

Quicklime application instantly increases soil aggregate stability**

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Received August 20, 2015; accepted January 19, 2016

Abstract. Agricultural intensification, especially enhanced mechanisation of soil management, can lead to the deterioration of soil structure and to compaction. A possible amelioration strategy is the application of (structural) lime. In this study, we tested the effect of two different liming materials, *ie* limestone (CaCO_3) and quicklime (CaO), on soil aggregate stability in a 3-month greenhouse pot experiment with three agricultural soils. The liming materials were applied in the form of pulverised additives at a rate of 2000 kg ha^{-1} . Our results show a significant and instantaneous increase of stable aggregates after quicklime application whereas no effects were observed for limestone. Quicklime application seems to improve aggregate stability more efficiently in soils with high clay content and cation exchange capacity. In conclusion, quicklime application may be a feasible strategy for rapid improvement of aggregate stability of fine textured agricultural soils.

Key words: stable aggregates, liming, quicklime, CaCO_3 , CaO

INTRODUCTION

Agricultural production has strongly increased in the last decades due to enormous intensification of land management. This was accomplished through the application of fertilisers and pesticides, as well as irrigation and mechanisation (Matson *et al.*, 1997). Intensive agriculture influences the chemistry, physics and biology of soils. Particularly, enhanced mechanisation in the form of farm machinery can cause soil compaction and deterioration of soil structure (Frey *et al.*, 2009). Changing soil pore characteristics, such as total length and volume, affect soil water and air permeability, which in turn affects the soil as a biogeochemical interface for microbial life and a medium for plant growth. It is for this reason that the stability of the soil structure is a key for sustainable agriculture (Amezketta,

1999) and an important mechanism for the stabilization of soil organic matter (Briedis *et al.*, 2012; Oades, 1988). A promising approach to stabilise soil aggregates and thereby improve the water and air permeability of soils is the use of polyvalent ions like Ca^{2+} (Becher, 2001) applied to the topsoil in the form of pulverised limestone (CaCO_3) or quicklime (CaO). The application of limestone is a common agricultural management practice (VDLUFA, 2000), as considerable increases in crop yields have been reported (Haynes and Naidu, 1998). However, the application of quicklime has so far not become a standard procedure in agricultural soil management, although it has recently been mentioned as ‘structural lime’ together with slaked lime applied to diminish P leaching (Bergström *et al.*, 2015; Ulén and Etana, 2014). So far, lime-treatment stabilisation studies using quicklime have focused on engineering geology and civil engineering to improve fine textured soil in terms of engineering properties for earthwork projects (Cuisinier *et al.*, 2011; Hashemi *et al.*, 2015; Metelková *et al.*, 2012). In this context, effective changes in soil properties, such as improvements in structure, stability, porosity, and aggregate strength, have been mentioned for silty and clayey soils (Little, 1995).

Quicklime reacts with water to form calcium hydroxide (Ca(OH)_2). The solubility product of Ca(OH)_2 (5.02×10^{-6}) is three orders of magnitude higher than that of CaCO_3 (3.36×10^{-9}) (Haynes, 2013), which has the consequence that it dissolves and reacts much faster. Hence, quicklime quickly reacts with clay in the soil and leads to a change in its structure, with clay minerals coalescing into larger aggregates (Little, 1995). The calcium ions from quicklime can replace other ions (*eg* Na^+ , K^+ , Mg^{2+} , H^+) in the clay

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**This study was financially supported by BoWaSan/Bodenkalk e. Gen., Graz, Austria, Project No. 9836, 2013-2015.

interlayers or on the surface of clay particles, which in turn favours flocculation; this process is strongly dependent on the soil cation exchange capacity (CEC). Flocculation was found to occur immediately after quicklime addition and to continue for several days (Metelková *et al.*, 2012).

We hypothesised that, due to its higher solubility, quicklime can improve soil aggregate stability more rapidly than limestone when applied at the same rate.

To test this hypothesis, a greenhouse pot experiment was conducted using the two above-mentioned liming materials and investigating their effects on soil aggregate stability over time.

MATERIALS AND METHODS

The soil samples for the greenhouse pot experiment were taken in August 2013 from the plough layer (0–15 cm) of three agricultural soils of Austria located in Strengberg, Pollham and Kemeten (Table 1). The soils are classified as Stagnosols with silty/clayey texture and an organic carbon (C_{org}) content between 1.3 and 1.8% (Table 2). The selected soils are intensively managed agricultural soils with fine textures; they are therefore prone to compaction and well suited to the question under investigation. From each location, homogenised soil material was brought to the greenhouse within one day. After crushing and sieving (<10 mm), the samples were air dried (to approx. 10% w/w water content) and stored in open pots.

Each of 36 pots (27.5 cm in diameter and 21.5 cm in height) was filled with washed coarse gravel up to about 2 cm and overlaid by a water permeable textile. Then, 11 to 12 kg of the sieved and well homogenised, dry soil material was added. To double-check the homogeneous filling of the pots, the soil texture was tested in 1 cm increments for location 'Pollham'. The average clay content of this sample pot was 26.7% and varied among the 1 cm increments only within a small range of about $\pm 0.48\%$, confirming that the pots were filled homogeneously. For water saturation to an average of about 25% w/w, the soils were capillary-wetted from the bottom for 24 h to reach homogeneity, which is essential for soil physical experiments. For equilibration prior to lime application, the pots were pre-incubated at ambient temperature and approximately 25% w/w soil water content in the greenhouse for one month (water contents at each sampling are given in Table 3).

Quicklime (CaO) and limestone ($CaCO_3$) were added in pulverised form at an application rate of 2000 kg ha⁻¹ and incorporated into the upper 7 cm. Within the greenhouse, the pots were positioned in a randomised block design to reduce the influence of factors such as solar radiation, temperature *etc.* The pots were sampled 2, 30 and 86 days after lime application. At each sampling time, one pot was destructively sampled and the material was used for aggregate stability testing in three replicates.

The method for aggregate stability determination is based on a common standard by the Austrian Standards Institute (OENorm-L1072, 2004). Although this is a local

Table 1. Site conditions and soil texture

Site	Location (GPS position)	Soil type	Elevation (m a.s.l.)	Crop	Clay	Silt (%)	Sand
Strengberg	N: 48°09'14.24'' E: 14°36'8.00''	Stagnosol	346	maize	34.2	56.6	9.2
Pollham	N: 48°14'55.31'' E: 13°51'39.31''		385	wheat	26.5	60.7	12.8
Kemeten	N: 47°14'37.56'' E: 16°10'14.10''		315	soy bean	39.6	32.2	28.2

Table 2. Basic chemical soil parameters

Site	C_{org} (%)	SOM (%)	N_{tot} (mg kg ⁻¹)	CEC_{pot} (mmol _c 100 g ⁻¹)	pH_{KCl}	Electrical conductivity (mS cm ⁻¹)	C/N ratio (1*)	$CaCO_3$ (%)
Strengberg	1.77	3.05	1850	20.58	6.43	0.983	9.5	–
Pollham	1.69	2.91	1550	12.22	7.63	0.720	10.9	7.1
Kemeten	1.31	2.25	1260	22.04	5.27	0.212	10.4	–

*Mass ratio.

Table 3. Soil acidity (pH) and water content. Response to lime application over time

Site	Days after application	pH (in 0.01 M CaCl ₂)			p-values	Water content (% w/w)		
		control	CaCO ₃	CaO		control	CaCO ₃	CaO
Strengberg	2	6.8 abc	7.4 c	9.6 d	lime p<0.01	23.7	23.3	24.0
	30	6.5 a	6.8 abc	7.2 bc	time p<0.001	22.8	22.7	22.4
	86	6.6 ab	6.5 a	6.8 ab	lime x time p<0.001	22.3	22.7	23.5
Pollham	2	7.3 ab	7.4 ab	10.5 c	lime p<0.001	24.4	25.7	24.1
	30	7.2 ab	7.2 ab	7.7 b	time p<0.001	22.1	23.7	23.1
	86	7.0 ab	7.0 a	7.0 ab	lime x time p<0.001	25.0	24.9	24.8
Kemeten	2	5.4 a	7.0 d	8.3 e	lime p<0.001	25.9	25.3	24.9
	30	5.4 a	6.5 cd	6.9 d	time p<0.001	20.3	19.4	20.1
	86	5.6 ab	6.1b c	6.3 bcd	lime x time p<0.001	22.6	22.0	21.9

Different letters for the same site indicate differences in multiple comparison of mean by Tukey HSD ($p < 0.05$ with a confidence level of 95%); the p values for 'lime' (form of lime), 'time' (time after application) and 'lime x time' are from a 2-way ANOVA (confidence level of 95%) and indicate significance of the individual factors or their interaction.

standard, it can be compared to internationally used methods, *eg* Dane *et al.* (2002) and Kemper and Rosenau (1986). Generally, the method is based on a wet sieving procedure of air dried soil samples. The sieving frequency is 42 hubs per minute, hub height is 2 cm whereby the soil sample is always covered by water. Sample size is 20 g. The mass of stable aggregates in the dimension of 1-2 mm was determined using a modified wet sieving equipment (Murer *et al.*, 1993).

Soil pH was measured in a 0.01 M CaCl₂ suspension (OENorm-L1083, 1999). 2.0 g of soil was suspended in 25 ml CaCl₂ solution and, after incubation for at least 2 h at room temperature, the pH value was determined with a calibrated pH-meter (Mettler Toledo, SG2; Vienna, Austria).

At each sampling, the gravimetric water content was determined from 2.3 g of soil by drying at 105°C for 24 h; values are given in Table 3.

Statistical analyses were performed using Statgraphics Centurion XVI (StatPoint Technologies, Inc, USA). Differences between treatments were tested with one-way ANOVA. For each location, the effects of lime and time were investigated using 2-way ANOVA with treatment ('lime') and sampling time ('time') as fixed factors. Significant differences were shown by Tukey HSD test at a confidence interval of 95%. The graphs were created with SigmaPlot 12.5.

RESULTS AND DISCUSSION

The liming effect of the applied limestone and quicklime materials was assessed by monitoring changes in soil acidity (Table 3). The application of CaCO₃ caused an increase in pH for site Kemeten which originally had an acidic soil pH; however, no significant changes were observed for the other two sites. The minor changes in soil pH with CaCO₃ in our study might be due to a delayed reaction and/or significantly lower application rates compared to other studies (~ 18 t ha⁻¹) (Acosta-Martinez and Tabatabai, 2000; Fuentes *et al.*, 2006). On the other hand, the application of CaO resulted in an immediate and much stronger increase of soil pH at all the sites (Table 3), but decreased at the third sampling (after 3 months) to the reference values of the controls. This is one indication for the quicker reaction of CaO compared to CaCO₃ due to its higher solubility in the soil.

Many studies have investigated the effects of organic matter and limestone on stable aggregates in soils (Chenu *et al.*, 2000; Six *et al.*, 2002; Spaccini and Piccolo, 2013). However, studies on the effects of quicklime in the context of soil sciences are scarce, or the specification is not clear, as a large body of literature only mentions the term 'lime' without further details on the material used. Quicklime and its ability to stabilise aggregates is described mostly in engineering papers (Beetham *et al.*, 2014; Cuisinier *et al.*, 2011; Idiart *et al.*, 2012), whereas its potential application in agricultural soils has attracted less scientific attention.

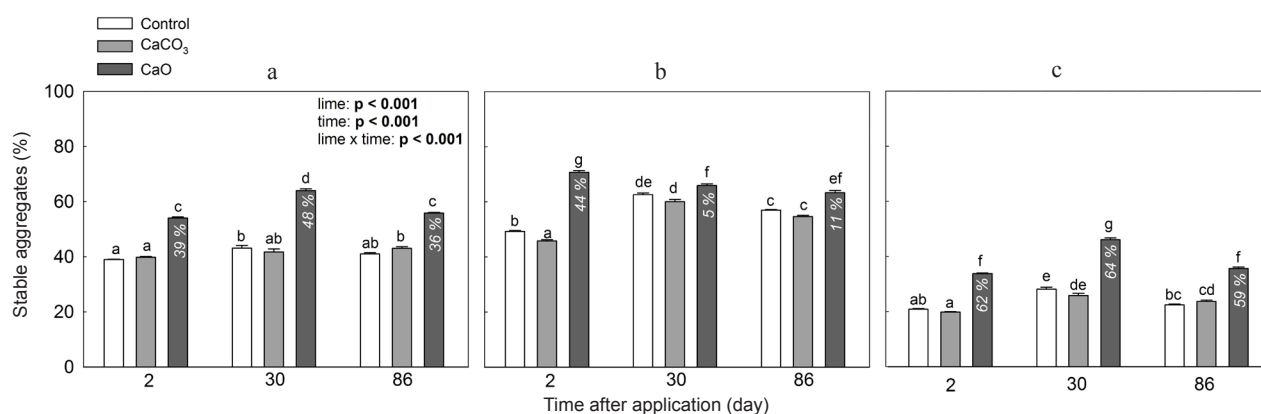


Fig. 1. Stable aggregates in mass % for the sites: a – Strengberg, b – Pollham and c – Kemeten. Different letters for the same site indicate differences in multiple comparison of mean by Tukey HSD ($p < 0.05$ with a confidence level of 95%); the p values for ‘lime’ (form of lime), ‘time’ (time after application) and ‘lime x time’ are from a 2-way ANOVA (confidence level of 95%) and indicate significance of the individual factors or their interaction. The percentage given in the dark grey bars (CaO), indicates the increase in stable aggregates relative to the control.

Therefore, our study analyses limestone and quicklime application as strategies for restoring structural stability in degraded agricultural soils. Our results clearly show a significant and instantaneous increase of stable aggregates after quicklime application (Fig. 1). This effect was measured already after 2 days and was sustained for the entire duration of the experiment (3 months). The effect of quicklime application on aggregate stability was strongly dependent on soil type and sampling time. The strongest effect was observed for site Kemeten which showed a relative increase in stable aggregates between 59 and 65% compared to the control over the entire course of the trial. The smallest increase in stable aggregates was observed for site Pollham, where it was only 5 and 11% compared to the control for the 2nd and 3rd sampling, respectively. The effect of quicklime on soil aggregate stability seems to be related to the soils clay content and cation exchange capacity (CEC): the soil of site Kemeten had the highest clay content and CEC, while this was opposite for Pollham soil (Table 2). Hence, the flocculating effect of added Ca^{2+} seems to increase with higher surface area (clay content) and available exchange sites (CEC). The lowest increase in aggregate stability at site Pollham could also be attributed to the fact that this soil already contained carbonate (Table 2) and showed relatively high aggregate stability, reducing the potential effect of additional liming. Also, the temporal trend of stable aggregates in the soil from site Pollham is interesting, as it clearly differed from the other two sites, showing a strong initial increase immediately after application of CaO (Fig. 1). A possible explanation for this may be the pH which reached 10.5 directly after the application (Table 3). Dissolution of clay minerals into silicate and aluminate species may occur under such highly alkaline conditions (Hashemi *et al.*, 2015), and pozzolanic reaction

may take place (Metelková *et al.*, 2012). Hence, such high pH conditions may be favourable for improved workability and reduced swelling and plasticity of soils, desirable for geotechnical applications. However, in agricultural soils this is an unwanted side effect of quicklime application as these environments might be exceptionally unfavourable for nutrient availability.

In addition to soil texture and CEC, also soil organic matter (SOM) content may influence the efficiency of lime application (Hashemi *et al.*, 2015). Organic coatings on soil particles may inhibit the flocculation reaction by decreasing the availability of mineral surfaces for sorption of polyvalent ions (Cook and Batchelor, 1996). It is supposed that SOM content above 1% reduces the reactivity of lime. All three soils under study showed SOM contents above two percent (Table 2), and the soil from Kemeten, which showed the largest increase in stable aggregates upon quicklime application, had indeed the lowest SOM of the studied soils (Table 2).

Contrary to the marked improvement of aggregate stability after quicklime application, there were no significant effects after the application of limestone. The results were similar for soils from all three locations and indicate once more that CaO reacts much faster than CaCO_3 because of its higher solubility in the soil.

Several studies reported an increase in aggregate stability in the long term after limestone application (Bennett *et al.*, 2014; Castro and Logan, 1991). However, we did not even see a delayed effect of CaCO_3 on aggregate stability after 3 months. One possible explanation is that CaCO_3 needs to be applied at higher rates to show similar effects as CaO in our short-term experiment. On the other hand, also reduced aggregate stability was reported, especially for tropical acidic soils, after the application of CaCO_3

(Roth and Pavan, 1991; Tarchitzky *et al.*, 1993). Such negative effects were determined only shortly (1 to 3 months) after limestone application at low rates (Roth and Pavan, 1991). However, in the longer-term (after 6 months), soil aggregation was reported to increase substantially, while the initial negative effect was less pronounced at higher application rates. The rate applied in our experiment was selected according to the Austrian guidelines for agricultural soil fertilisation and should be of practical relevance (Baumgarten, 2006).

Our study demonstrates that quicklime can rapidly and sustainably improve the aggregate stability of agricultural soils. This confirms the results from studies in engineering also for agriculture, even though the application rate in our experiment was one order of magnitude lower than those reported for engineering studies. We assume that the application of CaCO_3 may show beneficial effects on soil aggregate structure in the long-term and at higher application rates. The results support our hypothesis that quicklime can improve soil aggregate stability more rapidly than limestone. Quicklime application, therefore, seems to be a feasible strategy for rapid improvement of aggregate stability, particularly in intensively managed/trafficked agricultural soils prone to compaction and degradation.

CONCLUSIONS

1. Quicklime application shows a significant and instantaneous increase of stable aggregates.
2. The increase of stable aggregates due to the application of quicklime was observed already after 2 days and was sustained for the entire duration of the experiment (3 months).

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