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Effects of reduced tillage and liming on microbial activity and soil properties in a weakly-structured soil

Maria Stenberg[a,*], Bo Stenberg[b], Tomas Rydberg[a]

[a] Department of Soil Sciences, Swedish University of Agricultural Sciences, P.O. Box 7014, SE-750 07 Uppsala, Sweden
[b] Department of Microbiology, Swedish University of Agricultural Sciences, P.O. Box 7025, SE-750 07 Uppsala, Sweden

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Abstract

The effects of reduced tillage and lime on crop yield and soil physical and microbial properties were studied in a weakly-structured silty clay loam soil. Two autumn primary tillage practices were compared, mouldboard ploughing to 20–25 cm and cultivation to 12 cm. Seedbed preparation was carried out by several harrowing operations in the mouldboard ploughed treatment, and with a PTO-driven harrow in the same operation as sowing in the shallow cultivation treatment. The tillage treatments were applied alone or were combined with liming aimed at soil structural improvement. Lime was added as 6.5 Mg CaO ha^{-1} before the start of the experiment and mixed into the top 12 cm of soil with a disc cultivator. A 4-year crop rotation was used: spring barley, spring oilseed rape, spring/winter wheat and oats, and all crops were compared each year. Crop residues were retained in the experiment and incorporated at cultivation. Aggregate stability was improved by the shallower tillage depth, probably as an effect of an increase in soil organic matter and a more active microbial biomass. Liming had little effect on soil structure variables but increased microbial activity to some extent. This was reflected in higher crop yields, especially when the shallow tillage depth was combined with liming. Penetration resistance in the seedbed subsoil was highest when mouldboard ploughing was carried out in plots without liming. Data were examined with principal component analyses, and the structures in the data were presented as scores and loading plots, which revealed groupings between samples and relationships between variables, respectively. © 2000 Elsevier Science B.V. All rights reserved.

Keywords: Aggregate stability; Mouldboard ploughing; Reduced tillage; Soil microbial activity; Cereal–oil seed rotation; PCA; Penetration resistance

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1. Introduction

To maintain and improve good soil structure, the activity of soil organisms is crucial. The organisms form humus and particle aggregates and may improve soil aeration. Filamentous fungi, and actinomycetes in particular, entrap soil particles to form aggregates (Gupta and Germida, 1988; Dorioz et al., 1993). In addition, extracellular metabolites, e.g. polysaccharides, lipids and proteins from microbial degradation of plant residues and soil humus, function as gums and cementing agents, which stabilize the aggregates (Tisdall and Oades, 1982; Dorioz et al., 1993; Tisdall, 1994). Furthermore, the importance of soil organic carbon content for soil structural stability has been shown in several reports (e.g. Tisdall and Oades, 1982; Chaney and Swift, 1984). On weakly structured clay soils, hardening of the surface soil soon after sowing is often detrimental for crop establishment in spring (Stenberg et al., 1995). Generally these soils are also susceptible

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[*] Corresponding author. Tel.: +46-18-67-12-13; fax: +46-18-67-27-95.
E-mail address: maria.stenberg@mv.slu.se (M. Stenberg)

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to slaking of the soil surface after precipitation, which may promote excessive water losses through evaporation.

In an Australian soil, the tendency to hardset was inversely related to the soil organic carbon content (Chan, 1995). The input of fresh organic residues is especially important for the production of aggregating substances (Burns and Davies, 1986). Other management practices, which have a stimulating effect on the microorganisms, may have a similar outcome. Improvement of the pH by liming is one such practice (Balloni and Favilli, 1987).

Agricultural crop production in Sweden largely occurs on clay soils. These soils often have a favourable soil structure, deliver sufficient amounts of important plant nutrients and provide sufficient moisture if managed properly. However, clay soils with a high silt content have properties which often cause soil structure problems such as surface crust formation at plant establishment. In a laboratory experiment, addition of lime as CaO or $Ca(OH)_2$ increased aggregation and aggregate stability of clay soils (Berglund, 1971). In the field, improvements in soil structural stability of a clay soil may be sustained 8 years after application of lime in the form of CaO or $Ca(OH)_2$ (Ledin, 1981). Adding CaO or cement (64.4% (w/w) $CaCo_3$ as CaO) to a clay soil resulted in stabilization of soil against compaction, shrinkage and swelling. The addition of cement or gypsum ($CaSO_4$) to a sandy loam (12% clay) also stabilized the aggregates (Shanmuganathan and Oades, 1983).

In this investigation, the effects of reduced tillage and lime were evaluated in a weakly-structured silty clay loam soil. Crop yields and soil physical and microbial properties, characterizing the structure and fertility of this soil, were measured to evaluate the effects of soil management improvements.

2. Materials and methods

2.1. Experimental site and treatments

The experiment was started in autumn 1987 at Sundby in central Sweden (59°42′N, 16°40′E, altitude 30 m). The silty clay loam soil (Table 1) had previously been subjected to annual autumn mouldboard ploughing to 20–25 cm depth. The soil was a Cambisol (FAO) of postglacial origin. Soil water content in the plough layer at a matric tension of 1.5 MPa was 136 g kg^{-1}. Mean annual precipitation in the area in 1961–1990 was 578 mm and mean annual temperature (not measured) was estimated at 5.5°C from nearby meteorological data (Västerås and Sala Meteorological Stations; Alexandersson et al., 1991). The growing season usually extends from late April to October.

Table 1
Soil particle size distribution and organic matter content (g kg^{-1}) at Sundby

Depth (cm)	Particle size (μm)				Organic matter
	<2	2–20	20–200	200–2000	
0–20	392	320	258	31	25
40–60	554	272	161	13	–

When used for cereal and oil seed crop production, this soil is prone to slaking and crust formation. The experiment was started to evaluate the effect on soil properties of different management practices, such as addition of lime, tillage practices, nitrogen fertilization level and crop rotation. The crop rotation was spring/winter wheat–spring oats–spring barley–spring oilseed or peas. The experiment was divided into four sub-experiments with the full crop rotation running in each sub-experiment in such a way that all four crops were grown each year on the experimental site. All tillage, liming and nitrogen treatments were studied in each crop but without replication. Tillage and liming treatments were systematically placed between sub-experiments. The plot size was 12 m×22.5 m.

The measurements in this study were limited to two soil tillage systems (P and S) in plots with (WL: 6.5 Mg CaO ha^{-1}) or without (NL: no CaO) addition of lime at the start of the experiment and with normal nitrogen fertilizer amounts:

1. (P) Primary tillage: autumn stubble cultivation once (12 cm depth) and autumn mouldboard ploughing (20–25 cm depth) Secondary tillage: three harrowings (4–5 cm depth with a spring-tine harrow) as seedbed preparation and separate sowing.
2. (S) Primary tillage: stubble cultivation three times (12 cm depth) in autumn. Secondary tillage: seedbed preparation (4–5 cm with PTO driven harrow) and sowing in one operation.

In July 1987, at the start of the experiment when the experimental area was under black fallow, 6.5 Mg calcium oxide (CaO) ha^{-1} was added to WL plots and mixed into the soil with a disc cultivator to 12 cm depth. Annual stubble cultivation was carried out once soon after harvest in all plots, then two more times in S, the last one soon before ploughing in P. Crop residues were retained in the experiment and incorporated at cultivation. All plots were combi-drilled. That is, fertilizer was placed in every second inter-row about 2 cm below the seeds in the same operation as sowing. The rate of nitrogen fertilizer added in the spring was 90 kg ha^{-1} for all cereal and oil-seed crops except winter wheat where 90–110 kg ha^{-1} was used according to local recommendations based on expected crop yields. Sowing of spring-sown crops could generally be carried out some days earlier in S than in P. Pesticides were applied according to local recommendations. Grain yields were measured in each plot at harvest. Crop yields from 1988–1995 are presented.

2.2. Sampling

Soil sampling (40 disturbed samples per plot) for chemical and microbiological laboratory analyses and aggregate stability determinations were carried out on 26 April 1995, before fertilizing and sowing were carried out on 8 May. All samples were taken in the topsoil, which was divided into two layers: 0–12 and 12–24 cm. On 9–11 May, undisturbed cylindrical soil cores from the 4–9 and 17–22 cm soil layers were taken with steel cylinders, 50 mm high and 72 mm in diameter, for physical laboratory analyses. Air permeability was measured on 9–11 May. Penetration resistance was measured on 26 May.

2.3. Measurement of soil parameters

2.3.1. Physical soil analyses

To determine the stability of aggregates in the sampled soil, a number of measurements were carried out. Tensile strength (Y, N mm^{-2}) was measured by a crushing test on 20 oven-dried (105°C, 24 h) aggregates with 12 mm average diameter, sieved from each disturbed soil sample (Dexter and Kroesbergen, 1985). Aggregate stability in the wet condition determined as dispersed clay after shaking (Watts et al., 1996) was measured on 12 aggregates per sample, stored air-dry and then re-wetted before measurements. Dispersed clay after shaking was measured on a turbidimeter (T, mg dispersed clay g^{-1} dry soil aggregate). A stability index (AGS) was calculated from the aggregate stability measured in wet and dry conditions, respectively: $\mathrm{AGS}=(1-T/T_\mathrm{r})(1-Y/Y_\mathrm{r})$ where T_r and Y_r are reference values for artificially made, remoulded aggregates (Watts et al., 1996). The friability (Frb) of the aggregates was calculated as $\sigma_\mathrm{Y}/Y \pm \sigma_\mathrm{Y}/(Y(2n)^{1/2})$ where Y is the average tensile strength for each sample, σ_Y is the standard deviation of the measured values of tensile strength, n is the number of replicates and $\pm\sigma_\mathrm{Y}/(Y(2n)^{1/2})$ is the standard error of the coefficient of variation (Watts and Dexter, 1998).

Dry bulk density (BD, g cm^{-3}) and soil water content (WC, g $(100\,g)^{-1}$ soil) were measured on the undisturbed soil cores (two per plot). The cores were oven-dried at 105°C for 72 h before weighing.

Soil water content at 0.5, 3, 10, 60 and 300 kPa matric tension was also determined on the undisturbed soil cores using standard porous sand blocks and ceramic plates. The measurements were carried out after saturation of the cylinders, which occurred slowly from the base, but before BD determination. Total porosity (TPV, %) was calculated from the dry bulk density and particle density of the soil in the sampled cores. Equivalent pore diameters were calculated from the measured water contents at the different tensions (Childs, 1940; Andersson, 1962) and were expressed in eleven pore diameter classes: <1, >1, 1–5, <5, 5–30, <30, >30, 30–600, 30–100, 100–600 and >600 μm. Water content at −1500 kPa was determined on separate soil samples.

Soil penetration resistance (Pen, kPa) was determined with a Bush recording penetrometer (Anderson et al., 1980) with a cone diameter of 12.8 mm. The resistance was registered at 2 cm increments.

Soil air permeability was measured in the field after sowing operations (Green and Fordham, 1975; Lindström et al., 1990). Air permeability was measured on undisturbed soil in steel cylinders, 10 cm high and 72 mm in diameter, both with the cylinders in the ground ($K_\mathrm{ai}d$, μm^2) and removed ($K_\mathrm{ai}u$, μm^2) from the ground. The soil sample within the cylinder was 5 cm high.

2.3.2. Microbiological and chemical soil analyses

All microbiological tests were run in triplicate as described by Stenberg et al. (1998a).

The basal respiration rate (B-res, μg CO_2–C g^{-1} DM h^{-1}) and substrate induced respiration (SIR, μg CO_2–C g^{-1} DM h^{-1}) were analyzed. The evolution of CO_2 was determined hourly with a respirometer (Respicond III, Nordgren Innovations AB, Umeå, Sweden). The B-res was calculated as the average respiration rate over the 40 h interval between 200–240 h incubation. The SIR was measured after the basal respiration by mixing a substrate consisting of glucose, talcum powder and $(NH_4)_2SO_4$ into each sample. SIR was used as a microbial biomass indicator and was calculated with nonlinear regression as the sum of initial CO_2–C evolved by growing and nongrowing organisms (Stenström et al., 1998). The specific respiration (qCO_2) was calculated as the ratio between B-res and SIR.

The nitrogen mineralization capacity (N-min, μg $NH_4{}^+$–N g^{-1} DM 10 days) was analyzed under anaerobic incubation (Waring and Bremner, 1964). Samples were incubated for 10 days at 37°C before extraction and analysis of $NH_4{}^+$. The potential ammonium oxidation rate (PAO, μg $NO_2{}^-$–N g^{-1} DM min^{-1}) was assayed as accumulated nitrite according to the chlorate inhibition technique (Belser and Mays, 1980). The potential denitrification activity (PDA, μg N_2O–N g^{-1} DM min^{-1}) was assayed according to the C_2H_2 inhibition method (Smith and Tiedje, 1979). From these data the specific growth rate of the denitrifiers (μPDA, min^{-1}) was also calculated (Pell et al., 1996).

Soil pH was determined in 0.02N CaCl solution. Soil organic carbon content (C-org, %) and total nitrogen (N-tot, %) were measured on a Leco® CNS-2000.

2.4. Data analyses

Only interactions between treatments could be tested by analysis of variance due to the lack of replicates within each sub-experiment. Standard deviations for the variables are presented.

To reveal similarities and differences between the sampled plots, and the relationships between the different variables, principal component analysis (PCA, Wold et al., 1987) was performed on all analyzed soil data. For this the Unscrambler® software package (Camo A/S, Trondheim, Norway) was used. The components extracted in PCA models are linear representatives, which describe the maximum variation in the original data set. In a PCA model the objects (soil samples) are represented by their scores and the variables are represented by their loadings. The scores and loadings can be presented in graphs where two components (as score vectors or loading vectors) are plotted against each other. In score plots, similar samples will be positioned close to each other. In loading plots, positively and negatively correlated variables will be positioned close to each other, or opposite each other, respectively. Samples that are high in a specific variable will be pulled towards the area of the score plot where the variable in the corresponding loading plot is located. The number of components to be used was optimized through full cross validation (Wold et al., 1987). The number of variables was reduced by excluding those explained to less than 50% by the significant components.

3. Results and discussion

3.1. Crop yield

Crop yields, as means for all yields from 1988 to 1995, were higher on stubble cultivated soil than on mouldboard ploughed soil (Fig. 1 and Table 2). Liming also improved yields. Yields were highest in plots stubble cultivated and limed, but interactions were not statistically significant. In the last full crop sequence before soil property measurements, from 1991 to 1993 there were only small differences in yield between the treatments (data not shown). In 1994 all yields were relatively low, but considerably higher in the plots with reduced cultivation, especially in combination with lime (2538 kg ha^{-1} compared to mouldboard ploughed without lime 1305 kg ha^{-1}). In this year there were problems with early crust formation, which was followed by a long dry period. Thus, germination was inhibited. Stubble cultivation and liming reduced these problems compared to mouldboard ploughing.

3.2. Principal components

The reduced data set included 18 variables (Tables 3 and 4) and 81% of their total variation was explained by four significant principal components (Figs. 2–4). The omitted variables did not contribute to the separation of treatments. There were two exceptions:

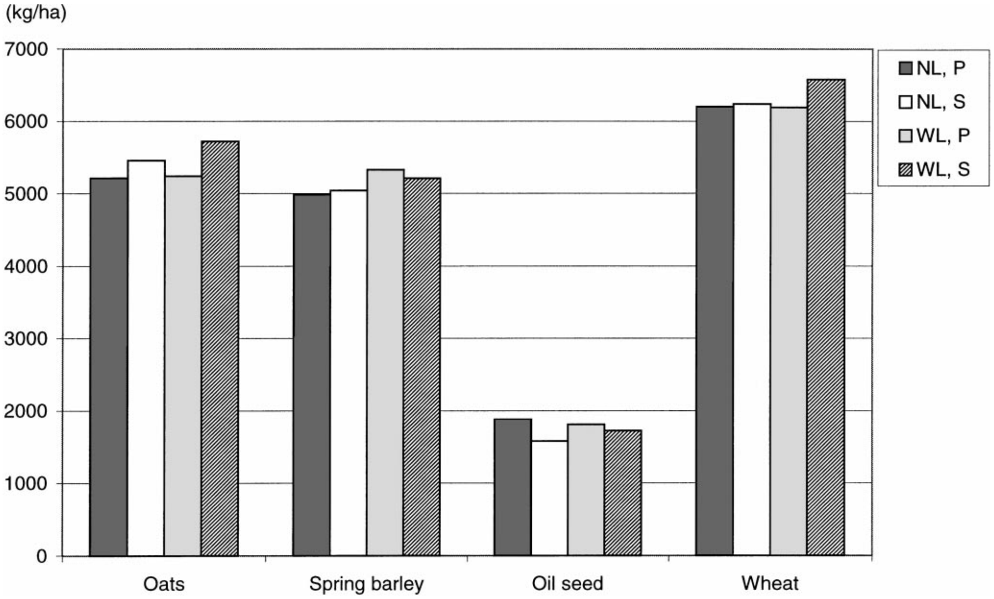

Fig. 1. Average yields (kg ha^{-1} at 85% dry matter) for each crop 1988–1995 at Sundby (NL=No CaO, WL=6.5 Mg CaO ha^{-1}, P=Mouldboard ploughing as primary tillage, S=Stubble cultivation as primary tillage).

(i) tensile strength of dry aggregates (Y) was not included as it correlated strongly (r^2=0.86) with the aggregate stability index (AGS) in which it is included, (ii) the total porosity (TPV) was excluded as it was derived from dry bulk density and as it strongly correlated to pores >30 μm (r^2=0.83). One sample, the 0–12 cm P–NL treatment cropped with oats, was excluded as an outlier, due to a large number of missing values.

Samples from the two layers of the topsoil and the different treatments were well separated by the four components, as illustrated by the score plots (Figs. 2–4). An increase in variables related to the organic matter, aggregate stability and pores <1 and >30 μm separated the stubble cultivated upper layers from the lower layers and somewhat from the intermediate mouldboard ploughed upper layers (Fig. 2B). In the 0–12 cm layer with reduced tillage a higher concentration of organic carbon was found, as was higher aggregate stability (Table 3). Substrate induced respiration (an index of microbial biomass), basal respiration rate and potentially mineralizable nitrogen were also increased (Fig. 2A, Table 3).

Table 2
Average grain yield (kg ha^{-1} at 85% dry matter) at Sundby 1988–1995 for all crops in treatments studied in the present investigation[a]

	Without CaO	With CaO	Average
Mouldboard ploughed	4570	4642	4606
Stubble cultivated	4579	4808	4693
Average	4575	4725	4650

[a] Interactions were not statistically significant.

The effects of shallower tillage in this experiment on microbial activities in the upper 12 cm are in agreement with other studies (e.g. Carter, 1991; Angers et al., 1993a; Friedel et al., 1996). As plant residues were only incorporated into the top layer in the S treatment, not only could a quantitative increase in organic matter be expected, but also a shift in quality towards younger and more labile fractions. Angers et al. (1993b) found significantly higher amounts of easily extractable carbohydrates in the surface layer under reduced tillage. The fraction ages of 1 to about 25 years are those making up the main pool for microbial degradation (Parton et al., 1985; Anderson and Domsch, 1986). Thus, the slightly higher metabolic quotient ($q\mathrm{CO_2}$) in the stubble cultivated top layer is in agreement with the theory of system development presented by Odum (1969) and adapted to soil

Table 3
Average variable values and standard deviations (S.D.) in the 0–12 cm layer for each treatment combination

Variable[a]	Stubble cultivated				Mouldboard ploughed			
	With CaO		Without CaO		With CaO		Without CaO	
	0–12	S.D.	0–12	S.D.	0–12	S.D.	0–12	S.D.
C-org	1.8	0.045	1.8	0.076	1.6	0.053	1.7	0.068
N-tot	0.16	0.007	0.17	0.009	0.15	0.007	0.16	0.005
C/N2	10.9	0.27	10.9	0.53	10.5	0.39	10.3	0.53
pH	6.9	0.136	6.2	0.066	6.9	0.039	6.0	0.123
B-res	0.44	0.037	0.43	0.058	0.29	0.053	0.27	0.036
SIR	6.4	0.59	6.3	0.37	4.4	0.40	5.0	0.84
*q*CO2	0.069	0.006	0.068	0.008	0.065	0.008	0.053	0.002
N-min	33	13.2	22	8.4	17	3.5	17	4.6
PAO	7.4	1.55	4.0	0.42	6.7	0.22	6.0	0.51
PDA	6.8	1.2	11.5	1.7	4.1	0.7	7.7	1.5
μPDA	0.0065	0.0011	0.0044	0.0013	0.0070	0.0005	0.0049	0.0013
WC	24.0	1.4	28.2	9.4	24.4	1.9	22.1	0.6
TPV[b]	49.3	2.7	49.6	2.7	49.4	2.5	48.6	3.2
<1	29.1	2.4	28.8	2.0	29.1	0.7	28.5	2.1
>30	13.8	5.5	14.4	4.9	14.0	2.7	13.8	5.5
BD	1.34	0.071	1.33	0.071	1.34	0.067	1.36	0.084
$K_{\mathrm{ai}}d$	143	30	397	206	93	81	240	227
$K_{\mathrm{ai}}u$	461	129	832	296	407	240	772	213
AGS	0.51	0.033	0.54	0.129	0.46	0.078	0.48	0.081
Y[b]	0.266	0.045	0.243	0.121	0.288	0.092	0.263	0.077
T[b]	16.9	1.3	16.5	5.2	20.0	5.8	19.9	4.4
Frb[b]	0.455	0.132	0.385	0.081	0.458	0.071	0.535	0.080
Pen	1039	91	1147	54	1066	109	1553	151

[a] C-org (total organic carbon, %); N-tot (total nitrogen, %); B-res (basal respiration rate, μg CO_2–C g^{-1} DM h^{-1}); SIR (substrate induced respiration, μg CO_2–C g^{-1} DM h^{-1}); $q$$CO_2$ (specific respiration, ratio between B-res; and SIR); N-min (nitrogen mineralization capacity, μg NH_4^+–N g^{-1} DM 10 days); PAO (potential ammonium oxidation rate, μg NO_2^-–N g^{-1} DM min^{-1}); PDA (potential denitrification activity, μg N_2O–N g^{-1} DM min^{-1}); μPDA (specific growth rate of the denitrifiers, min^{-1}); WC (actual water content, g $(100\,g)^{-1}$ soil); TPV (total porosity, %); <1 (porosity from pores with equivalent diameter <1 μm); >30 (porosity from pores with equivalent diameter >30 μm); BD (dry bulk density, g cm^{-3}); $K_{\mathrm{ai}}d$ (field air permeability with cylinders into soil, μm^2); $K_{\mathrm{ai}}u$ (field air permeability with cylinders removed from soil, μm^2); AGS (aggregate stability index); Y (dry tensile strength, N mm^{-2}); T (dispersed clay, mg dispersed clay g^{-1} dry soil aggregate); Frb (soil friability); Pen (penetration resistance, kPa).

[b] Not included in the model (not shown in Figs. 2–4).

microbiology by Anderson and Domsch (1985) who proposed qCO_2 as an index of system age. A change towards increased amounts of labile organic matter would result in a younger system with a higher turnover rate of organic matter.

The positive influence of organic matter on aggregate stabilisation is generally suggested to act through the activity of microorganisms. Microbially produced extracellular metabolites such as polysaccharides and proteins cement microaggregates together and improve their stability (Lynch, 1984; Gupta and Germida, 1988; Dorioz et al., 1993). The intermediate position of the 0–12 cm P samples on the first component was mainly due to the larger pores and lower bulk density in the topsoil layers, otherwise differences were small compared to the 12–24 layers (Tables 3 and 4). Interestingly, it was not possible to distinguish between stubble cultivation and mouldboard ploughing in the 12–24 cm layer. Thus, microbial activity and organic matter content were not decreased by shallow tillage due to reduced input of organic residues in the lower topsoil layer, as they increased due to increased input in the upper layer. Subsequently, there were no indications of a depletion of organic matter in the lower layers by reduced tillage, and organic matter content and microbial activity increased overall in the

Table 4
Average variable values with standard deviations (S.D.) in the 12–24 cm layer for each treatment combination

Variable[a]	Stubble cultivated				Mouldboard ploughed			
	With CaO		Without CaO		With CaO		Without CaO	
	12–24	S.D.	12–24	S.D.	12–24	S.D.	12–24	S.D.
C-org	1.6	0.083	1.6	0.071	1.6	0.051	1.6	0.097
N-tot	0.15	0.003	0.16	0.006	0.15	0.007	0.15	0.004
C/N2	10.5	0.61	10.5	0.53	10.4	0.46	10.3	0.73
pH	6.9	0.101	6.1	0.122	6.8	0.103	6.0	0.103
B-res	0.26	0.054	0.22	0.046	0.28	0.029	0.23	0.034
SIR	4.0	0.41	4.3	0.26	4.7	0.31	4.7	0.66
*Q*cO2	0.066	0.012	0.052	0.013	0.061	0.010	0.049	0.009
N-min	15	5.7	20	8.3	20	4.5	17	4.9
PAO	6.2	0.58	4.8	0.70	6.7	0.77	5.3	0.38
PDA	4.3	0.8	7.1	2.3	5.4	0.4	8.7	3.5
μPDA	0.0069	0.0006	0.0052	0.0012	0.0066	0.0009	0.0040	0.0016
WC	22.9	0.2	23.1	0.3	30.5	3.6	26.8	0.4
TPV[b]	41.6	1.6	41.7	2.5	44.7	1.4	44.2	1.7
<1	31.2	1.6	31.6	2.1	33.6	1.6	32.6	1.4
>30	4.9	3.5	4.7	5.1	3.2	2.6	4.3	3.3
BD	1.55	0.043	1.55	0.066	1.47	0.036	1.48	0.044
$K_{ai}d$	31	12	36	10	1	1	4	47
$K_{ai}u$	261	280	360	284	29	38	90	23
AGS	0.32	0.114	0.26	0.083	0.24	0.043	0.35	0.104
Y[b]	0.465	0.103	0.590	0.134	0.639	0.054	0.475	0.115
T[b]	23.1	8.0	21.6	1.9	18.9	7.4	19.9	3.7
Frb[b]	0.450	0.138	0.559	0.021	0.423	0.130	0.549	0.096
Pen	1669	105	1682	64820	86	951	95	

[a] See Table 3 for explanation of variable abbreviations.

[b] Not included in the model.

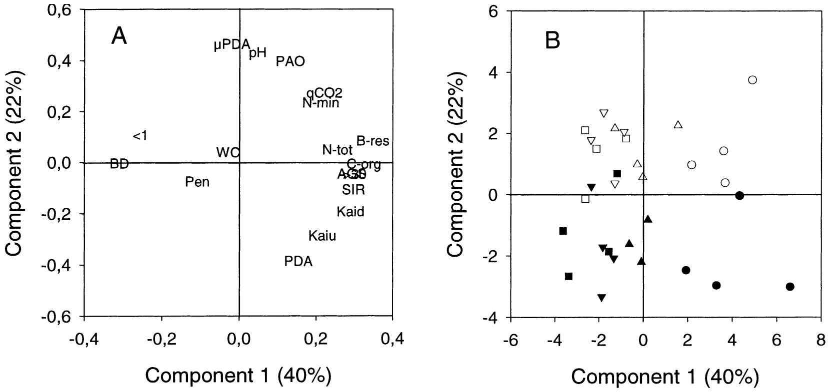

Fig. 2. Results of the PCA analyses. Principal components 1 vs 2. (A) Loading plot showing the relations between variables; (B) Score plot showing the relations between samples. Open symbols=with lime; Filled symbols=no lime; ●=stubble cultivated 0–12 cm; ■=stubble cultivated 12–24 cm; ▲=mouldboard ploughed 0–12 cm; ▼=mouldboard ploughed 12–24 cm. (A) and (B) can be read interactively as their respective quadrants correspond to each other (see Section 2.3). Abbreviations are explained in Table 3. The % variance explained by each component is given in parenthesis.

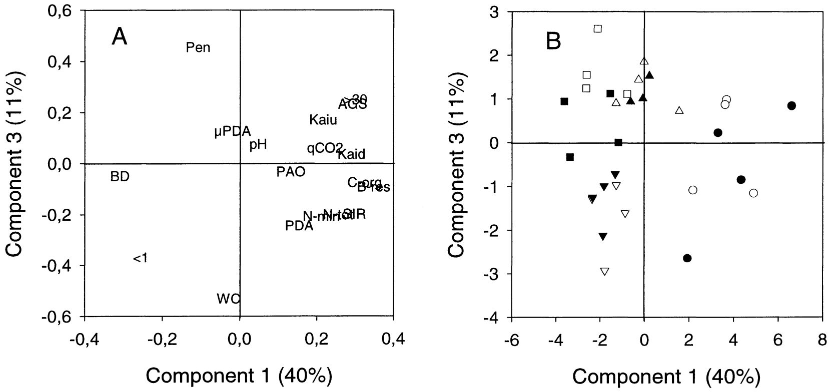

Fig. 3. Results of the PCA analyses. Principal components 1 vs 3. (A) Loading plot showing the relations between variables; (B) Score plot showing the relations between samples. Open symbols=with lime; Filled symbols=no lime; ●=stubble cultivated 0–12 cm; ■=stubble cultivated 12–24 cm; ▲=mouldboard ploughed 0–12 cm; ▼=mouldboard ploughed 12–24 cm. (A) and (B) can be read interactively as their respective quadrants correspond to each other (see Section 2.3). Abbreviations are explained in Table 3.

upper 24 cm. The explanation for this is probably a combination of effects. A carbon input remained in the 12–24 cm layer from root-exudates and residues, and dissolved organic carbon from the upper 12 cm could have leached down as suggested by Eghball et al. (1994). [b] In addition, with the higher yields under reduced tillage (Table 2), there would have been a higher total input of crop residues, although not measured here.

The second component separated liming and no liming (Fig. 2B). This was of course a result of higher pH in the limed plots. Higher nitrification capacity, higher specific growth rate of denitrifiers and lower potential denitrification rate were also apparent (Fig. 2A). None of the variables describing the structure of the soil had any strong influence on the second component. Liming for structure has been found to have its main effect on heavy clay soils, while less clayey, and coarse

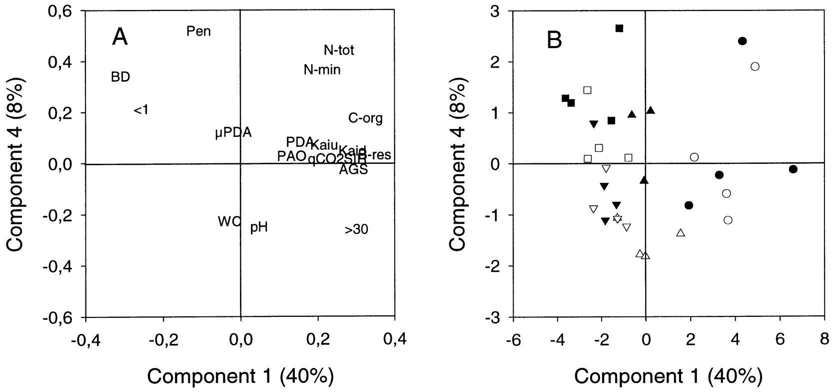

Fig. 4. Results of the PCA analyses. Principal components 1 vs 4. (A) Loading plot showing the relations between variables; (B) Score plot showing the relations between samples. Open symbols=with lime; Filled symbols=no lime; ●=stubble cultivated 0–12 cm; ■=stubble cultivated 12–24 cm; ▲=mouldboard ploughed 0–12 cm; ▼=mouldboard ploughed 12–24 cm. (A) and (B) can be read interactively as their respective quadrants correspond to each other (see Section 2.3). Abbreviations are explained in Table 3.

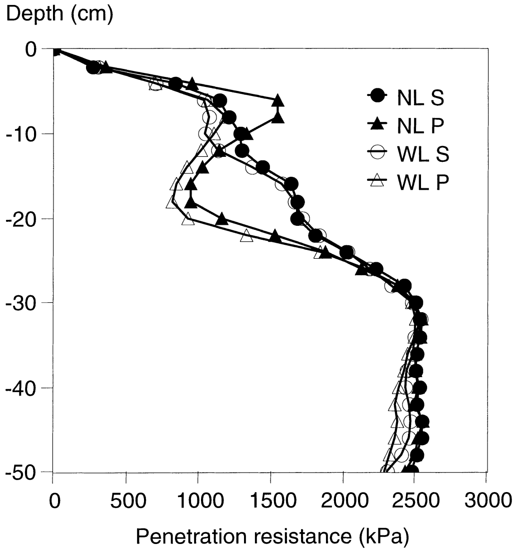

Fig. 5. Penetration resistance in 0–50 cm at Sundby 1995. WL=with lime, NL=no lime, S=stubble cultivation, P=mouldboard ploughing.

textured soils are more dependent on the organic matter content (Berglund, 1971; Ledin, 1981). However, the potentially mineralizable nitrogen appeared to be partly dependent on the organic matter content and partly on the pH, which could to some extent explain the higher yield in the limed treatments. Nitrifiers are a rather small group of organisms sensitive to pH (Haynes, 1986; Stenberg et al., 1998b). A pH closer to the physiological optimum probably affected the growth rate of denitrifiers positively. The relation to pH is in agreement with earlier studies (Stenberg et al., 1998b). As denitrification occurs under anaerobic conditions, the lower potential in the limed plots could be explained by poorer aeration there. However, none of the structure variables support this. On the contrary, the air permeability tended to be decreased by liming. The explanation could instead be stronger competition for nitrogen in the limed plots, from plants and other organisms, due to the more favourable pH.

The third component separated between the tillage treatments in the lower topsoil (Fig. 3B). The main factor here was the penetration resistance, which was highest in the lower S and lowest in the lower P layer (Fig. 3A). The penetration resistance in the experiment throughout the profile is shown in Fig. 5 (SD in Tables 3 and 4). The water content at the time of sampling was correspondingly highest in the lower P layer, which probably explains the lower penetration resistance there, as expressed by the third component. However, most of the remaining variance of the penetration resistance was explained by the fourth component (38 out of a total explained penetration resistance variance of 89%), while this was not the case for the water content (only 8 out of 71% was explained by PC4) (Fig. 4A). Thus, in the fourth component the penetration resistance was largely corrected for differences in water content. Nevertheless, with one exception the separation between tillage treatments in the lower layers remained in the fourth component (Fig. 4B). The high resistance in the lower S layer was most likely due to the lack of cultivation for 8 years. In addition, the mouldboard ploughed limed and unlimed plots were separated in the 0–12 cm layer, with a lower penetration resistance in the limed plots. Except for a small part of the variation in bulk density and pores >30 μm, none of the other structure variables were explained by the fourth component.

4. Conclusions

The concentration of plant residues in the upper topsoil by reduced depth of primary tillage increased the organic matter content, stimulated the microbial biomass and supported an increase in aggregate stability. Although the differences were small they accommodated an increase in grain yield in this treatment, mainly by reducing the effects in 1994 of weather conditions promoting crust formation in the soil surface. A similar result from liming in this year indicated that it improved the structure in a way that was not accounted for by any of the measured structure variables in this weakly-structured soil.

Reducing tillage to stubble cultivation in the upper 12 cm in this silty clay loam improved biological properties and physical conditions important for sustainable agriculture. Liming for improved structure increased the positive effects.

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