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Structure liming reduces draught requirement on clay soil

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ABSTRACT

Liming with 'structure lime', comprising approximately 80–85% ground limestone and 15–20% slaked lime, has been promoted in subsidised environmental schemes in Sweden since 2010 to increase clay aggregate stability and mitigate particulate phosphorus losses to surface waters. To date, approximately 65,000 ha have been structure-limed. Apart from stabilising aggregates, liming may also improve other physical properties, such as soil strength. This study examined the effect of increasing application rate (0–16 t ha^{-1}) of structure lime on soil strength, approximated by horizontal (draught requirement) and vertical (penetrometer resistance) measurements, in eight field soils (clay content 26–38%) to which structure lime had been applied two, three, four or six years previously. Draught requirement when cultivating with a multipurpose cultivator significantly decreased (by 11%) with the highest application rate of structure lime (16 t ha^{-1}) compared with an unlimed control. This reduced the wheel power requirement by 7.1 kW and diesel consumption by 1.2–1.4 L ha^{-1}, and lowered CO_2 emissions by 3–4 kg ha^{-1}. To clarify the general effect of structure liming, the mean value of all limed treatments was compared with that of the unlimed control. This showed that structure liming in general significantly reduced the draught requirement (by 7%). However, penetrometer resistance measurements revealed no significant effects of structure liming and no relation between draught requirement and penetrometer resistance measurements. Overall, the results indicate that structure liming can reduce fuel consumption, due to easier soil tillage, and thus lower CO_2 emissions.

1. Introduction

Lime as a soil amendment is used primarily to counteract acidity and increase soil pH (Holland et al., 2018), which in turn improves the availability of plant nutrients (Dinkecha and Tsegaye, 2017). Liming can also improve soil biological characteristics (Mccallum et al., 2016 and physical properties (Falah et al., 2018; Ulén and Etana, 2014). However, the predicted soil physical transformations do not always materialise (Hellner et al., 2018), probably because of diminishing effects of liming over time (Bölscher et al., 2021) and interference from soil disruption during tillage (Auler et al., 2017; Frank et al., 2019). Effects of liming on soil characteristics have also been shown to be site-specific (Bölscher et al., 2021) and can even vary within short distances in the field (Blomquist et al., 2018).

One of the soil physical traits that may be affected by liming is shear strength, the magnitude of which is determined by cohesion of the soil material and friction between soil particles (Marshall et al., 1996). Cohesion of soil is influenced by inherent properties, such as texture and mineralogy, but is also strongly dependent on soil moisture, increasing rapidly with decreasing soil water content (Löfkvist, 2005). Schjønning (2021) showed that normal load, preload suction stress, bulk density, clay and organic matter content explained > 90% of the variation in shear strength in light clay soils (3.8–15.7% clay).

The compactness of the soil is another crucial factor, since both cohesion and friction increase as the soil particles come into closer contact (Löfkvist, 2005). A link between soil strength and draught requirement has been demonstrated by Tullberg (2000), who detected increased draught requirement in soil following wheel traffic.

The aim of the present study was to determine the effect of liming on soil strength in eight arable Swedish soils with varying clay content. Soil strength was approximated by horizontal (draught requirement at tillage) and vertical (penetrometer resistance) measurements in the

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field. The liming product used was 'structure lime', an ~80–20 mixture of ground limestone and slaked lime, which has been used in subsidised environmental schemes in Sweden for the past decade to mitigate phosphorus losses from clay soils. The product is similar to the lime kiln dust tested in other studies (Alakukku and Aura, 2006). Structure liming is recommended by the Swedish Board of Agriculture in order to reduce nutrient losses from agriculture (Andersson et al., 2021). In particular, it has been demonstrated to reduce the risk of particulate phosphorus losses by improving aggregate stability on clay soils (Blomquist et al., 2018). Structure liming may also have other positive impacts on agronomic soil properties and functions, such as a reduction in draught requirement at tillage and reduced soil mechanical resistance to root growth.

Soil variables such as soil moisture content (Arvidsson et al., 2004), organic matter content (Watts et al., 2006) and clay content (Arvidsson and Keller, 2011) can affect the draught requirement. Previous studies have also shown that application of calcium carbonate or calcium oxide can reduce the draught requirement (Siman et al. (1984) and that application of calcium carbonate can reduce penetrometer resistance in field soils (Kirkham et al., 2007; Valzano et al., 2001). However, to our knowledge the impacts of structure lime products currently in use in Sweden on the draught requirement for tillage have not been studied previously. The present study therefore quantified the effect of increasing application rate of structure lime on draught requirement and penetrometer resistance in clay soils at four sites in southern Sweden.

2. Materials and methods

2.1. Study area and sites

The work was carried out within a set of existing field trials examining the effect of structure lime on clay aggregate stability and the accompanying risk of phosphorus losses. Those trials, located at multiple sites in Scania, the southernmost county of Sweden (Table 1), encompassed soils with different characteristics known to modify the effect of structure lime and phosphorus losses, such as clay and organic matter content. Two field trials at each of four sites (Kornheddinge, Stureholm, Skottlandshus and Hulta) were selected for this study.

At the different field sites, structure lime was applied in summer-autumn 2014, 2016, 2017 and 2018 (Table 1). The product was spread on the soil surface and incorporated by disc or tine cultivator to 5–15 cm depth within one or two days of spreading. Measurements of draught requirement and penetrometer resistance in the field plots were carried out in August and September 2020, i.e. two, three, four or six years after application of structure lime. Site coordinates, date of application of structure lime and date of soil strength measurements are summarised in Table 1.

2.2. Soil characteristics

Soil texture, SOM content and pH_{H2O} value at the eight field trials are summarised in Table 2. Soil clay content at the field trials ranged from 26% to 38%, and soil organic matter (SOM) content ranged from 2.6% to 5.2%. The variation in SOM and clay content, properties expected to be decisive for soil strength, between the field trials is illustrated in Fig. 1.

Table 1
Site coordinates, date of application of structure lime and date of measurements of draught requirement and penetrometer resistance.

Site	Coordinates	Date of liming	Date of draught requirement and penetrometer measurements
Kornheddinge	55.63°N, 13.29°E	28 Sept. 2014	11 Aug. 2020
Stureholm	56.19°N, 12.76°E	30 July 2016	2 Sept. 2020
Skottlandshus	56.07°N, 14.06°E	24 Aug. 2017	12 Aug. 2020
Hulta	56.19°N, 12.66°E	22 Aug. 2018	11 Aug. 2020

Table 2
Soil organic matter (SOM), soil texture and pH_{H2O} value (0–20 cm) at the eight field trials before structure liming. Values are averages of all 12 plots in each trial.

Field trial	SOM[a]	Sand[b]	Silt[c]	Clay[d]	pH_{H2O}
		> 60 μm	2–60 μm	< 2 μm	
Kornheddinge LC	2.8	49.9	24.3	25.8	7.8
Kornheddinge HC	2.6	45.8	25.8	28.5	7.8
Stureholm LC	4.4	35.8	28.9	35.3	7.0
Stureholm HC	4.4	30.0	32.4	37.6	7.0
Skottlandshus LO	4.1	18.0	44.4	37.6	8.3
Skottlandshus HO	5.2	18.8	50.2	31.0	7.1
Hulta LP	3.8	45.3	25.9	28.8	7.0
Hulta HP	3.9	43.8	29.1	27.1	7.3

[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.

2.3. Experimental design and liming product

The experiments were laid out in a randomised block design with three replicates (plot size 12 m x 20–24 m) and included four treatments with increasing application rate of structure lime. These treatments were an unlimed control (SL0) and 4 (SL0.5), 8 (SL1) and 16 (SL2) t structure lime ha^{-1}, where 8 t ha^{-1} is the standard rate in Sweden, and the other two limed treatments are aimed to represent half and double application rates. The structure lime product used (Nordkalk Aktiv Struktur/Fostop Struktur; Nordkalk Corporation, Pargas, Finland) was a mixture of approximately 80–85% ground limestone and 15–20% slaked lime, with a water content of 15–25% and bulk density 0.8–1.0 t m^{-3}. The general chemical composition of the structure lime product is shown in Table 3.

2.4. Water content measurements

At the time of draught measurements and penetration measurements in 2020, soil samples (0–10 cm depth) were collected for determination of water content. A sample of approximately 100 g of loose soil from each plot was weighed, oven-dried overnight at 105 °C and weighed again, and soil gravimetric water content was calculated.

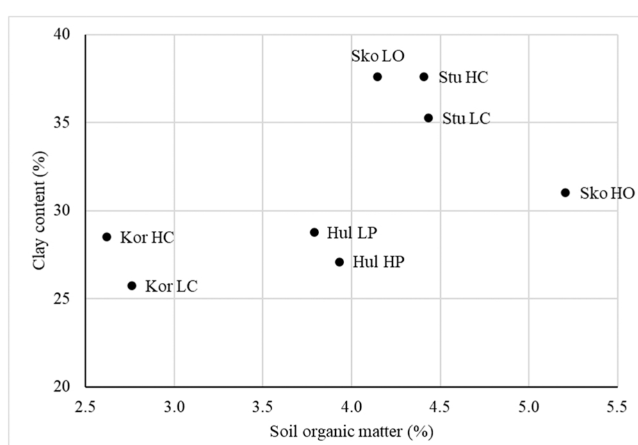

Fig. 1. Plot of initial soil organic matter and clay content at the eight field sites before structure liming. Kor=Kornheddinge, Stu=Stureholm, Sko=Skottlandshus, Hul=Hulta. LC/HC=low/high clay content, LO/HO=low/high organic matter content, LP/HP=low/high plant-available phosphorus content.

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.

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	1–58
S	0.1–1.7	Zn	70–280
P	0.07–0.2		

Source:Source: Nordkalk Corporation.

2.5. Draught requirement measurements

Draught requirement is a composite of several strength components in the soil, with horizontal resistance probably being the greatest contributor. The draught requirement was measured within a few days of harvest in untilled stubble of the preceding crop, using a multipurpose cultivator (Väderstad TopDown 400) with 4 m working width and fitted with discs and tines (80 mm point width), pulled by a tractor (John Deere 6215 R) (Fig. 2).

The tractor, cultivator and measuring equipment were provided and maintained by the cultivator manufacturer (Väderstad AB, Väderstad, Sweden). A cultivator towing eye fitted with an integral traction meter connected to a computer was used for the draught requirement measurements. It is based on a 50 mm towing eye (Scharmueller GmbH & Co. KG, Fornach, Austria) and fitted with sensors developed by Väderstad AB that can measure forces in three directions and which have been calibrated using strain gauges (Fig. 3).

The forward speed of the tractor plus cultivator was 8 km h^{-1} and the working depth was set at 12 cm. During measurements of draught requirement, the cultivator discs were lifted and only the tines worked the soil. The consolidating roller behind the cultivator was kept floating with its own weight and without pressing the soil.

At the Kornheddinge site, two passes were made through each experimental plot with the cultivator and during each pass the draught requirement was measured for 3 s, which gave approximately 1500 measured values per pass on 6.67 m per plot. At Stureholm, Skottlandshus and Hulta, four passes were made through each plot with the cultivator and during each pass the draught requirement was measured for 2 s, which gave approximately 1000 measured values per pass on 4.44 m per plot. The measured values were converted to kN.

Fig. 2. Draught requirement measurements at the Hulta HP site in August 2020.

Fig. 3. The cultivator towing eye fitted with a built-in-traction meter to measure forces in three directions.

2.6. Penetrometer resistance measurements

Since draught requirement measurements are expensive and time-consuming, complementary penetrometer resistance measurements were made to determine vertical resistance in the soil, as they can be carried out easily. These measurements were made with an Eijkelkamp Penetrologger (Eijkelkamp Soil & Water, Giesbeek, the Netherlands) with 1.0 cm^2 cross-sectional area, 60^o cone and penetration velocity of 2 cm s^{-1}. At 10 points within each test plot, the penetrometer was inserted to a depth of at least 15 cm in untilled soil. The measurements were made in a zigzag pattern, with five measurements in the right-hand side of each plot and five measurements in the left-hand side, all at least 3 m from the plot boundary. The measurements were made in Newtons and recalculated to MPa.

Measurements in August 2020 were made under very dry conditions and in the Hulta LP plots the penetrometer could not be used due to very hard, desiccated soil. Tramlines passing through the area also interfered with the draught requirement measurements in those plots. For these reasons, data for the Hulta LP plots were excluded and soil resistance data from only seven locations were analysed and included in the results. However, water content data for all eight locations were included.

2.7. Statistical analyses

Gravimetric water content values were analysed using General Linear Model in Minitab (Minitab 18, Minitab Inc.), while draught requirement and penetrometer resistance values were analysed using PROC MIXED in SAS version 9.4 (SAS Institute, Cary, NC, USA). To compare the untreated control with the treatments in general, the control value for each experimental site was compared against the mean value of the three liming treatments. Backward elimination of soil variables and water as covariates to draught requirement was executed using a Mixed Model in Minitab, with trial, treatment and the interaction between trial and treatment used as fixed factors, and block nested in trial as a random factor. Pairwise comparisons of treatment averages were made according to Tukey's test. Unless otherwise stated, the significance level used in the calculations was $p \leq 0.05$.

3. Results and discussion

3.1. Water content

Analysis of variance showed significant differences in gravimetric water content between the eight trials ($p < 0.001$). The average water content in the four treatments across all eight trials was 11.8–12.0%, which is close to the physical wilting point on these types of soils (Andersson and Wiklert, 1972), with no significant differences between the treatments ($p = 0.798$). Gravimetric water contents from all trials are presented in Supplementary Table 1.

In a previous study, Arvidsson et al. (2004) compared different tillage implements (mouldboard plough, chisel plough, disc harrow) and showed that working depth, draught requirement and specific draught requirement (force per cross-sectional area of worked soil) were heavily dependent on moisture content, with e.g. draught requirement increasing with decreasing water content. In a subsequent study, Arvidsson and Keller (2011) observed a strong relationship between soil water content and soil strength, both for cohesion (calculated from shear vane measurements) and penetrometer resistance. The relationship between moisture content and draught requirements measurements was also pointed out by Berglund (1977), who found that soil water content affects the draught requirement more strongly on clay soils than on lighter soil types. Thus, as soil water content affects both draught requirement and penetrometer resistance, it was of crucial importance that the moisture content did not differ between the treatments in the present study and possibly mask the effect of structure liming.

3.2. Draught requirement

The analyses showed that initial pH, plant-available calcium (Ca-AL content), SOM content and sand content, or combinations of these variables, did not significantly influence the effect of liming treatment on draught requirement. The only variable that affected the outcome was clay content ($p = 0.021$). For this reason, the analysis continued with clay content as a covariate. The mean draught requirement at tillage as a function of lime application rate is shown in Fig. 4. Draught measurements from seven trials are presented in Supplementary Table 2.

With clay content included as a covariate, there were significant differences in draught requirement between the trials ($p < 0.001$), and significant treatment effects ($p = 0.002$), but no interaction between trial and treatment ($p = 0.43$). Pairwise comparisons revealed significant differences between SL0 and SL2, but not between on the one hand the control SL0 and on the other hand SL0.5 and SL1 (Fig. 4).

Structure lime was applied in four different years at the four different sites. On analysing the different sites (two trials per site) separately, a significant treatment effect ($p = 0.014$) was found for Kornheddinge (average clay content 27% for both trials). At Stureholm (average clay content 36% for both trials), there was no significant treatment effect ($p = 0.11$) and the same results were achieved for Skottlandshus (average clay content 34% for both trials, $p = 0.28$ for treatment) and Hulta HP (average clay content 28% for the trial, $p = 0.61$ for

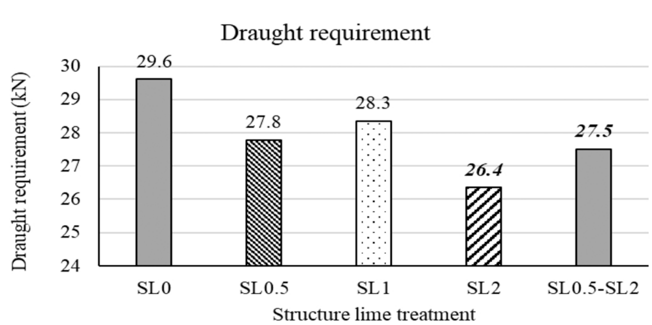

Fig. 4. Draught requirement at tillage (August-September 2020) as a mean for seven of the eight trials studied (Hulta LP excluded) with increasing application rate of structure lime: SL0 = control, SL0.5, SL1 and SL2 = 4, 8 and 16 t ha^{-1} structure lime, respectively. Values in bold italics indicate a significant difference compared with the control. Included is also the contrast (SL0.5-SL2) which is the average of the limed treatments compared to the unlimed control.

treatment). In other words, there was a significant treatment effect on draught requirement at the site where the structure lime had been applied six years prior to the draught requirement measurements, but not at the sites where lime had been applied only two, three and four years prior to the measurements. This can indicate that the processes involved in structure formation when lime is mixed with soil, which include cation exchange, flocculation, carbonation and pozzolanic reactions as described by Choquette et al. (1987), may take time to develop. Such time-dependency was observed by Kavak and Baykal (2012) when measuring unconfined compression strength over a 10-year period following application of hydrated lime to a kaolinite clay.

To assess the general effect of structure lime on draught requirement, the values obtained for the untreated control at the different experimental sites were compared against the mean value of all structure liming treatments (4, 8 and 16 t ha^{-1}). This revealed a significant effect of structure liming ($p = 0.002$), with a mean decrease in draught requirement of 7% (27.5 kN in limed treatments compared with 29.6 kN in the control according to Fig. 4).

In previous studies, different soil variables have been found to be related to the draught requirement. For example, Watts et al. (2006) evaluated the relative importance of clay content (18–38%), soil organic carbon (1.13–1.51%) and management practices such as application of farmyard manure on specific draught using a mouldboard plough in the long-term field experiments at Rothamsted, UK. They found that specific draught requirement increased with increasing clay content and decreased with increasing soil organic carbon content. With clay as covariate in the model in the present study, the coefficient showed that draught requirement increased by 0.31 kN for each 1% increase in total clay content, which is in line with findings by Watts et al. (2006) and also Peltre et al. (2015). However, for soil organic matter we found only a non-significant effect on draught requirement, which was slightly surprising as the SOM content in the field soils ranged from 2.6% to 5.2% (Table 2). Likewise, in lighter Danish soils (clay content 8.9–10.6%), SOC in the range from 0.98% to 1.36% had little effect on draught requirement (Peltre et al., 2016).

A field study by Ericsson et al. (1975) examined draught requirement on a heavy clay soil with increasing application rate of calcium oxide from 0 to 40 t ha^{-1}, under dry and moist conditions, and found that higher rates decreased the draught requirement considerably under dry conditions. However, the draught requirement was decreased markedly by 25 mm of rain falling approximately one week later, when the measurements were repeated, with e.g. the draught requirement in unlimed soil decreasing by 85% compared with that measured under dry conditions. Ericsson et al. (1975) found that draught requirement measurements performed on a silty soil were unaffected by the lime treatments, leading them to suggest that clay content is a determinant of soil structural changes as a result of liming.

In field trials, Siman et al. (1984) evaluated the effect of increasing application rates of calcium carbonate or calcium oxide on draught requirement, measured with a goosefoot point pulled at 2 km h^{-1} at a working depth of 15 cm. Measurements carried out over a 10-year period after lime application showed that both liming products significantly decreased the draught requirement, but in different ways. Stepwise increases in the application rate of calcium oxide successively decreased the draught requirement, whereas for calcium carbonate the decrease in draught requirement was independent of the application rate and occurred already with the lowest application rate (Siman et al. (1984). No plausible explanation was given for the findings relating to calcium carbonate, but they fit rather well with our finding of no clear linear relationship between application rate and draught requirement for a structure lime product consisting of approximately 80% percent calcium carbonate (Fig. 4).

Addition of organic material has been shown to reduce both mouldboard plough draught requirement and fuel consumption on clay (Liang et al. (2013). Likewise, the results in the present study pointed to lower draught requirement with structure lime application as a management strategy, which in turn means reduced fuel consumption. The significant draught requirement decrease of 3.2 kN at the highest liming rate (16 t ha^{-1}) compared with the control corresponded to a reduction in wheel power requirement of 7.1 kW at cultivation depth 12 cm, 4 m cultivator working width, and working speed 8 km h^{-1}. The fuel to wheel efficiency for a diesel vehicle is in the range of 20–24% (Kobayashi et al., 2009). Based on this and the reduction in wheel power requirement, the reduction in diesel fuel input to the engine is in the range of 30–35 kW. With a lower heating value in diesel fuel of 10.0 kWh L^{-1}, calculated from 42.6 MJ kg diesel^{-1} (Kumar and Chaurasia, 2019) and a density of 846 kg m^{-3} diesel (Kumar and Chaurasia, 2019) the fuel savings will be 3–3.5 litre diesel per working hour. With a field working capacity in the cultivation of 2.56 hectare per hour, when the working efficiency is set to 80%, the reduced diesel consumption is calculated to 1.2–1.4 L ha^{-1}. According to Mickūnaitis et al. (2007) the amount of CO_2 emission of burnt diesel fuel is 2.69 kg L^{-1}. Based on this data and the reduced diesel consumption per hectare, the savings of CO_2 emissions can be calculated as 3.1–3.7 kg CO_2 per hectare, at the highest liming rate. Therefore, structure liming can benefit both practical farm management and the environment.

The lowest draught requirement, and the only significant change with increasing lime application rate, was achieved with the highest liming rate tested (16 t ha^{-1}), which was twice the current standard rate in Sweden. This is in accordance with findings in our previous study at the same field sites (Blomquist et al., 2022) on the effect of structure lime on aggregate stability, where the 16 t ha^{-1} rate further increased aggregate stability beyond what was achieved with the standard liming rate. This indicates that the standard application rate of 8 t ha^{-1} is not sufficient. However, doubling the standard rate would bring drawbacks in terms of higher investment costs and also increasing pH, which could lead to micronutrient deficiency.

3.3. Penetrometer resistance

Differences in penetrometer resistance was analysed for the mean value of the 1–10 cm layer. There were no significant treatment effects for all trials analysed together or separately, mainly due to the fact that the variation in the response was large. The mean penetrometer resistance for every 1–10 cm in the unlimed control was also compared with the mean values for the structure-limed treatments. This analysis showed no significant differences (all p-values >0.05). Therefore, while measurements of penetrometer resistance may be simple and more convenient, they did not provide an acceptable approximation of changes in draught requirement in field soil in this study. This is also obvious from the low R^2 value (4.7%) considering the values of draught versus the values of penetrometer resistance for the 84 plots. Penetrometer resistance data from seven trials are presented in Supplementary Table 3.

4. Conclusions

This study showed that application of structure lime (80–85% ground limestone and 15–20% slaked lime) improved the agronomic properties of clay soils (26–38% clay), as indicated by a 7% reduced draught requirement down to 12 cm depth. The implications of reduced draught requirement were a lower energy requirement for tillage, and thus 1.2–1.4 L ha^{-1} lower fuel consumption and reduced CO_2 emissions.

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Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data Availability

Data will be made available on request.

Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.still.2023.105703.

References

Alakukku, L. & Aura, E. Zero tillage and surface layer liming promising technique to reduce clay soil erosion and phosphorus loading. ASABE 2006 annual international meeting, July 9–12, 2006, Portland, Oregon: paper number 062191, 2006. 39: American Society of Agricultural and Biological Engineers.

Andersson, E., Kvarmo, P., Malgeryd, J., Hjelm, E., Stenberg, M., Listh, U., Börling, K., Jonsson, P., Johansson, C., 2021. Rekommendationer för gödsling och kalkning 2021. Jordbruksinformation 12-2020. Statens Jordbr. ⟨https://www2.jordbruksverket.se/download/18.dc97d8e176cea4b0ec29b80/1609846154443/jo20_12.pdf⟩.

Andersson, S., Wiklert, P., 1972. Markfysikaliska undersökningar i odlad jord XXIII (Soil Physical Studies in Cultivated Soils XXIII). Om de vattenhållande egenskaperna hos svenska jordarter. (Water-holding properties of Swedish soils.). Grundförbättring, Uppsala, pp. 53–143.

Arvidsson, J., Keller, T., 2011. Comparing penetrometer and shear vane measurements with measured and predicted mouldboard plough draught in a range of Swedish soils. Soil Tillage Res. 111, 219–223.

Arvidsson, J., Keller, T., Gustafsson, K., 2004. Specific draught for mouldboard plough, chisel plough and disc harrow at different water contents. Soil Tillage Res. 79, 221–231.

Auler, A.C., Pires, L.F., Caires, E.F., 2017. Surface and incorporated liming effects on clay dispersion, water availability, and aeration capacity of a Dystrudept soil. Bragantia 76, 433–446.

Berglund, G., 1977. Mikroaggregatanalysen som testmetod vid strukturkalkning. Institutionen för markvetenskap, Avdelningen för lantbrukets hydroteknik. Lantbrukshögskolan, Uppsala.

Blomquist, J., Simonsson, M., Etana, A., Berglund, K., 2018. Structure liming enhances aggregate stability and gives varying crop responses on clayey soils. Acta Agric. Scand. Sect. B Soil Plant Sci. 68 (4), 311–322.

Blomquist, J., Englund, J.-E., Berglund, K., 2022. Soil characteristics and tillage can predict the effect of 'structure lime'on soil aggregate stability. Soil Res.

Bölscher, T., Koestel, J., Etana, A., Ulén, B., Berglund, K., Larsbo, M., 2021. Changes in pore networks and readily dispersible soil following structure liming of clay soils. Geoderma 390, 114948.

Choquette, M., Bérubé, M.-A., Locat, J., 1987. Mineralogical and microtextural changes associated with lime stabilization of marine clays from eastern Canada. Appl. Clay Sci. 2, 215–232.

Dinkecha, K., Tsegaye, D., 2017. Effects of liming on physicochemical properties and nutrient availability of acidic soils in Welmera Woreda. Cent. Highl. Ethiop. Chem. Mater. Res. 9, 30–37.

Ericsson, J., Berglund, G., Persson, J., 1975. Kalktillstånd, kalk och kalkning. *Rapporter från avdelningen för växtnäringslära*. Lantbr. Upps. (nr 90).

Falah, M., Pouya, K.R., Tolooiyan, A., Mackenzie, K., 2018. Structural behaviour of an Australian silty clay (coode island silt) stabilised by treatment with slag lime. Appl. Clay Sci. 157, 198–203.

Frank, T., Zimmermann, I., Horn, R., 2019. The need for lime in dependence on clay content in arable crop production in Germany. Soil Tillage Res. 191, 11–17.

Hellner, Q., Koestel, J., Ulen, B., Larsbo, M., 2018. Effects of tillage and liming on macropore networks derived from X-ray tomography images of a silty clay soil. Soil Use Manag. 34, 197–205.

Holland, J., Bennett, A., Newton, A., White, P., Mckenzie, B., George, T., Pakeman, R., Bailey, J., Fornara, D., Hayes, R., 2018. Liming impacts on soils, crops and biodiversity in the UK: a review. Sci. Total Environ. 610, 316–332.

Kavak, A., Baykal, G., 2012. Long-term behavior of lime-stabilized kaolinite clay. Environ. Earth Sci. 66, 1943–1955.

Kirkham, J., Rowe, B., Doyle, R., 2007. Persistent improvements in the structure and hydraulic conductivity of a Ferrosol due to liming. Soil Res. 45, 218–223.

Kobayashi, S., Plotkin, S., Ribeiro, S.K., 2009. Energy efficiency technologies for road vehicles. Energy Effic. 2, 125–137.

Kumar, R., Chaurasia, O.P., 2019. A review on performance and emissions of compression ignition engine fueled with ethanol-diesel blend. J. Eur. Des. Syst. Autom. 52, 205–214.

Liang, A., Mclaughlin, N.B., Ma, B., Gregorich, E.G., Morrison, M.J., Burtt, S.D., Patterson, B.S., Evenson, L.I., 2013. Changes in mouldboard plough draught and tractor fuel consumption on continuous corn after 18 years of organic and inorganic N amendments. Energy 52, 89–95.

Löfkvist, J., 2005. Modifying soil structure using plant roots. https://pub.epsilon.slu.se/838/. Swedish University of Agricultural Science, Uppsala.

Marshall, T.J., Holmes, J.W., Rose, C.W., 1996. Soil Physics. Cambridge University Press.

Mccallum, H.M., Wilson, J.D., Beaumont, D., Sheldon, R., O'brien, M.G., Park, K.J., 2016. A role for liming as a conservation intervention? Earthworm abundance is associated with higher soil pH and foraging activity of a threatened shorebird in upland grasslands. Agric. Ecosyst. Environ. 223, 182–189.

Mickūnaitis, V., Pikūnas, A., Mackoit, I., 2007. Reducing fuel consumption and CO_2 emission in motor cars. Transport 22, 160–163.

Peltre, C., Nyord, T., Bruun, S., Jensen, L.S., Magid, J., 2015. Repeated soil application of organic waste amendments reduces draught force and fuel consumption for soil tillage. Agric. Ecosyst. Environ. 211, 94–101.

Peltre, C., Nyord, T., Christensen, B., Jensen, J., Thomsen, I., Munkholm, L., 2016. Seasonal differences in tillage draught on a sandy loam soil with long-term additions of animal manure and mineral fertilizers. Soil Use Manag. 32, 583–593.

Schjønning, P., 2021. Topsoil shear strength–measurements and predictions. Soil Tillage Res. 212, 105049.

Siman, G., Berglund, K., Eriksson, L., 1984. Effect of large lime quantities on soil structure, nutrient balance and crop yields. A. Effect of lime on soil properties, crop yields and nutrient concentrations in yield products (in Swedish). Rapport 148, Avdelningen för Växtnäringslära, Institutionen for Markvetenskap. Sveriges Lantbruksuniversitet, Uppsala.

Tullberg, J., 2000. Wheel traffic effects on tillage draught. J. Agric. Eng. Res. 75, 375–382.

Ulén, B., Etana, A., 2014. Phosphorus leaching from clay soils can be counteracted by structure liming. Acta Agric. Scand. Sect. B Soil Plant Sci. 64, 425–433.

Valzano, F., Murphy, B., Greene, R., 2001. The long-term effects of lime (CaCO3), gypsum (CaSO4. 2H2O), and tillage on the physical and chemical properties of a sodic red-brown earth. Soil Res. 39, 1307–1331.

Watts, C., Clark, L., Poulton, P., Powlson, D., Whitmore, A., 2006. The role of clay, organic carbon and long-term management on mouldboard plough draught measured on the Broadbalk wheat experiment at Rothamsted. Soil Use Manag. 22, 334–341.