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Effect of liming products on soil detachment resistance, measured with a cohesive strength meter

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ABSTRACT
Good soil structure is important for achieving high productivity of agricultural land and also affects the ability of soil to withstand erosive forces. Given the importance of soil structure, efforts are commonly made to improve it, usually by application of amendments of different kinds (e.g. lime, biochar, compost, manure etc.). However, little is known about the effect of these amendments on the soil resistance to detachment. This study assessed the resistance to detachment of soil cores treated with different liming products, using a cohesive strength meter (CSM) which measures the rate of soil detachment under the action of water jets at different pressures. The amount of soil removed by the water jets was taken as an indirect measure of soil resistance to detachment, under the assumption that more resistant soils will lose less material than more susceptible soils at a given water jet pressure. The results showed that all soil amendments studied reduced detachment of particles under the action of water jets compared with unamended soil (control).

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Erosion; detachment susceptibility; detachment resistance; liming; cohesive strength meter

Introduction

Soil erosion is one of the most important challenges in food production and food security. One way to characterise the susceptibility of a soil to erosion is by measuring its erodibility, commonly expressed as the magnitude of an applied shear stress that the soil can withstand before the initiation of particle/aggregate detachment and movement (Grabowski et al. 2011). Since measurement of the critical shear stress for erosion is still challenging, erodibility is usually estimated by applying other forces of different types to soil, an example being the cohesive strength meter (CSM) test (Grabowski et al. 2010). The CSM test uses water jets that apply vertical forces onto the soil surface and measures the amount of soil detached. The magnitude of applied jet pressure that causes the particles to begin to detach and move can be taken as the erosion threshold. Soil erodibility is a complex condition that is correlated with many factors, including physical soil properties (particle size distribution, bulk density etc.), geochemical properties (clay mineralogy, water chemistry etc.), biological properties (burrows, roots etc.) (Grabowski et al. 2011) and soil aggregate stability (Amezketa 1999). Different kinds of soil amendments (lime, biochar, compost, manure etc.) are frequently used in agriculture to improve soil aggregate stability, and are therefore likely to affect soil erodibility.

The effects of some soil amendments on soil erosion characteristics have already been explored, although most studies tend to focus on the effect of soil amendments on soil aggregate stability, and not on soil erodibility. For example, it has been shown that biochar application improves soil aggregate stability and reduces soil erosion (Li et al. 2017). Biochar combined with organic amendments has also been shown to reduce soil aggregate detachment even more than biochar only (Doan et al. 2015; Peng et al. 2016). Lime application, in the form of slaked lime [$Ca(OH)_2$] and in a mixed form consisting of a blend of slaked lime [$Ca(OH)_2$] and calcium carbonate [$CaCO_3$], has been found to enhance the stability of aggregates in clayey soils (Blomquist et al. 2017). The few studies that have assessed the effect of amendments on soil erodibility have not measured it directly, but rather have calculated erodibility based on its relation with other variables (Castro and Logan 1991; Ekwue 1992; Nishimura et al. 2005; Özdemir et al. 2015; Kumar et al. 2019).

With growing recognition of liming as an environmental protection measure, various mixed products

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containing calcium carbonate and calcium hydroxide have become available on the Swedish market (Blomquist et al. 2017). To our knowledge, the effect of these mixed products on soil erodibility remains unexplored. The aim of this work was thus to assess the effects of different commercially available liming products on soil erodibility, using the CSM test. Erodibility was estimated and expressed as relative amount of soil detached by the action of CSM water jets of different pressures. The hypothesis was that liming products decrease soil erodibility, indicated by lower amounts of soil detached under water jet pressure, compared with unlimed soil and that the effect can be detected with the CSM test.

Materials and methods

Study site

Field trials were conducted at two neighbouring sites, Ultuna 3 and Ultuna 9, located 5 km south of Uppsala in east-central Sweden (Figure 1). Each field site was divided into 16 plots arranged in a randomised block design with four treatments (three liming treatments and a control plot) and four blocks (Figure 2). Three different types of liming product were used: (i) Mixed lime (a mixture of approximately 15% slaked lime [$Ca(OH)_2$] and around 85% calcium carbonate [$CaCO_3$]), (ii) slaked lime and (iii) tunnel kiln slag (a mixture of an approximately 20% calcium oxide [CaO], charcoal and silica oxides). The liming treatments were applied as part of a project examining soil structure improvement and phosphorus loss reduction in agricultural soils (Berglund et al. 2017). The doses used in the treatments were based on achieving an equal supply of calcium [Ca] with a liming rate of 3 t CaO ha^{-1}, irrespective of the liming product.

Soil sample collection and preparation

A total of 96 undisturbed samples (cylinders of 7.2 cm diameter, 5 cm height) were taken from the topsoil (5–10 cm depth) at the two field trial sites (48 samples each from Ultuna 3 and Ultuna 9, i.e. three samples from each of the 16 plots). In the laboratory, these soil samples were saturated with water and then drained to a drainage equilibrium of 0.5 m water pressure prior to the CSM tests, in order to obtain soil samples with a standardised moisture content.

Additional 16 samples (one per plot) were taken at an approximate depth of 5–10 cm at each field trial site for particle size distribution analysis. These samples were air-dried and sieved through a 2-mm mesh. Organic matter was then removed by boiling the soil and adding hydrochloric acid (HCl) and hydrogen peroxide (H_2O_2).

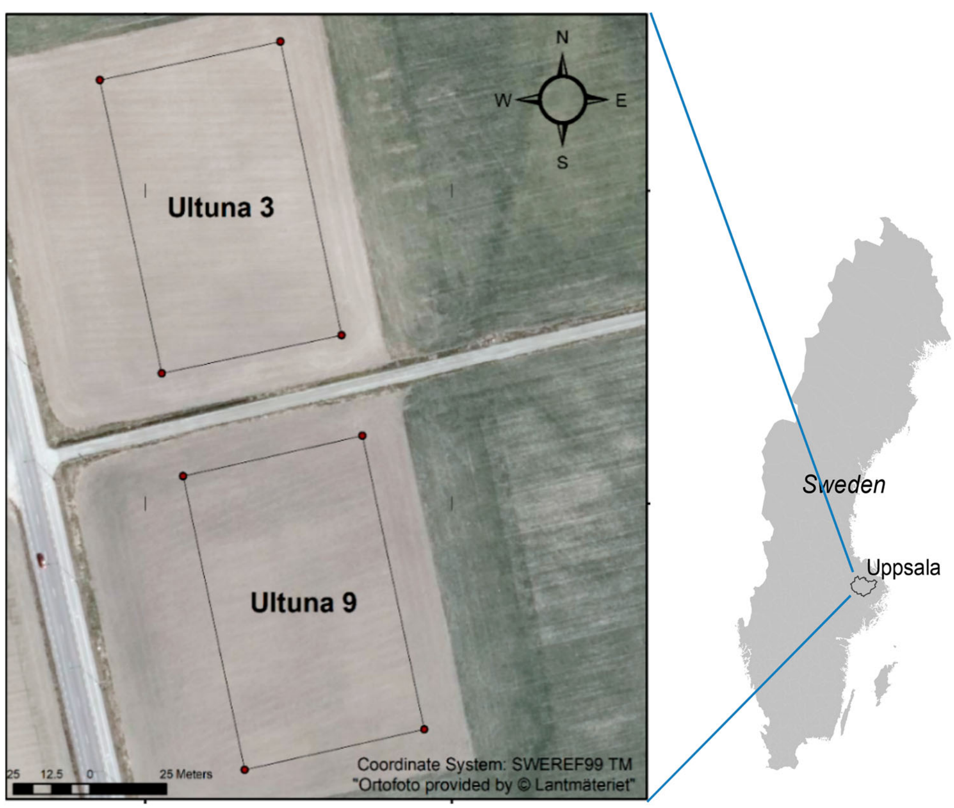

Figure 1. The field trial sites Ultuna 3 and Ultuna 9 in central Sweden. Orthophoto provided by © Lantmäteriet.

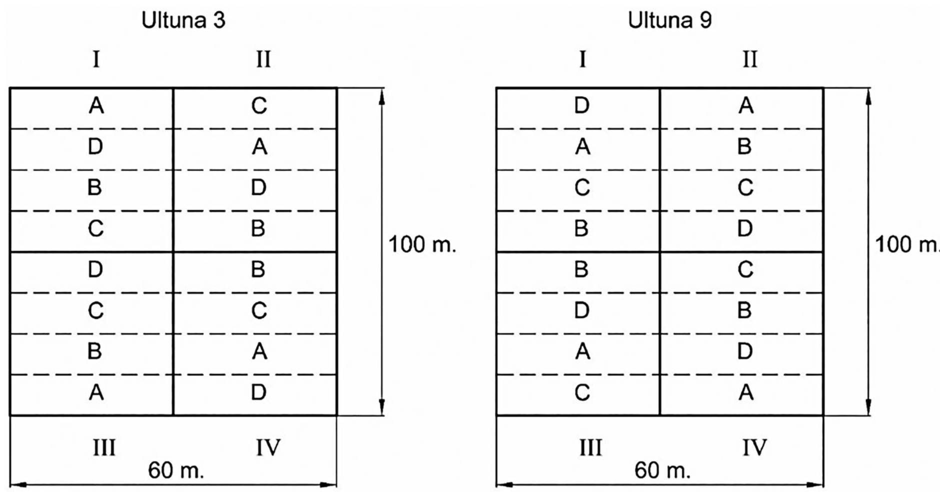

Figure 2. Treatment plot layout at the Ultuna 3 and Ultuna 9 field sites. A = control, B = slaked lime, C = mixed lime, D = tunnel kiln slag. I–IV are blocks.

Laboratory analysis

In order to classify the soil texture, a set of particle size analyses was carried out using a laser diffraction particle size analyser (LA-950, Horiba Scientific. Kyoto, Japan), which derives the size and number of particles from the forward diffraction of the laser beam (Eshel et al. 2004). The LA-950 device is capable of measuring particle sizes ranging from 10 nm to 3 mm. The prepared samples were placed in a magnetic stirrer, to allow the particle analyser to take a small representative sample. The analyser measures applies the Mie scattering theory to calculate the size and number of particles in the sample. This method provides a high degree of repeatability, greatly reduces testing times and requires small soil samples (Avilés et al. 2018).

Cohesive strength meter (CSM)

The excess shear model for erosion takes the form (Papanicolaou et al. 2006; Grabowski et al. 2011):

$$\varepsilon = k_d(\tau - \tau_d)^a$$

where ε (m s^{-1}) is the erosion rate, k_d (m^2 s kg^{-1}) is an erodibility coefficient, τ is the shear stress applied, τ_d is the critical shear stress and a is an empirical coefficient usually assumed to be 1. The CSM test aims to provide an estimate of τ_d in an indirect manner. The device applies water jet pulses of increasing pressure to the soil surface and records the jet pressure and light transmittance. The light transmittance value [%] is a relative measure of the amount of soil detached and suspended in the test chamber by the action of the water jets. The CSM output is then normally analysed to determine the pressure at which the transmittance value falls below the proposed threshold value of 90% (Tolhurst et al. 1999). This pressure is used to derive an equivalent horizontal shear stress (Black 2015), which is a measure of the amount of shear force that needs to be exceeded to cause particle/aggregate detachment and movement.

The CSM test was carried out as follows: Soil cores at standardised soil moisture content were placed in the CSM testing chamber and the device was filled with water. In the routine used for testing in this study (called Fine 1), each jet is fired for 1 s, then the pressure and light transmittance across the test chamber are logged for 3 s every 0.1 s (30 times). After the logging is finished, the next water jet is fired at a higher pressure and the process is repeated. The water jet pressure in the Fine 1 routine starts at 0.69 kPa and increases in 0.69 kPa steps up to 16.54 kPa, then in steps of 2.07 kPa up to 41.36 kPa and finally in steps of 13.79 kPa up to 413.67 kPa. Thus by at the end of the test, 63 jets have been fired at increasing pressure (Partrac 2011). The Fine 1 routine was selected for the present study since the required pressure to start particle/aggregate detachment was unknown, and the routine covers a wide range of jet pressures supplied by the equipment, which was assumed to include (and exceed) the pressure required to cause particle/aggregate detachment. The Fine 1 routine also involves small pressure increments, allowing closer inspection of the changes in transmittance level (soil detachment).

As the CSM test proceeds, light transmittance decreases with increasing pressure steps. This change can be taken as a measure of erodibility. It is worth noting that 100% transmittance means that no soil particles have been detached and put into suspension, while 0% transmittance means that the soil sample has been completely destroyed by the water jet.

Table 1. Soil texture fractions (per cent by weight) at the Ultuna 3 and Ultuna 9 sites, determined using an ultrasonic particle analyser, in the different treatment plots and the control at each site.

Treatment	Fine clay (<0.2 µm)	Coarse clay (0.2–2 µm)	Silt 2–20 µm)	Sand (20–2000 µm)
Ultuna 3				
Control	6.3 ± 0.7	35.2 ± 2.5	48.0 ± 0.4	10.5 ± 2.0
Mixed lime	6.6 ± 0.1	34.1 ± 0.9	48.8 ± 0.7	10.6 ± 0.6
Slaked lime	6.5 ± 0.3	34.8 ± 0.8	49.3 ± 0.8	9.4 ± 1.2
Tunnel kiln slag	6.4 ± 0.3	35.0 ± 1.2	48.4 ± 0.9	10.2 ± 0.9
Ultuna 9				
Control	5.8 ± 0.6	28.7 ± 1.0	47.6 ± 0.7	17.9 ± 2.1
Mixed lime	6.2 ± 0.2	29.0 ± 0.4	46.6 ± 0.6	18.1 ± 0.9
Slaked lime	5.7 ± 0.4	28.4 ± 0.6	46.9 ± 0.8	19.0 ± 1.1
Tunnel kiln slag	5.8 ± 0.4	28.4 ± 0.5	47.1 ± 1.0	18.6 ± 1.3

Statistical analysis of CSM data

Statistical analysis was performed in R (R Core Team 2013). Analysis of variance (ANOVA) was used to decide whether the different liming treatments had a significant effect on the transmittance values for the different jet pressures applied. The Tukey test was then used to find significant differences between treatments.

Results and discussion

Based on the particle size distribution analysis (Table 1), the soil at the sites was classified as silty clay (Ultuna 3) and silty clay loam (Ultuna 9), with higher clay levels at Ultuna 3 (41.2% clay) than at Ultuna 9 (34.5% clay). The measured transmittance values obtained at the selected jet pressures are shown in Table 2 (Ultuna 3) and Table (Ultuna 9).

The Fine 1 CSM routine selected involved 63 water jets of increasing pressure within the range 0.69–413 kPa, of which seven were selected for the ANOVA test. These pressures were within the range 0.69–96.5 kPa because the detachment process appeared to change rapidly in that range, as seen in the rapid decrease in transmittance level in Tables 2 and 3. Prior to ANOVA analysis, the data were transformed using Box–Cox transformation in order to meet the requirements of ANOVA regarding normality of residuals and equality of variances. The ANOVA results revealed significant treatment effects ($P < 0.05$) for pressures 10.3, 15.2, 20.7, 55.2 and 96.5 kPa, but not for the lower pressures of 1.4 kPa and 5.5 kPa (Tables 2 and 3). For the case of Ultuna 3, slaked lime and mixed lime were found to be significantly different from the control (Table 2), based on the marked differences in transmittance values obtained for the different treatments and pressures. For instance, at a pressure of 20.7 kPa, the average transmittance value for the control was 24.3%, whereas for mixed lime it was 69.7% and for slaked lime it was 54.6%.

The greater drop in transmittance for the Ultuna 3 control (100–24.3 = 75.7%) indicates that more soil was detached from that soil than from the soil treated with mixed lime (100–69.7 = 30.3%) or the soil treated with slaked lime (100–54.6 = 45.4%). In the case of Ultuna 9, at water jet pressures of 55.2 kPa and 96.5 kPa similar

Table 2. Transmittance values [%, mean ± variance] obtained in cohesive strength meter (CSM) tests on soil samples from Ultuna 3. The last six lines show the results of pairwise comparisons.

Ultuna 3		Jet pressure [kPa]						
Block	Treatment	1.4	5.5	10.3	15.2	20.7	55.2	96.5
I	Control	88.3	63.7	40.1	31.0	22.8	6.3	3.0
	Mixed lime	88.9	84.0	77.6	73.3	66.9	38.5	16.1
	Slaked lime	90.4	81.0	63.8	52.3	46.3	12.4	1.6
	Tunnel kiln slag	91.5	82.1	42.1	29.7	21.3	5.5	1.6
II	Control	93.7	87.0	79.1	43.6	32.3	3.5	1.2
	Mixed lime	86.4	82.0	79.5	79.4	78.9	66.0	29.5
	Slaked lime	93.4	84.8	82.6	68.8	64.7	13.4	6.3
	Tunnel kiln slag	94.2	72.1	50.4	41.3	34.6	21.6	12.6
III	Control	94.7	73.4	33.6	24.8	20.7	10.5	5.6
	Mixed lime	90.2	82.4	79.2	77.0	66.3	55.3	39.9
	Slaked lime	85.9	77.4	69.2	54.9	49.3	29.1	12.3
	Tunnel kiln slag	81.7	82.5	71.0	56.7	57.3	31.0	10.6
IV	Control	85.1	67.0	55.4	33.5	21.5	2.8	0.8
	Mixed lime	92.2	77.2	75.7	70.9	66.7	44.5	22.4
	Slaked lime	87.7	74.7	70.4	63.0	58.0	37.3	15.3
	Tunnel kiln slag	88.1	72.9	62.4	55.0	52.4	13.3	3.3
Average	Control	90.5 ± 20.6	72.8 ± 106.1	52.1 ± 408.7	33.2 ± 61.2	24.3 ± 29.0	5.8 ± 12.2	2.7 ± 4.8
	Mixed lime	89.4 ± 5.9	81.4 ± 8.6	78.0 ± 3.0	75.2 ± 14.3	69.7 ± 37.7	51.1 ± 147.3	27.0 ± 104.2
	Slaked lime	89.4 ± 10.7	79.5 ± 19.3	71.5 ± 63.0	59.8 ± 57.2	54.6 ± 70.2	23.1 ± 148.7	8.9 ± 37.5
	Tunnel kiln slag	88.9 ± 29.1	77.4 ± 32.1	56.5 ± 163.2	45.7 ± 160.9	41.4 ± 274.7	17.9 ± 17.9	7.0 ± 29.1
Control – Slaked lime		–	–	*	**	***	***	*
Control – Mixed lime		–	–	***	***	***	***	**
Control – Tunnel kiln slag		–	–	–	–	*	**	–
Mixed lime – Slaked lime		–	–	–	–	–	–	–
Tunnel kiln slag – Slaked lime		–	–	–	–	–	–	–
Tunnel kiln slag – Mixed lime		–	–	**	***	***	***	***

Significance level: ***$P < 0.001$; **$P < 0.01$; *$P < 0.05$, '–' not significant.

Table 3. Transmittance values [%, mean ± variance] obtained in cohesive strength meter (CSM) tests on soil samples from Ultuna 9. The last six lines show the results of pairwise comparisons.

Ultuna 9		Jet pressure [kPa]						
Block	Treatment	1.4	5.5	10.3	15.2	20.7	55.2	96.5
I	Control	88.0	76.9	64.0	51.3	30.7	18.5	5.8
	Mixed lime	93.4	86.7	79.8	77.6	70.9	61.2	42.7
	Slaked lime	91.9	83.7	75.7	67.3	56.5	48.9	30.0
	Tunnel kiln slag	92.4	84.2	77.1	53.4	61.9	54.0	39.2
II	Control	90.3	76.0	70.6	62.9	58.2	20.2	4.6
	Mixed lime	86.2	83.9	79.4	79.3	68.3	60.2	44.0
	Slaked lime	88.2	80.5	78.5	69.6	71.0	63.0	41.4
	Tunnel kiln slag	91.4	85.8	76.0	76.0	66.5	40.5	19.6
III	Control	81.7	75.3	51.8	62.0	48.0	25.8	9.2
	Mixed lime	90.5	80.7	79.1	73.1	71.4	53.4	23.8
	Slaked lime	89.5	84.0	81.4	66.7	68.7	45.6	24.3
	Tunnel kiln slag	85.4	66.2	60.8	66.1	50.0	32.2	13.3
IV	Control	91.3	70.8	46.0	48.3	33.5	20.0	8.7
	Mixed lime	92.6	79.6	72.1	75.9	66.7	50.3	38.9
	Slaked lime	93.5	81.7	76.5	61.8	60.3	45.3	24.4
	Tunnel kiln slag	93.3	82.3	69.0	53.9	59.7	44.0	19.3
Average	Control	87.8 ± 18.6	74.8 ± 7.4	58.1 ± 125.7	56.1 ± 55.0	42.6 ± 165.6	21.1 ± 10.3	7.1 ± 5.0
	Mixed lime	90.7 ± 10.4	82.7 ± 10.3	77.6 ± 13.5	76.5 ± 7.0	69.3 ± 4.9	56.3 ± 27.9	37.4 ± 86.3
	Slaked lime	90.8 ± 5.6	82.5 ± 2.8	78.0 ± 6.4	66.4 ± 10.8	64.1 ± 47.0	50.7 ± 69.9	30.0 ± 64.6
	Tunnel kiln slag	90.6 ± 12.7	79.6 ± 82.1	70.7 ± 56.6	62.4 ± 117.3	59.5 ± 48.3	42.7 ± 81.5	22.9 ± 127.2
Control – Slaked lime		–	–	–	–	–	***	***
Control – Mixed lime		–	–	**	**	***	***	***
Control – Tunnel kiln slag		–	–	–	–	–	**	***
Mixed lime – Slaked lime		–	–	–	–	–	**	**
Tunnel kiln slag – Slaked lime		–	–	–	–	–	**	**
Tunnel kiln slag – Mixed lime		–	–	–	*	*	***	***

Significance level: ***$P < 0.001$; **$P < 0.01$; *$P < 0.05$, '–' not significant.

behaviour as for Ultuna 3 soil was seen, with soil from all treatments showing less detachment than control soil (Table 3).

Significant differences between treatments were also found. In the case of Ultuna 3, for example, tunnel kiln slag was significantly different ($p < 0.01$) from mixed lime for pressures 10.3, 15.2, 20.7, 55.2 and 96.5 kPa, with the transmittance levels decreasing more for tunnel kiln slag than for mixed lime (Table 2). A similar trend was found for Ultuna 9, where tunnel kiln slag was significantly different ($p < 0.05$) from mixed lime at pressures 15.2, 20.7, 55.2, 96.5 kPa, again with transmittance levels decreasing more for tunnel kiln slag than for mixed lime (Table 3). When the results for the two field sites were compared, it was found that, for all treatments, the soil from Ultuna 9 generally detached less (lower transmittance values for a certain pressure) and that higher pressures were required to achieve a certain transmittance level than for the soil from Ultuna 3. Given the difference in clay content (41.2% clay at Ultuna 3, 34.5% clay at Ultuna 9) and considering findings that clay content increases the shear stress required for detachment (Grabowski et al. 2010; Gao et al. 2019), the soil from Ultuna 3 could have been expected to give lower transmittance values for each pressure step than the soil from Ultuna 9. In fact, the opposite was found. Thus the clay content did not explain the differences in behaviour between the soils from Ultuna 3 and 9 in the CSM test and no other possible cause for the difference could have been found. Closer scrutiny of the transmittance values showed that the soil at both field sites reached the proposed critical threshold of transmittance value below 90% (Tolhurst et al. 1999) at a water jet pressure of around 1.4 kPa (Tables 2 and 3). This implies that the soils have the same threshold for detachment, i.e. the same erodibility value. This was unexpected given the fact that, among the lime products considered in this study, slaked lime and mixed lime have been shown to improve aggregate stability (Blomquist et al. 2017) and that aggregate stability affects the erosion resistance of soils (Amezketa 1999). It has been suggested that the CSM test might not be fully adequate for the agricultural soils studied here (Avilés et al. 2018) and that the definition of the threshold for erosion (90% transmittance value) might not be enough to assess the differences in resistance to detachment. This idea was explored by considering the shapes of the transmittance-pressure curves obtained for the Ultuna 3 and Ultuna 9 soils (Figure 3).

Transmittance levels are an indirect measure of the amount of soil detached and put into suspension inside the test chamber, where 100% transmittance means no soil particles in suspension. The shape of the curves in Figure 3 shows that, as pressure increased, the detachment process increased and more soil from all treatments was put into suspension inside the test chamber, causing a gradual drop in the transmittance values. Comparing, for instance, control soil with mixed lime soil for Ultuna 3, it can be seen that, for the same range of applied CSM jet

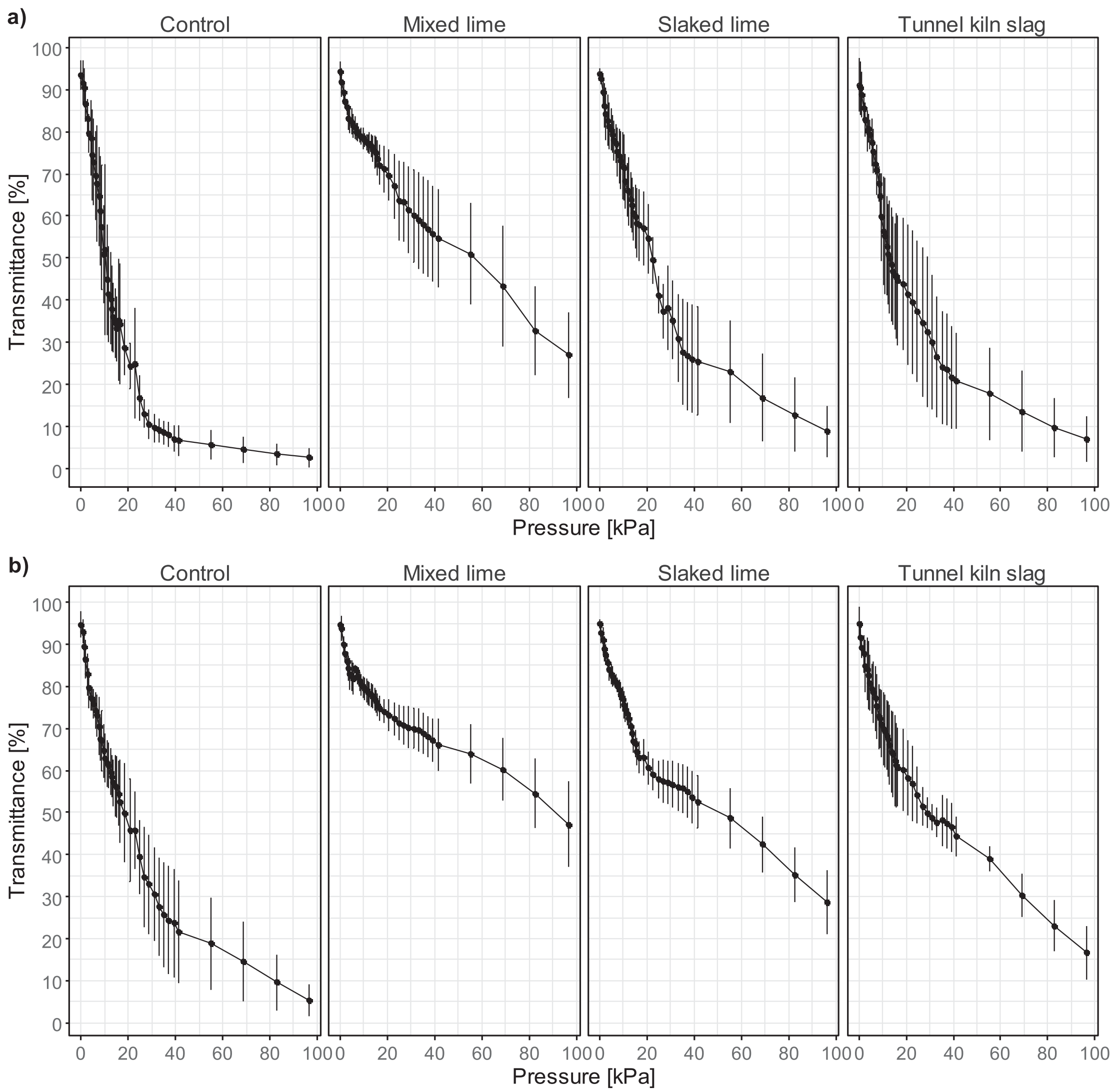

Figure 3. Transmittance values obtained in cohesive strength meter (CSM) tests plotted against water jet pressure applied for: (a) Ultuna 3 soil and (b) Ultuna 9 soil. The vertical lines indicate inter-block standard deviation.

pressures, the soil treated with mixed lime had fewer soil particles in suspension. The same was true for Ultuna 9 control and mixed lime soil (Figure 3). A similar analysis comparing the curves for control soil and soil treated with slaked lime revealed that the soil treated with slaked lime had less soil detached than the control soil, particularly for pressures above 20 kPa. Thus, although the criterion of 90% transmittance value was met for both study sites and for all treatments at the same pressure level (1.4 kPa), the soils behaved differently at higher pressures, with the control soil being more prone to detach (lower transmittance values) than the soils treated with the different lime products (Figure 3).

Further analysis of the detachment process can be done by considering different transmittance levels (Figure 4). The results showed that in other to reach different detachment levels (e.g. 70%, 50%, 30% or 10%) the water jet pressure required were generally higher for the soils with liming treatments. Although different detachment levels (transmittance values) might be reached as particles of different sizes start detaching at higher water jet pressures, issue that was not investigated in this study, the soils with liming treatments showed lower detachment values at increasing water jet pressures. Therefore, the liming treatments improved the resistance to detachment of soil particles (Figure 4), with mixed lime being the best liming product at reducing soil detachment.

The CSM results in Figure 4 showed that soil with liming treatments detached less than the control soil under the action of water jets acting within the same pressure range (0.69–96.5 kPa). In the analysis, we used some transmittance levels and their corresponding pressure levels for comparisons. However, the whole curves shown in Figure 3 could also be used to make comparisons. Curves that were higher on the transmittance scale (vertical axis in Figure 3) detached less than those at lower

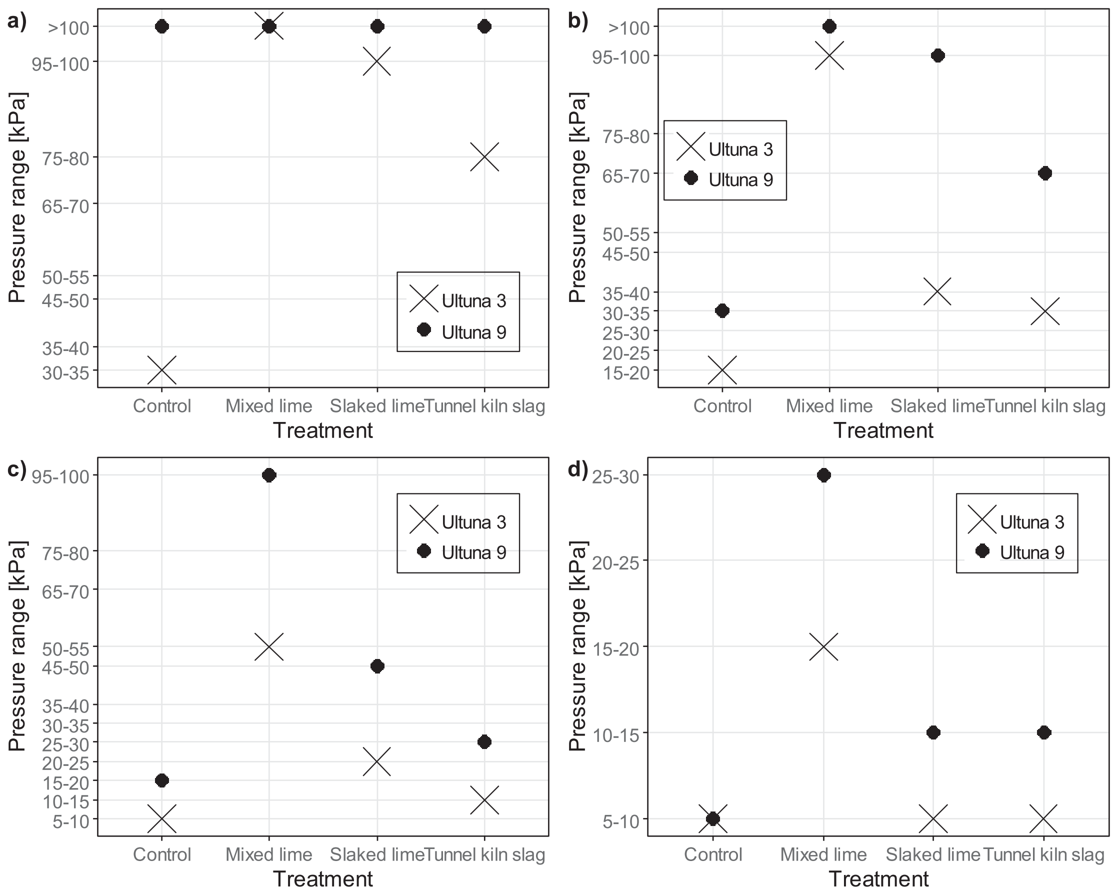

Figure 4. Critical jet pressures in cohesive strength meter (CSM) tests when applying a transmittance threshold value of: (a) 10%, (b) 30%, (c) 50% and (d) 70% to soils from the control and different liming product treatments at Ultuna 3 and Ultuna 9. Pressure range estimates are taken from Figure 3.

values for a particular range of applied pressures. Thus the control soil curves reached lower transmittance values at lower pressures than the curves of the soils with different liming treatments (Figure 3). This provides a visual indication that the liming treatments improved soil resistance to detachment. The results of CSM tests could be complemented by determining the relationship between CSM jet pressure and the pressure acting at the soil surface, using methods similar to those proposed by Vardy et al. (2007) or novel methods for measuring the pressure acting at the soil surface. This could shed light on the actual water forces involved in the detachment process as characterised with the CSM. Regardless of the absolute pressure acting at the surface of the soil sample, the CSM measurement is sufficient for comparison purposes, since is the result of direct measurements under the same conditions.

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Disclosure statement

No potential conflict of interest was reported by the authors.

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Ingrid Wesström is an Associate professor (Docent) in Soil Science specialising in Hydrotechnics at the Swedish University of Agricultural Sciences. Her research has been focused within the area of agricultural water management at different spatial and temporal scales in different climate zones. Her current research involves climate adaption of farming methods for optimising the use of land and water resources while minimising negative environmental side effects.

Abraham Joel is an Associate professor (Docent) in Soil Sciences specializing in Agricultural Water Management at the Swedish University of Agricultural Sciences. His research has been focus in soil and water management in agriculture with special attention to understanding and assessing the dynamics of runoff, soil erosion, water fluxes in soil/field. He is also work with development of methods for assessing some of the soil physical properties such as infiltration capacity, particle size distribution, soil erodibility and soil shear strength. The more applied research is related to the implementation of this knowledge in technologies for soil and water management such as irrigation, water harvesting, soil conservation, water diversion and storage and crop production systems.

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