soil phosphorus availability in the short term (9 months), which was not the case with coarser fractions (>2 mm, >4 mm) (Viade et al. 2011). If small particle size of the lime product used is a determinant for maximising the surface area available for dissolution, maximum contact between lime and soil should also logically be achieved with a finer tilth compared with a coarser tilth. Since it is reasonable to expect an effect of particle size of both lime and soil, tillage presumably affects the outcome of liming in terms of soil to lime contact area.

Increased aggregate stability at soil surface

The finer tilth at the early liming date can probably explain the improvement in aggregate stability observed one year after liming. The improvement in aggregate stability achieved by liming can thus be partly attributed to the weather and tillage advantage provided by an early start to autumn tillage. Turbidity (Turb. A2) in leachate was lower (by 11%) at early compared with normal liming date and there was no interaction between site and liming date, i.e. all soils showed similar trends. This observation is supported by an increased EC indicating a faster dissolution at the early liming date. In our study there was no treatment without structure lime. However similar findings when examining effects of the interaction between tillage and lime on the outcome of liming have been made in previous studies. Valzano et al. (2001) found greater proportions of aggregates in unstable size classes for nine lime-gypsum treatments in direct-drilled plots than in plots with reduced tillage, and attributed this to the extra tillage operation resulting in more even distribution of lime through the soil. Joris et al. (2016) found that incorporation (0–20 cm) of lime resulted in faster neutralisation than surface spreading, while Conyers et al. (2003) found that the expected increase in pH due to liming was slower with direct drilling than when lime was incorporated by discing (0–10 cm). Chan and Heenan (1998) also compared liming-direct drilling with liming-incorporation (0–10 cm) and found significant aggregate stability increases in cultivated soils three years after liming-incorporation, but not after liming-direct drilling. McGrann et al. (2016) found that soil tillage intensity when incorporating lime at different rates to control clubroot (*Plasmodiophora brassicae*) gave variable results in field trials and concluded that ploughing is a more efficient tillage method. These findings on how tillage interacts with the chemical, physical and biological effects of liming and the results obtained in the present study underline the decisive importance of soil tilth for the outcome of liming.

Temperature effects

Ambient temperature differed between the two liming dates compared in this study. This might have enhanced the positive effect of the finer tilth at the early liming date, as higher temperature generally leads to higher solubility of solids and faster chemical reactions. Cumulative temperature (i.e. the sum of positive differences between diurnal average temperature and 0 ˚C) at the early liming date exceeded that at the normal date by approximately 400 day degrees. Taking into account that pozzolanic reactions are inhibited below 4 ˚C (Bell 1996) and only considering cumulative day degrees above 4 ˚C, the temperature sum was still 300 day degrees higher at the early liming date. However, in this study the effect on carbonation or cementation in the soils cannot be proven, as no detailed studies were conducted on these reactions at aggregate level.

Concentration versus dilution of lime

Of the four trial sites, only Kornheddinge had significantly lower turbidity A2 (Fig. 2) at the early liming date, although there was a tendency for turbidity to be lower with early liming at Krageholm. These observations are interesting in light of the differences in tillage depth between the two sites (Table 4). The tillage depth at early liming at Krapperup could not be measured, due to heavy rain shortly after liming, but the tillage equipment used had the same settings on both occasions, so tillage depth should have been similar (15 cm). At Råbelöf, tillage depth was approximately 15 cm on both occasions and at Krageholm it was approximately 11 cm on both occasions, but at Kornheddinge tillage depth was only 7.0 and 8.3 cm at the early and normal liming date, respectively. The same amount of structure lime was applied at all sites, so it was concentrated in the top 7–8 cm at Kornheddinge but diluted to approximately 15 cm depth at Krapperup and Råbelöf. The Krageholm site, with intermediate tillage depth, also showed intermediate results for turbidity, with a tendency (*p*=0.061) for lower turbidity values at the early liming date. These results suggest that the effect of liming on aggregate stability can be affected by lime concentration or dilution due to tillage depth. This way of reasoning is in line with Stenberg et al. (2000), who found a much less pronounced soil crust in a year with early crust formation, and therefore considerably higher yields, in treatments with reduced tillage in combination with lime compared with mouldboard ploughing without lime. Measurements of aggregate size distribution one year after liming showed a weak but significant trend for a finer tilth after the normal liming date. This result was surprising and contradicted the initial hypothesis.

No structure stability changes in lysimeters

Leaching tests on lysimeters from the trial sites taken three years after structure liming revealed a significant interaction between site and liming date regarding turbidity and phosphorus concentrations in leachate from the lysimeters. This finding derived partly from the Krapperup and Kornheddinge sites, which reacted in opposing ways to liming date, possibly due to differences in weather conditions at and after liming. Finer tilth at the early liming date can explain the results at Kornheddinge, but not those at Krapperup, where turbidity in leachate from the lysimeters was significantly higher, by almost 60%, and the concentration of Part-P by almost 90%, at the early liming date. These sharp increases may have been the result of unfavourable conditions at and after early liming at Krapperup. At the early date, the tilth at Krapperup was slightly too wet and not perfectly workable but, to create as great a window as possible between the early and normal dates, liming went ahead. In addition, rain fell shortly after spreading and incorporation of lime at the early date, which could have carried soluble calcium down into the soil profile before any major reactions took place (Eslamian et al. 2018). The exact rainfall amount was not recorded at the Krapperup site, but three days after early liming it was impossible to measure the tillage depth as loose and friable aggregates in the lower tilth had disintegrated and more or less blended into the seedbed base.

Management effects

The lysimeter study indicates that the unfavourable field conditions causing damages to soil structure at early liming at Krapperup in 2015 still remained three years later in 2018 as shown by a significantly higher turbidity L2 at early liming (Table 5) and also significantly higher phosphorus losses (Tot-P and Part-P). Bad soil structure causing cracks can lead to preferential flow which is a dominant pathway for phosphorus losses from clay soils (Djodjic et al. 1999).

The main driving force for the difference in phosphorus losses between the lysimeters from the two sites Krapperup and Kornheddinge was probably that 20 t ha^{-1} of pig slurry (approximately 10–15 kg P ha^{-1}) was incorporated on 29 August 2018 at Krapperup, in the midst of the rainy period and only seven days before lysimeter extraction. Surface spreading of mineral fertiliser phosphorus on clay soil after drought conditions poses a risk of phosphorus losses by preferential flow following heavy rainfall (Grant et al. 2019), while cattle slurry application can lead to high losses of soluble phosphorus (Ulén and Mattsson 2003). This was supported by the fact that concentrations in lysimeter leachate of all phosphorus fractions were 6–7 times higher for Krapperup than for Kornheddinge at early liming date.

Timing based on conditions instead of date

The results obtained for Kornheddinge and Krapperup challenge the current recommendations on structure liming by showing that early liming alone does not necessarily improve soil structure, since weather and soil conditions also need to be favourable. Conditions are likely to be more suitable for structure liming in early autumn than in late autumn but, as shown in the present study, this is not always the case. Therefore, the effects of conditions (e.g. temperature, soil water content, tilth/aggregate size distribution, precipitation, tillage depth etc.) before, at and after structure liming should be further investigated and the recommendations modified accordingly. Such investigations should also cover tillage equipment, as the results for Kornheddinge demonstrate.

Conclusions

Aggregate size distribution measurements showed a considerably finer tilth at early structure liming and incorporation, with significantly lower proportions of clods (>64 mm) and higher proportions of smaller aggregates (<2 mm), compared with the normal liming date. A finer tilth enabled closer contact between soil and lime at the early date.

One year after liming, aggregate stability was significantly higher after early spreading. Increased contact area between lime and soil due to the finer tilth at early liming date can explain this increase in aggregate stability, and indirectly the decreased risk of particulate phosphorus losses, which is the objective with structure liming.

Three years after liming, structure stability in topsoil lysimeters subjected to simulated rainfall events showed no significant differences between the early and normal liming dates. However, there was a strong interaction between liming date and site, indicating different reactions in different soils. Contradictory patterns for two sites with significant differences in turbidity, Part-P and PO_4-P concentrations can be attributed to prevailing conditions at the early and normal liming dates. Therefore, early liming date in combination with a finer tilth can give better soil structure and reduce phosphorus losses to surface waters, but only if accompanied by favourable soil conditions.

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III

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

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Abstract

In Sweden “structure lime” – i.e. mixtures of 80-85 % ground limestone and 15-20 % slaked lime – is used in subsidised environmental schemes to improve aggregate stability and mitigate phosphorus losses on clay soils. Increasing application rates of 0-16 tons hectare^{-1} of structure lime (SL0, SL4, SL8 and SL16) were tested in 30 field trials in Sweden. Soil aggregates (2-5 mm) were collected 1 year after liming and subjected to 2 rainfall events in a rain simulator. Turbidity of the leachate after the second simulated rainfall event decreased significantly, by 13% and 20% respectively, in SL8 and SL16 compared with SL0, indicating improved aggregate stability. However, there was a near-significant interaction (p=0.056) between treatment and trial. Grouping by initial pH$_{(H2O)}$ (range 6.2-8.3), clay content (10-61%), soil organic matter content (SOM, 2.2-7.1) and clay mineralogy (SmV index, 0.2-3.8) revealed different effects on turbidity due to soil characteristics. Discriminant analysis including soil characteristics supplemented with 4 tillage variables correctly classified the outcome (significantly or non-significantly improved aggregate stability in SL4-SL16 compared with SL0) for 27 of the 30 trials. The results show that structure liming can improve aggregate stability 1 year after liming, and can thereby prevent particulate P losses from soils with high clay and SOM content, low SmV index and low initial pH. The discriminant analysis results also showed the importance of tillage for the outcome of structure liming.

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

Introduction

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

Liming also affects soil physical conditions in clay soils (Holland et al., 2018), with different soil physical changes reported in the literature. Agricultural lime ($CaCO_3$) has been found to decrease bulk density and increase pore continuity (Frank et al., 2020), and has also been found to decrease soil penetration resistance and increase hydraulic conductivity (Kirkham et al., (2007). However, Frank et al. (2019) found that soil physical improvements, such as increased plant-available water capacity, recorded 6 months after liming were absent 12 months after liming, when the soil structure collapsed after soil tillage by ploughing and chiselling.

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

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

There is now increasing interest in liming using products containing CaO and/or $Ca(OH)_2$ in Swedish agriculture, as one of the side-effects can be a lower risk of particulate phosphorus (PP) losses from clay soils due to expected increase in aggregate stability. In Sweden commercially available mixes of 80-85 % ground limestone and 15-20 % slaked lime are referred to as "structure lime". Agriculture is the largest single source of P losses to the seas surrounding Sweden, accounting for 45% of total anthropogenic net P loads (Hansson et al., 2019). In neighbouring waters such as the Baltic Sea, P is the growth-limiting nutrient for algal growth, so P inputs must be reduced to alleviate eutrophication (Boesch et al., 2006). Losses of P from soils are a function of soil texture and crops grown, as well as precipitation and discharge dynamics. On clay soils particulate P is both released and transported to a greater extent than in the more coarse-grained soils (Johnsson et al., 2019) since P is bound to clay particles that are transported by preferential flow (Bergström et al., 2015). Both surface and subsurface transport are episodic (Johnsson et al., 2019), but P losses can possibly be reduced by structure liming, through improved soil structure stability (Blomquist et al., 2018) and chemical precipitation of Ca-P compounds limiting the solubility of phosphate ions (Aronsson et al., 2019).

In a laboratory experiment, Lee et al. (2011) compared $Ca(OH)_2$ with $CaCO_3$ and $CaSO_4{\cdot}2H_2O$ and found $Ca(OH)_2$ to be the most effective in converting water-soluble P into lesser soluble forms. Similarly, in a field experiment on a clay soil (top soil clay content 26%, $pH_{(H2O)}$ 7.1) containing high levels of plant-available P, application of $Ca(OH)_2$ reduced dissolved reactive phosphorus (DRP) levels in discharge from individually drained plots (Ulén and Etana, 2014). In another field experiment on a soil with a high clay content (top soil clay content 60%, $pH_{(H2O)}$ 6.3), total-P (tot-P) and particulate P (PP) concentrations in drainage water were found to be significantly reduced following application of pure CaO (Svanbäck et al., 2014). However, Eslamian et al. (2018) found that total dissolved phosphorus (TDP) concentrations were reduced with the addition of only 2 out of 4 CaO-containing liming products tested, whereas tot-P was significantly increased with all 4 products. These contrasting results indicate that the expected decrease in the risk of P losses due to structure liming does not always materialise.

In Sweden, use of pure CaO and/or $Ca(OH)_2$ in agriculture is very limited, but since 2010 approximately 60,000 hectares of clay soils have been structure-limed with commercial mixed products containing ~15-20% slaked lime and ~80-85% ground limestone. Application of these mixes of structure lime is a recommended measure in the water management plan for Sweden (VISS, 2020) and is subsidised in national environmental schemes with the general aim of mitigating P losses. Despite growing use of these mixed structure liming products in Sweden, there are few studies investigating their effectiveness, as pointed out by Greipsland et al. (2014).

As mixed structure liming products are relatively untested in a research context, the aim of this study was to answer a few important questions within practical structure liming and to bridge a knowledge gap. In the study, aggregate stability was used as a proxy for risk of P losses. Specific objectives were to: (1) determine whether structure liming increases aggregate stability, measured approximately 1 year after application, on clay soils; (2) determine whether the optimal structure liming rate is greater at higher clay content; (3) investigate whether other initial soil variables, apart from clay content, determine the effect on aggregate stability; and (4) assess whether it is possible to use a set of soil properties to predict which clay soils will react to structure liming with increased aggregate stability.

Materials and Methods

Study area, trial sites and experimental design

In 30 field trials, structure lime was spread and incorporated in autumn 2014, 2016 and 2017. Of these 30 trials, 28 were situated in the southernmost county of Sweden (Scania), within an area bounded by the corner points at 56.19ºN, 12.71ºE (trial site Lönhult); at 56.07ºN, 14.06ºE (trial site Skottlandshus); at 55.50ºN, 13.76ºE (trial site Krageholm) and at 55.62ºN, 13.33ºE (trial site Svinarp). The remaining two trials were situated further north in the regions Östergötland at 58.52ºN, 16.50ºE (trial site Bjärstad) and Uppsala at 59.55ºN, 16.97ºE (trial site Brunnsholm). Field trials, denomination, date of spreading, clay mineralogy characterisation (SmV index) and tillage before and after spreading the structure lime to a normal depth of 5-15 cm are summarised in Supplementary Table S1 together with the crop grown in the 1st year after structure liming. The trials had a randomised block design with 3 (occasionally 4) replicates, and included 4 treatments with different application rates of structure lime. The standard application rate in Sweden is approximately 8 t ha^{-1} of a mixed liming product. The treatments in all trials were:

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

In the first year (2014) the structure liming product used was marketed under the name Nordkalk Aktiv Struktur, later changed to Nordkalk Fostop Struktur. The product was a mixture of approximately 80-85% ground limestone ($CaCO_3$) and 15-20% slaked lime ($Ca(OH)_2$) with a water content of 15–25%. The chemical composition is shown in Supplementary Table S2.

The 16 trials in the first year were situated at 4 different sites. At each site 4 trials were established, with the aim of covering successively increasing clay content under similar trial conditions. The 8 trials in 2016 followed the basic idea from 2014, i.e. to cover different clay contents at the same site, but with only 2 trials per site, 1 with a low clay content (LC) and the other with a high clay content (HC). The 4 trials in 2017 followed a similar design to 2016 in having 2 soils at the same site, but selection was made after low soil organic matter (SOM) content (LO) and high SOM content (HO), instead of clay content. Only 4 trials were possible to carry out in 2017, due to wet conditions preventing structure lime from being spread properly. All 28 trials listed above were situated in Scania, but 2 additional trials were performed further north in Sweden in autumn 2017. All trials were sampled plotwise before liming in August-September each year, to characterise the texture and nutritional status of the soils (Supplementary Table S3). The SOM content varied between 2.2% and 7.1% in the field trials and plant-available calcium (Ca-AL) content varied between 950 and 11450 mg kg^{-1}. Data on $pH_{(H2O)}$ and clay content for the 30 trials are depicted in Figure 1, to show the range in soil properties at the trials. No soil classification according to the FAO initiated World Reference Base for Soil Resources (WRB) was done at the 30 trials. However, such soil classification surveys have been conducted for neighbouring Swedish long-term fertility experiments in the past (Carlgren and Mattsson, 2001, Kirchmann et al., 1996). Therefore all 28 trials in the county of Scania can as an approximation be classified as Haplic Phaeozems or Eutric Cambisols, and the northernmost trial at Brunnsholm as a Gleyic Cambisol. Approximately 1 year after liming, the trials were resampled plotwise to explore the short-term effect of structure liming.

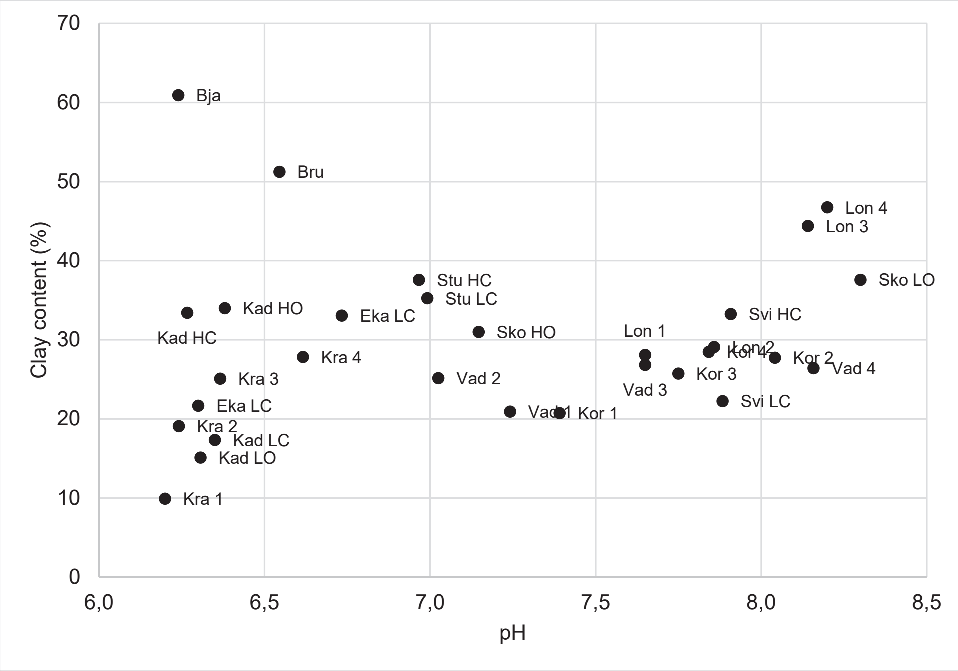


Figure 1. Plot of initial $pH_{(H2O)}$ and clay content in the 30 trials. The trials had no liming requirement according to pH recommendations in Sweden which for the trial soils were in the range 6.2-6.5 (with sugar-beets + 0.5 pH unit). site denomination according to Supplementary Table S1.

Clay mineralogy determination

1 topsoil sample (0-20 cm) per trial or trial site, consisting of a pooled sample of equal numbers of subsamples from all plots in the trial, was examined with X-ray diffraction analysis to determine the mineralogy in the clay fraction. To demonstrate this semi-quantitatively, the intensity (=surface) of the three most pronounced clay mineralogy reflections in the X-ray curves at 14, 10 and 7 Å was measured. The percentage contribution from each of these three reflection curves was then used to calculate a SmV index as: (Intensity 14 Å/(Intensity 10 Å + Intensity 7 Å)). The SmV index gives an estimate of the relationship between swelling and non-swelling clay minerals. It also indicates the relative proportions of clay minerals with high (smectite and vermiculite, intensity 14 Å) and low (illite, chlorite, kaoline, intensity 10 Å + intensity 7 Å) cation exchange capacity (CEC). A soil with a high proportion of swelling clay minerals is thus characterised by high SmV index. The SmV index varied between 0.4 and 3.8 at the trial sites (Supplementary Table S1).

Aggregate stability, sampling and measurements

Sampling of the soil for aggregate stability measurements was performed in the first year after liming, in 5 trials in the spring shortly after drilling of a spring crop and in the remaining 25 trials in the autumn after harvesting a cereal crop, approximately 1 year after spreading and incorporation of the structure lime (Supplementary Table S1). The sampling was performed after shallow spring tillage or after shallow tillage down to approximately 6-8 cm in the autumn. The loose soil was sieved into 3 different size classes (average aggregate diameter >5 mm, 2-5 mm and <2 mm). The fraction of aggregates with diameter 2-5 mm was collected and stored dry and aerated until the aggregates were transported to SLU in Uppsala.

Aggregates (average diameter 2-5 mm) were air-dried to equalise differences in water content and thereafter subjected to 2 simulated rainfall events 24 hours apart, with an intensity of 32-39 mm per hour in both events. The simulated rainfall event lasted for 1 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 5 minutes in the 1-hour period. The leachate was collected after each rainfall event and turbidity and electrical conductivity (EC) were determined (Turbidity A1/A2 and EC A1/A2). The muddy water was shaken for 10 minutes and then allowed to sediment for 4.5 hours. After sedimentation, a supernatant sample was taken at a depth of 5.6 cm and the turbidity measured with a turbidimeter (Hach TL 2360 Turbidimeter, Hach, Loveland, Co.). The turbidity in the supernatant provides an estimate of the concentration of clay in the leachate (Etana et al., 2009) and is thereby a proxy for aggregate stability and risk of particulate P (PP) losses (Puustinen et al., 2005, Ulén et al., 2012). Electrical conductivity rises with liming and gives an indication of whether there is soluble calcium in the soil solution. Only turbidity and EC data from the second simulated rainfall event (turbidity A2 and EC A2) are reported here.

Statistical analyses

Values of turbidity and electrical conductivity (from aggregate stability measurements after the second rainfall event were log-transformed before statistical analysis, to meet the requirement of normally and homoscedastic residuals. The log-transformed variables were analysed by analysis of variance (ANOVA) (General Linear Model in Minitab 18, Minitab Inc.), and the mean values were back-transformed to be calculated and presented as relative numbers.

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

Discriminant analysis was performed using the program R (package lda) with 2 groups (significant or non-significant effect on turbidity A2 for the single trial). The variables used for classification were 4 soil variables and 4 variables that reflected the conditions at liming and incorporation. The purpose of the discriminant analysis was to test whether it was possible to classify the effect of structure liming on the soil using these variables.

Results

Aggregate stability

The aggregate stability (measured as turbidity A2) of aggregates 2-5 mm, sampled approximately 1 year after liming, and the electrical conductivity (EC A2) are shown in Figure 2.

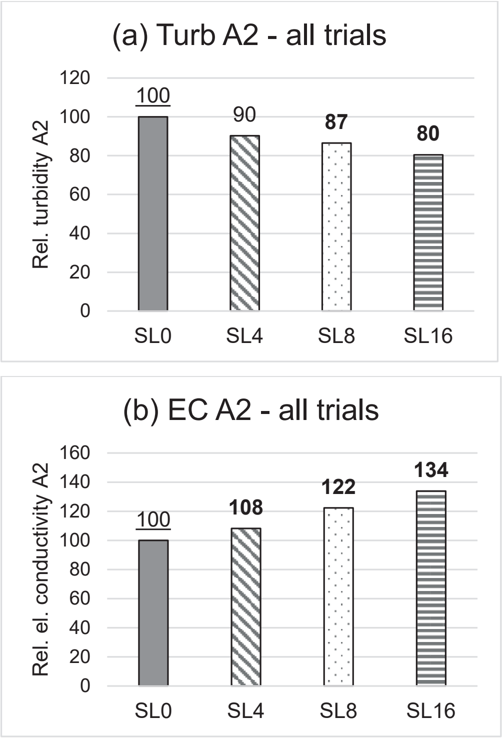
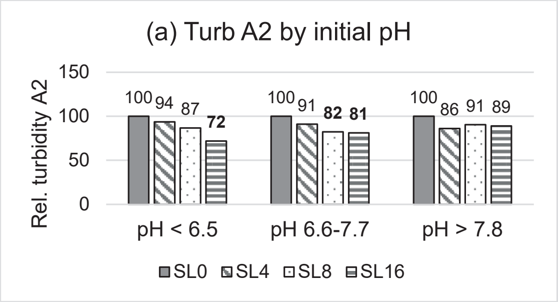


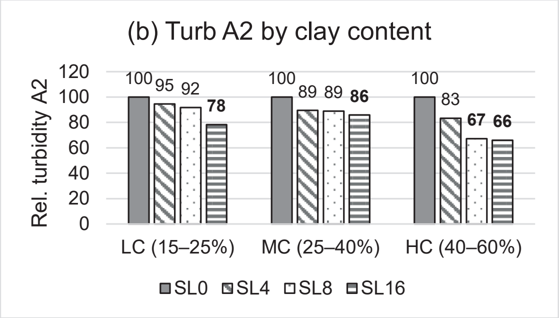
Figure 2. (a) Relative turbidity and (b) relative electrical conductivity after a second simulated rainfall event on 2-5 mm aggregates of tilled soil collected one year after structure liming. Results for 30 trials with increasing application rates of structure lime. Treatment SL0 = 100. Values in bold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

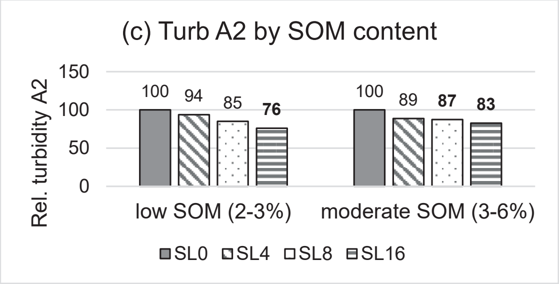
After the second simulated rainfall event, there were statistically significant differences in turbidity between the treatments ($p<0.001$). In treatments SL8 and SL16, turbidity decreased significantly, by 13% and 20%, respectively, while in treatment SL4 there was a non-significant decrease of 10%. Treatments SL4 and SL8 did not differ significantly, and nor did treatments SL8 and SL16, but the difference between treatments SL4 and SL16 was statistically significant. However, there was a near-significant interaction between treatment and trial ($p=0.056$). This means that the 30 different trials tended to react differently to the treatment with structure lime, making the results in Figure 2 only generalisable with a great deal of caution. Electrical conductivity (EC A2) was also significantly affected by the treatments ($p<0.001$). However, for EC A2 there was again a significant interaction ($p=0.002$) between treatment and trial. This means that the electrical conductivity was altered to different degrees by liming in the different soils in the 30 trials.

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

Based on the nearly significant interaction between treatment and trial for turbidity A2 ($p=0.056$), the trials were divided into different groups. Figures 3a-d show the trials divided into different classes with respect to initial pH, clay content, SOM content and SmV index.







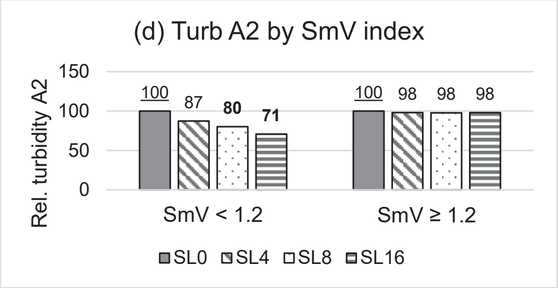


Figure 3. Relative turbidity classified according to soil (a) initial pH, (b) clay content, (c) SOM content and (d) SmV index. Treatment SL0 = 100. Values in bold indicate a significant difference from treatment SL0. Treatment SL0 = control and treatment SL4, SL8 and SL16 = 4, 8 and 16 t ha^{-1} structure lime, respectively. Initial pH on average: Group pH <6.5: 6.3 (10 trials), Group pH 6.6-7.7: 7.1 (10 trials), Group pH >7.8: 8.0 (10 trials). Clay content on average: Light clay soils (LC): 20% (10 trials), Medium clay soils (MC): 31% (16 trials), Heavy clay soils (HC): 51% (4 trials). SOM content on average: Low: 2.5% (10 trials), Moderate: 4.3% (20 trials). SmV index on average: SmV <1.2: 0.9 (15 trials), SmV >1.2: 2.4 (15 trials)

In each pH group, there were 10 trials (Figure 3a). The group with starting pH below 6.5 before liming (mean initial pH 6.3) showed significant differences between treatments ($p<0.001$), but no interaction ($p=0.113$) between treatment and trial. In this group, treatment SL16 differed significantly from treatment SL0, with turbidity decreasing by 22% compared with SL0. The group with initial pH within the range 6.6-7.7 before liming (mean initial pH 7.1) also showed significant differences between treatments ($p=0.011$), but no significant interaction ($p=0.153$) between treatment and trial. In the pairwise comparison, there were significant differences between treatments SL8 and SL16 compared with treatment SL0, with decreases in turbidity of 18% and 19%, respectively, relative to SL0. In the group with initial pH >7.8 (mean initial pH 8.0), there were no significant differences between treatments ($p=0.237$).

Classification by clay content (Figure 3b) was made on the basis of the functional groups used in Sweden: light clay soils (LC, 15-25% clay content), medium clay soils (MC, 25-40% clay content) and heavy clay soils (HC, 40-60% clay content). This classification did not divide the 30 trials into equally sized groups, but provided the advantage of making results compatible with a general conceptual framework used in the Swedish farming community when referring to different soil types. The group of light clay (LC) soils consisted of 10 trials in which 9 trials were true light clay soils (clay content 15-25%), but 1 trial had only 10% clay content and should therefore actually not have been included in the LC group. The clay content in the LC group was on average 20% (range 10-25%). There were significant differences between the treatments ($p=0.020$) for this group, but no interaction between treatment and trial site ($p=0.119$). Pairwise comparison showed that treatment SL16 in the LC group differed significantly from treatment SL0, with a turbidity decrease of 22%. The group of medium clay soils (MC) consisted of 16 trials where the clay content was on average 31% (range 26-38%). There were significant differences between the treatments for this group ($p=0.027$), but no interaction between treatment and trial site ($p=0.168$). Pairwise comparison showed that for the MC group, treatment SL16 differed significantly from treatment SL0, with a turbidity decrease of 14%. The group of heavy clay soils (HC) consisted of only 4 trials with an average clay content of 51% (range 44-61%). There were significant differences between the treatments ($p=0.015$), but no interaction between treatment and trial site ($p=0.309$). Pairwise comparisons for the HC group showed that treatments SL8 and SL16 differed significantly from treatment SL0, with a turbidity decrease of 33% and 34%, respectively.

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

Subdivision by SmV index was made arbitrarily, by splitting the 30 trials into 2 groups (Figure 3d) with the dividing point set at 1.2. In the group with SmV index <1.2, there were significant differences ($p<0.001$) between the treatments, with SL8 and SL16 showing lower turbidity than SL0. However, there was a significant interaction between treatment and trial site ($p=0.031$) for this group, indicating that there were different reactions to structure liming within the group, so differences between treatments should not be over-interpreted. In the group with

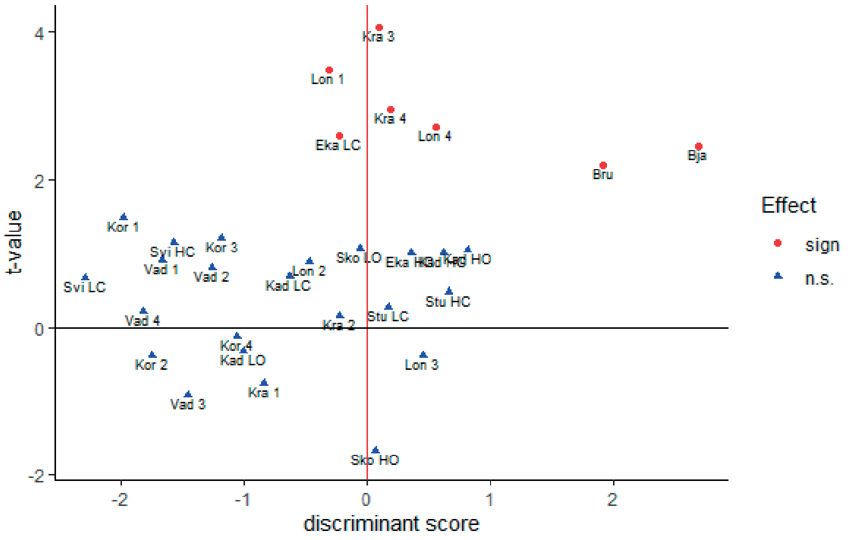
SmV index ≥1.2, there were no significant differences between the treatments ($p=0.569$) and no interaction between treatment and trial site ($p=0.831$).

Discriminant analysis

To investigate whether the soil variables studied were able to predict the effect of structure liming, the 30 trials were classified into two classes: the 7 trials that had a significantly higher value of log(Turb A2) in treatment SL0 compared with the mean of treatments SL4, SL8 and SL16, and the 23 trials that did not have a significantly higher value for this difference. This comparison thus indicated whether structure liming as the mean of treatments SL4, SL8 and SL16 decreased or increased turbidity A2 (had an effect on aggregate stability) compared with the untreated control in treatment SL0. The t-value for this comparison is plotted on the y-axis in Figures 4a-b. The 7 fields where structure liming had a significant effect (red dots in Figure 4) also formed their own group separately from the 23 non-significant fields (blue triangles).

Once the classification was made, discriminant analysis was performed using the software package R (package lda) in an attempt to classify the group to which each trial belonged (significantly or not significantly different from the control) using the independent variables. This discriminant score is shown on the x-axis in Figures 4a-b.

(a) Discriminant analysis based on four variables



(b) Discriminant analysis based on eight variables

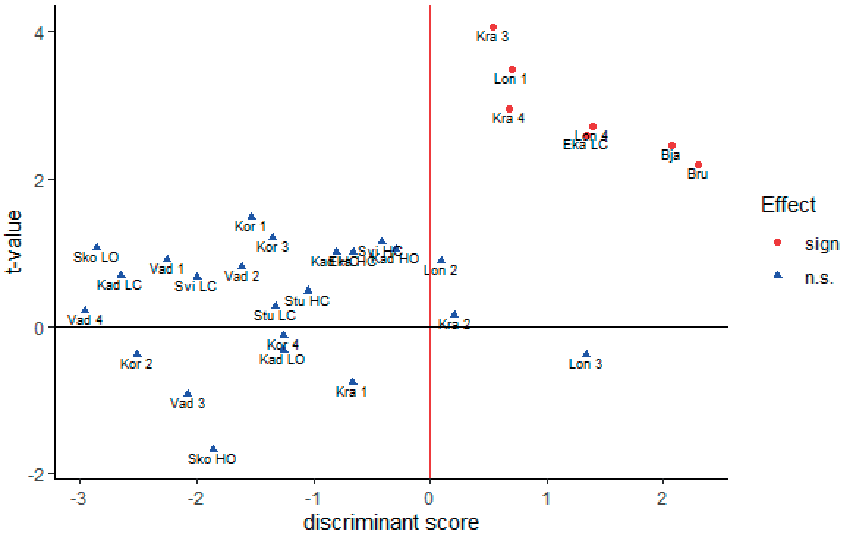


Figure 4. Discriminant score (x-axis) calculated based on (a) four soil variables (pH, clay content, SOM content and SmV index) and (b) these four soil variables plus four tillage variables according to Table 1, and the corresponding t-value for the difference in turbidity A2 between the control treatment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

In the first analysis, the 4 soil variables initial pH, clay content, SOM content and SmV index were tested (Figure 4a). In the second analysis, 4 more variables describing field conditions, tillage and management of the soil before and after structure liming (see Supplementary Table S1) were added (Figure 4b). The standardised coefficients of each variable used to calculate the discriminant score are compiled in Table 1, and the consequences of the outcome in Figures 4a-b are summarised in Table 2. In Table 2, the soils are divided into 4 categories, depending on whether liming would be recommended or not according to the outcome of the discriminant analyses, and whether the effect on turbidity was significant or not.

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

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

Table 2. Outcome of discriminant analyses using four soil variables (pH, clay content, SOM content and SmV index) and using the same four soil variables plus four soil tillage variables. Data from Figures 4a and 4b. Numbers in bold indicate that the recommendation (Rec) was correct, where correct is defined as recommendation not to lime where it would not give a significant change and to lime where it would lead to a significant change in turbidity

Using 4 variables	Rec: structure lime NO	Rec: structure lime YES	Sum
Sign. effect turb A2	2	**5**	7
No sign. effect turb A2	**16**	7	23
Sum	18	12	∑ 30
Using 8 variables	Rec: structure lime NO	Rec: structure lime YES	Sum
Sign. effect turb A2	0	**7**	7
No sign. effect turb A2	**20**	3	23
Sum	20	10	∑ 30

Based on the discriminant component calculated from the 4 soil variables (pH, clay content, SOM content and SmV index), structure liming would be recommended for 12 trials with a positive value of the discriminant component (to the right of the vertical red line in Figure 4a). Of these 12 trials, 5 trials (Kra3, Kra4, Lon4, Bru and Bja) showed a significant effect of liming and 7 a non-significant effect (Table 2). Negative values of the discriminant score were found for the remaining 18 trials, i.e. structure liming would not be recommended. Of these 18, the recommendation to avoid structure liming was correct for 16 trials (non-significant effect) and not correct for 2 trials (Lon1 and EkaLC), for which a positive significant effect of structural liming was observed. With these 4 soil variables, the recommendation would thus be correct for 16 + 5 = 21 of the 30 trials (values in bold in Table 2), where 'correct' is defined as a recommendation not to lime where it would not give a significant positive change and to lime where it would lead to a significant positive change in aggregate stability (turbidity).

Basing the discriminant analysis on the 4 soil variables plus 4 other variables characterising soil tillage before and after spreading structure lime increased the accuracy of the analysis (Table 2). In 10 trials (positive discriminant score), structure liming would be recommended based on the discriminant component calculated from the total of 8 soil and soil tillage variables (Figure 4b, Table 2). Of these 10 trials, 7 trials showed a significant effect of liming and 3 a non-significant effect. The remaining 20 of the 30 fields had negative discriminant components, so the recommendation would be not to lime. This recommendation was correct for all 20 fields (non-significant effect). With the 4 soil variables supplemented with four 4 tillage variables, the recommendation would thus be correct for 20 + 7 = 27 of the 30 trials (values in bold in Table 2 lower), where 'correct' is again defined as a recommendation not to lime where it would not give a significant positive change and to lime where it would lead to a significant positive change in aggregate stability (turbidity). In the case with only 4 soil variables (Figure 4a) or with 4 soil variables plus 4 tillage variables (Figure 4b), the trial site Lönhult B3 fell into the 4th quadrant, i.e. the recommendation would be to lime, but a post-liming decrease in aggregate stability was observed in this trial.

Discussion

In considering the results, it is appropriate to bear in mind that the trial soils had no liming requirements according to pH recommendations in Sweden which for the trial soils were in the range 6.2-6.5 depending on the clay content (with sugar beet + 0.5 pH unit).

More stable aggregates on average

The primary interest in this study was the expected short-term effect on aggregate stability achieved by structure liming. Effects on aggregate stability using ground limestone ($CaCO_3$) have been reported to be significant (Chan and Heenan, 1998) or non-significant (Grieve et al., 2005). Chan et al. (2007) found statistically significant effects on aggregate stability 4 years after liming with $CaCO_3$, but also distinguished between different aggregate size ranges and observed that the increased macroaggregate (>250 µm) stability was entirely due to a significant increase in the fraction 0.25-2 mm, and not in the fraction >2 mm. A laboratory comparison of $CaCO_3$ and CaO showed no effect on aggregate stability with the use of $CaCO_3$, but a significant increase when applying CaO to 3 agricultural soils (Keiblinger et al., 2016), which agrees with results presented by Berglund (1971) and Bohne and Hartge (1984). However, to our knowledge mixes of $CaCO_3$ and $Ca(OH)_2$ have not been tested extensively.

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

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

Different reactions on different soils

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

The results showed that the effect of structure liming, measured as change in turbidity, was greater on soils with lower compared with higher initial pH values (Figure 3a). In the group with initial pH <6.5, both pH and Ca-AL increased significantly in treatments SL4-SL16 measured 1 year after liming, whereas in the group with initial pH >7.8 no significant changes were observed in Ca-AL and only SL16 showed a significant increase in pH compared with SL0 (data not shown). Thus, the observed decrease in turbidity seemed to be a function of initial pH, and indirectly of the solubility and speed of release of Ca^{2+} ions from the structure lime.

Bivalent Ca^{2+} ions in the soil solution minimise the diffuse double layer (Vargas et al., 2019). The attraction between clay particles then increases, leading to flocculation, which is a prerequisite for aggregation (Payne, 1988). The increase in concentration of Ca^{2+} in the soil matrix should be an indicator of aggregate stability and might explain why turbidity decreased more clearly with low as opposed to high initial pH. A higher degree of explanation would probably be possible to achieve if data on EC or base saturation before liming were available. This is however not the case, but for future studies such measurements are recommendable. Our results did not fully coincide with those of Olsson et al. (2019), although they sampled soil only 6 months after liming, which might explain the lack of consistency.

Aggregate stability increased at high clay and SOM content

The decrease in turbidity was greater on heavy clay (HC) compared with light (LC) and medium (MC) clay soils (Figure 3b). Similarly, Keiblinger et al. (2016) observed increasing aggregate stability with increasing clay content after quicklime (CaO) application. Turbidity also decreased significantly at lower structure lime application rates (treatment SL8) on soils with moderate SOM content than on soils with low SOM content (Figure 3c). SOM and clay content are often positively correlated, so the effect of greater SOM could actually be an effect of greater clay content. The pattern also suggests an interaction between Ca and SOM on aggregate stability, as proposed by Edwards and Bremner (1967) for a basic structural unit of clay size (<2 µm) consisting of clay-polyvalent cation-organic matter (C-P-OM). These compound building blocks unite to $(C\text{-}P\text{-}OM)_x$ and further to $[(C\text{-}P\text{-}OM)_x]_y$ reaching the magnitude of fine sand and silt-sized microaggregates (<250 µm). Muneer and Oades (1989c) integrated previous results on the role of Ca-SOM interactions with ^{14}C-labelled glucose (Muneer and Oades, 1989a) and ^{14}C-labelled wheat straw (Muneer and Oades, 1989b) to create a conceptual model where Ca is involved in linking clay aggregates to SOM. If there is a quantitative relationship between Ca application and SOM present in soil, our results (Figure 3c) fit well with previous findings. However, Cook and Batchelor (1996) suggest that SOM interferes with pozzolanic reactions in soil, hindering growth of cementing compounds, making the question of an interaction between Ca and SOM unclear.

Clay mineralogy matters

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

The effect of structure liming can be predicted

The division into different classes of pH, clay content, SOM content and SmV index led to the preliminary conclusion that structure liming in this set of trials had the most beneficial environmental impact on soils with low initial pH values, low SmV index and high clay and SOM content. These variables can also be used to predict soils in which a significant effect of structure liming on aggregate stability can be expected, as indicated by the results of the discriminant analysis (Figures 4a and 4b). It is clear that the 4 soil variables alone (pH, clay content, SOM content, SmV index) were not sufficient to predict whether structure liming will have a beneficial effect (Figure 4b). Combining them with 4 variables describing how the soil was tilled before and after liming gave slightly better accuracy (Figure 4b). This is in line with studies by Blomquist and Berglund (2021) demonstrating the importance of timing and soil conditions at structure liming. Using 8 variables, all 7 trial sites that showed a significant effect of structure liming were correctly classified as suitable for structure liming.

For soil scientists and statisticians, it is gratifying and rewarding if structure liming gives significant positive changes in aggregate stability. For water conservation purposes, it is beneficial if structure liming reduces the potential risk of P losses (above 0 on the y-axis in Figures 4a and 4b), even if the effect is not statistically significant. For farmers, the best outcome would probably be if structure liming leads to decreased risk of P losses from arable land, combined with noticeable improvements in soil aggregate stability and positive yield effects, regardless of whether they are statistically significant or not. Structure liming of a soil in the 4th quadrant in Figures 4a and 4b will not produce effects that satisfy any of these stakeholders, since aggregate stability was poorer (increased turbidity A2) on structure-limed soil compared with non-limed soil. The 2 trial sites (Skottlandshus HO and Lönhult B3) were found in this quadrant in the discriminant analysis with only 4 soil variables, but only Lönhult B3 remained in this quadrant when 8 soil and tillage variables were used. This level of uncertainty must perhaps be accepted with the current level of knowledge.

Not all clay soils should be structure-limed

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

There was no clear evidence on whether the optimum structure liming application rate is greater at higher clay content. On the one hand, the turbidity response for different clay content groups (Figure 2b) showed that a higher application rate (treatment SL16) was required on light and medium clay soils to achieve a significant change, whereas a lower application rate (treatment SL8) gave a significant effect on the 4 trials with heavy clay soils. With results from more soils in the high clay content group, this interpretation may change.

The discriminant analysis showed that clay content contributed most to the composite discriminant score. The value of the discriminant score increased with increasing clay and SOM content, but decreased with increasing SmV index and increasing pH (Table 1). Since a positive value of the discriminant score entails a recommendation to structure lime, the results suggest that structure liming improves aggregate stability more, and is more effective as a measure against P losses, on soils with high clay content, high SOM content, low SmV index and low pH. The results also indicate that soil tillage before and after spreading to incorporate the structure lime is of equal importance. In the future, data from more field experiments can fine-tune the recommendations on which soils should and should not be structure-limed. Our on-going research will show if the admixture of 15-20% of slaked lime in "structure lime" is enough for a longer-term aggregate stabilisation to occur (Choquette et al., 1987, Eades and Grim, 1960).

Conclusions

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

1. Significantly increased aggregate stability, and thereby indirectly decreased risk of P losses, with 8 and 16 t ha^{-1} of structure lime, but with great variation between soils and a near-significant interaction between treatment and trial.
2. Significantly increased aggregate stability on soils with initial $pH_{(H2O)}$ below 7.7, but not on soils with initial pH above 7.7.
3. A more pronounced effect, and an effect on aggregate stability, at standard structure liming application rates (SL8) on soils with clay content exceeding 40%, as opposed to soils with clay content below 40%.
4. Significantly increased aggregate stability at standard structure liming application rates on soils with 3-6% SOM, but with significant aggregate stability increases only at double the standard structure liming application rate on soils with 2-3% SOM.
5. Significantly increased aggregate stability at standard and double structure liming application rates on soils with SmV index <1.2, but no effect on soils with SmV index ≥1.2.
6. Discriminant analyses using clay content, SOM content, initial pH, SmV index and four variables describing soil conditions and management before and after structure liming correctly classified the outcome of liming on aggregate stability for 27 of the 30 trials.

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Conflicts of interest

No potential conflict of interest is reported by the authors.

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Data availability

The data used is not available publically.

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Supplementary Table S1

Table S1. Denomination, calculated SmV-index in the clay fraction (< 2 µm), date of spreading and tillage of the soil before and after the spreading of structure lime on the 30 trial sites. LC=low clay content, HC=high clay content, LO=low SOM content and HO=high SOM content. In the column Tillage before spreading no differentiation is made between different types of tillage, but the column describes whether the soil was not tilled (0) or tilled (1–2) with 1 and 2 indicating the number of passes before the spreading of lime. In the columns Tillage after spreading tines refers to equipment working mainly with tines, whereas Tillage after spreading discs refers to shallow working equipment with only discs. The column Tillage after spreading combination refers to combination cultivators working with discs, tines and reconsolidating packers. Abbreviations for crops grown are WW = winter wheat, SuB = sugar beet, SB = spring barley, WOSR = winter oil seed rape

Trial	Denom.	SmV index	Date of spreading	Tillage before spread.	Tillage after spread. - tines	Tillage after spread. - discs	Tillage after spread. - combi	Crop grown 1st year after liming
Krageholm 1	Kra 1	0.6	2014-09-05	0	1	1	0	WW
Krageholm 2	Kra 2	0.6	2014-09-05	0	1	1	0	WW
Krageholm 3	Kra 3	0.6	2014-09-05	0	1	1	0	WW
Krageholm 4	Kra 4	0.6	2014-09-05	0	1	1	0	WW
Lönhult 1	Lon 1	1.1	2014-08-28	1	0	1	1	WW
Lönhult 2	Lon 2	1.1	2014-08-28	1	0	1	1	WW
Lönhult 3	Lon 3	1.1	2014-08-28	1	0	1	1	WW
Lönhult 4	Lon 4	1.1	2014-08-28	1	0	1	1	WW
Vadensjö 1	Vad 1	2.9	2014-08-27	2	1	1	2	SuB
Vadensjö 2	Vad 2	2.9	2014-08-27	2	1	1	2	SuB
Vadensjö 3	Vad 3	2.9	2014-08-27	2	1	1	2	SuB
Vadensjö 4	Vad 4	2.9	2014-08-27	2	1	1	2	SuB
Kornheddinge 1	Korn 1	3.1	2014-09-20	2	0	0	2	WW
Kornheddinge 2	Korn 2	3.1	2014-09-28	1	1	1	0	SB
Kornheddinge 3	Korn 3	1.9	2014-09-28	2	0	0	2	WW
Kornheddinge 4	Korn 4	1.9	2014-09-28	2	0	0	2	WW
Kadesjö LC	Kad LC	1.1	2016-09-02	1	2	0	0	WW
Kadesjö HC	Kad HC	1.0	2016-09-02	1	2	0	0	WW
Stureholm LC	Stu LC	1.6	2016-07-30	1	2	1	0	WOSR
Stureholm HC	Stu HC	1.0	2016-07-30	1	2	1	0	WOSR
Eka LC	Eka LC	1.8	2016-08-15	0	2	1	0	WW
Eka HC	Eka HC	1.2	2016-08-15	0	3	2	0	WW
Svinarp LC	Svi LC	3.5	2016-08-05	0	2	1	0	WW
Svinarp HC	Svi HC	3.8	2016-08-05	0	2	1	0	WW
Bjärstad	Bja	0.80	2017-09-29	1	2	0	0	WW
Brunnsholm	Bru	0.40	2017-09-19	0	2	0	0	SB
Skottlandshus LO	Sko LO	1.08	2017-08-24	1	2	2	0	WW
Skottlandshus HO	Sko HO	1.30	2017-08-24	1	2	2	0	WW
Kadesjö LO	Kad LO	1.55	2017-09-03	0	2	1	0	WW
Kadesjö HO	Kad HO	1.02	2017-09-03	1	2	1	0	WW

Supplementary Table S2

Table S2. Chemical composition, including variation width, of structure liming product Nordkalk Aktiv Struktur/Fostop Struktur – a mixture of approximately 80–85% ground limestone and 15–20% slaked lime – used in trials 2014–2017. Water content 15–25% depending on storage. Nutrients and compounds are expressed as concentrations of dry matter. Bulk density 0.8–1.0 t m^{-3}. Source: Nordkalk Corp.

Macronutrient or compound	Concentration (%)	Micronutrient	Concentration (mg kg^{-1})
Total Ca as CaO	50.0–51.0	Cd	1.0–1.8
Mg	0.6–1.0	Co	2–9
SiO_2	2.0–5.4	Cr	9–26
Al_2O_3	1.0–3.4	Cu	8–48
Fe_2O_3	0.3–1.5	Hg	< 0.02
K	0.1–2.5	Ni	5–28
Na_2O	0.5–1.0	Pb	4–58
S	0.5–1.7	Zn	160–280
P	0.07–0.2		

Supplementary Table S3

Table S3. Texture and soil nutritional status in topsoil (0–20 cm) of the 30 trials prior to structure liming in autumns 2014, 2016 and 2017

Trial	SOM[a]	Sand[b] > 60 µm	Silt[c] 60-2 µm	Clay[d] < 2 µm	pH H_2O	P-AL[e] mg kg^{-1}	K-AL[e] mg kg^{-1}	Mg-AL[e] mg kg^{-1}	K/Mg ratio	Ca-AL[e] mg kg^{-1}
Krageholm 1	2.2	69.0	21.1	9.9	6.2	68	72	59	1.3	950
Krageholm 2	2.4	39.5	41.4	19.1	6.2	25	82	95	0.9	1570
Krageholm 3	2.2	23.6	51.3	25.1	6.4	38	125	153	0.9	1370
Krageholm 4	2.5	19.5	52.7	27.8	6.6	29	111	151	0.8	1850
Lönhult 1	5.0	43.4	28.5	28.1	7.7	129	188	146	1.4	4040
Lönhult 2	3.9	49.1	21.8	29.1	7.9	133	200	165	1.3	4580
Lönhult 3	4.2	30.8	24.8	44.4	8.1	138	291	282	1.1	7860
Lönhult 4	3.9	29.1	24.1	46.8	8.2	127	307	353	0.9	10540
Vadensjö 1	4.0	46.3	32.8	20.9	7.2	130	97	121	0.8	3100
Vadensjö 2	4.1	42.3	32.5	25.2	7.0	165	126	159	0.8	3240
Vadensjö 3	4.1	40.2	33.0	26.8	7.7	116	117	178	0.7	4410
Vadensjö 4	3.3	44.1	29.5	26.4	8.2	89	148	229	0.7	11430
Kornheddinge D1	2.8	53.8	25.4	20.8	7.4	48	99	87	1.1	3040
Kornheddinge D2	3.6	39.8	32.4	27.8	8.0	133	153	195	0.8	7320
Kornheddinge D3	2.8	49.9	24.3	25.8	7.8	58	173	154	1.3	6090
Kornheddinge D4	2.6	45.8	25.7	28.5	7.8	114	203	218	1.1	7050
Kadesjö LC	2.7	53.2	29.5	17.3	6.4	46	118	83	1.4	1800
Kadesjö HC	3.4	12.9	53.7	33.4	6.3	22	138	146	1.0	2290
Stureholm LC	4.4	35.8	28.9	35.3	7.0	36	189	234	0.8	3730
Stureholm HC	4.4	30.0	32.4	37.6	7.0	28	187	207	0.9	3940
Eka LC	7.1	26.1	52.2	21.7	6.3	52	106	93	1.1	3190
Eka HC	4.3	30.9	36.0	33.1	6.7	30	172	137	1.3	3610
Svinarp LC	3.3	58.2	19.5	22.3	7.9	98	127	153	0.8	3690
Svinarp HC	4.7	29.9	36.8	33.3	7.9	88	173	314	0.6	5430
Bjärstad	4.0	7.0	32.1	60.9	6.2	32	243	675	0.4	3620
Brunnsholm	2.6	12.7	36.0	51.3	6.5	61	303	366	0.9	2330
Skottlandshus LO	4.1	18.0	44.4	37.6	8.3	258	180	195	0.9	11450
Skottlandshus HO	5.2	18.8	50.2	31.0	7.1	78	131	132	1.0	4330
Kadesjö LO	2.5	52.1	32.8	15.1	6.3	61	99	58	1.8	1550
Kadesjö HO	5.7	22.6	43.4	34.0	6.4	83	158	163	1.0	3530

[a] ignition loss

[b] wet sieving

[c] calculated as difference between fractions Sand and Clay

[d] hydrometer sedimentation

[e] extraction with 0.1 M ammonium lactate + 0.4 M acetic acid, pH 3.75 (Egnér et al., 1960)

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This thesis evaluated the effect of structure liming on aggregate stability, aggregate size distribution, draught requirement and crop response with results from approximately 70 Swedish field trials on clay soil. On average, structure lime increased aggregate stability and could thereby reduce the associated risk of particulate phosphorus losses. Trial-treatment interactions indicated different soil reactions with clay content, initial pH, soil organic matter content and clay mineralogy being decisive variables for aggregate stability. Site-specific application of structure lime is therefore suggested.

Jens Blomquist received his graduate education at the Department of Soil and Environment, SLU, Uppsala. He holds a Master of Science (MSc) in Agriculture from the same university.

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