Non-inverting Tillage: Early-Stage Effects on Soil Mechanical Behaviour

L.J. Munkholm*, Danish Institute of Agricultural Sciences, Department of Crop Physiology and Soil Science, Research Centre Foulum, P.O. Box 50, DK-8830 Tjele, Denmark. Lars.munkholm@agrsci.dk

P. Schjønning, Danish Institute of Agricultural Sciences, Department of Crop Physiology and Soil Science, Research Centre Foulum, P.O. Box 50, DK-8830 Tjele, Denmark. Per.Schjonning@agrsci.dk

K.J. Rasmussen Danish Institute of Agricultural Sciences, Department of Agricultural Engineering, Research Centre Bygholm, P.O. Box 536, DK-8700 Horsens, Denmark. KarlJohan.Rasmussen@agrsci.dk

ABSTRACT

Organic farmers often claim positive effects of non-inverting and reduced tillage systems. There is a need of quantifying tilth characteristics in the former plough layer of soil converted to such tillage systems. A non-inverting tillage system (NINV) was tested in a field experiment conducted on a Danish sandy loam soil. It included deep loosening and shallow intensive cultivation and was compared to a conventional ploughing-harrowing tillage system (CONV).

A hierarchical analytical procedure was applied in studies of soil fragmentation and soil strength characteristics for the 7-14 cm soil layer. A visual description was carried out and ease of fragmentation was evaluated in the field using a soil drop test. Soil strength was measured in the field with a cone penetrometer and a torsional shear box method, and in the laboratory using an annulus shear strength method. Tensile strength was determined in the laboratory on field-sampled aggregates.

The CONV treated soil displayed a higher ease of fragmentation in the field in May as well as in September. In general, aggregates from the NINV treated soil were stronger than aggregates from the CONV treatment. The soils had similar friability indices in May. In September, however, a higher friability index was found for the CONV treated soil (k=0.22 and 0.16, respectively for CONV and NINV). The NINV treated soil also displayed the highest soil strength.

The soil tilth was evaluated to be best in the CONV treated soil. Supposed meliorating actions during the growing season did not eliminate the differences between the treatments.

INTRODUCTION

In low-input farming systems (e.g. organic farming) plant production relies on the inherent properties of the soil and the state of the inherent properties as affected by the history of farming practice for the specific soil. Soil tillage is a basic management tool with a heavy impact on crop establishment and growth. Non-inverting and reduced tillage systems are often claimed to be optimal for organic farming (e.g. Lampkin, 1990). However, several investigations have shown that side effects in terms of condensed soil layers may develop in non-ploughing systems (Douglas et al., 1980; Douglas and Goss, 1987; Rydberg, 1987; Schjønning, 1989). Soil tilth is of paramount importance for the establishment and growth of crops. A soil with a desirable tilth may be characterised by a high ease of tillage and low impedance to seedling and root penetration (e.g. SSSA, 1996). There is a need of studying the more subtle effects of non-ploughing tillage systems in terms of soil friability and ease of tillage.

The "ease of tillage" may be characterised by descriptive field methods as well as by quantitative field and laboratory methods. Reduced tillage has been found to increase soil friability in some cases (e.g. Chan, 1989; Macks et al., 1996) whereas Perfect and Kay (1994) reported no marked effect when compared with conventional tillage. Watts et al. (1996) and Watts and Dexter (1997) found that aggregate tensile strength increased with the energy input in tillage. They also reported that the negative effects of intensive tillage on aggregate tensile strength and soil friability decreased markedly within three weeks after tillage. Recent results by Schjønning et al. (submitted) indicate a pronounced negative influence of intensive tillage and traffic intensity on ease of soil fragmentation.

Bulk soil strength and aggregate strength gives information on the ability of roots to penetrate the soil (e.g. Bennie, 1996). Bulk soil shear strength can be determined *in situ* by the use of a cone penetrometer (e.g. Olsen, 1988) and by the use of a torsional shear box (Payne and Fountaine, 1952). The latter provides estimates of soil cohesion and angle of internal friction according to Coulomb's law when using different normal loads. These properties may also be deduced from the annulus shear strength laboratory method as suggested by Schjønning (1986).

To obtain optimal soil tilth, Weichel (1994) suggested employing a soil tillage system that combines non-inverting deep tillage with shallow intensive tillage for seedbed preparation. Hampl (1995) argues that a non-inverting tillage system is especially applicable in organic farming. Sommer and Zach (1992) have reported promising results of non-inverting tillage in conventional farming. Crop yield was at the level of conventional mouldboard ploughing tillage. Also for key physical parameters like porosity and penetration resistance the non-inverted soil performed similar to the conventionally managed soil in the top 20 cm of the soil.

In this study the effect of a non-inverting tillage system on soil tilth was evaluated. A hierarchical analytical strategy was followed in order to be able to directly relate quantitative measures of soil physical properties to soil behaviour in the field. This included qualitative and quantitative characterisation of the soil physical behaviour in field as well as quantitative measures of soil physical properties under well-defined conditions in the laboratory.

MATERIALS AND METHODS

Tillage Experiment

The experiment was established in 1997 at the organically managed Rugballegård Experimental Station, Denmark. The soil is a sandy loam developed on diluvial clay, sand and gravel. The soil contains 13% clay, 13% silt (2-20 μm), 38% fine sand (20-200 μm) 33% coarse sand (200-2000 μm) and 3% organic matter. Mean annual precipitation is 677 mm. Prior to the initiation of the tillage experiment, the soil was grown with small grain cereals. Conventional tillage was applied, which included annual mouldboard ploughing to about 20 cm depth.

This paper reports the results from a tillage experiment applied in two consecutive years (1997 and 1998). Fodder beets (*Beta vulgaris* L.) were grown the first year and a mixture of spring barley (*Hordeum vulgare* L.) and pea (*Pisum sativum* L.) with grass/clover undersown were grown in the second year where field measurements and sampling took place. Two tillage treatments were applied to 12x90 m plots in a randomised block design with four replicates. A conventional ploughing-harrowing tillage system, labelled CONV, was compared with a non-inverting deep tillage system, labelled NINV, which combines subsoil loosening to 35 cm with a shallow intensive secondary tillage. In the CONV system the soil was mouldboard ploughed to 20 cm. Seedbed preparation and sowing was performed by a combination of a front mounted furrow press and a rear mounted S-tine compact harrow and a seed drill. In the NINV treatment, soil tillage was carried out using a combined tillage and sowing implement. This consisted of a 3 m wide non-inverting rigid tine subsoiler with four 65 cm broad shares mounted with a rotovator and a seed drill.

The spring barley/pea crop was harvested as whole crop ultimo July. The traffic related to the harvest operations was the only traffic on the field between spring tillage and September sampling.

Sampling

Areas with comparable soil textural composition (Rasmussen et al., 1995) within each plot were selected for field sampling and measurements in order to minimize soil variability. These sampling areas constituted at least 1/5 of each plot. Soil sampling and field measurements were carried out exclusively in these areas, except for cone penetration. Samples were collected at plant emergence in three ½ m^2 surfaces within each plot. Additionally, a more comprehensive field sampling and measurements programme were carried out in September when the soil had almost reached a matric potential between -300 and -1000 hPa following the dryer summer season (Table 1).

Minimally disturbed soil cores (6.1 cm diameter, 3.4 cm height, 100 cm^3 volume) were collected in May and September 1998 at the 7 to 11 cm depth in metal cylinders. The cylinders were held in position by a special flange ensuring a vertical downward movement into the soil and forced into the soil by means of a hammer. After careful removal of the soil-filled cylinder from the bulk soil, the end surfaces were trimmed with a knife and mounted with plastic caps to protect the soil from mechanical disturbance and evaporation. In May, three samples were collected in each plot (i.e. one per sampling surface) and used for determination of bulk density and water content at sampling. In September, twenty-four replicate cores were taken from the 7 to 11 cm depth. These were used for determination of water content at sampling and at adjusted matric potentials as well as for determination of shear strength. All 100 cm^3 soil cores were sealed with plastic caps and stored at 2° C until analysis took place.

Bulk soil was sampled in plastic containers from the 7 to 14 cm depth in May and September 1998. The three subsamples from each plot were bulked. These samples were air-dried by spreading the soil in a dry, ventilated room at app. 20°C immediately following arrival at the laboratory. The air-dry soil was separated into four size-classes 8-16, 4-8, 2-4 and 1-2 mm and then stored at 20° C until analysis.

Field Tests

Visual evaluation

A visual evaluation of soil structure in the 7-14 cm layer was performed according to the *spade analysis* method (Munkholm, 2000). The spade analysis is a descriptive method developed on the basis of the spade diagnosis by Görbing and Preuschen (Preuschen, 1983). A flat spade (length 30 cm, width 20 cm) was used to a take out a minimally disturbed soil block of the upper 30 cm of the soil profile (length 30 cm, width 20 cm, depth 10 cm). One soil block was described in each plot in the beginning of July at a time when the soil was moist.

Bulk soil fragmentation

A *soil drop test* was performed to assess soil fragmentation behaviour in the field as outlined by Schjønning et al. (submitted). An undisturbed cubic soil sample (7.0 x 8.0 x 11.5 ~ 650 cm^3) was collected from the 7-14 cm layer and dropped from a height of 75 cm into a metal box. The soil was passed through a nest of sieves with the openings of 32, 16, 8, 4 and 2 mm and aggregate size distribution was determined. Four replicate tests were performed in each plot in May and repeated in September. Within each plot, two tests were done at sampling surface 1 and one at sampling surface 2 and 3.

Penetration resistance

The measurements were carried out using an automated cone penetrometer (Olsen, 1988) mounted with an ASAE R313.1-recommended 20.27 mm diameter / 30^o semi-angle cone. The cone index was automatically recorded for every cm increment in the 7-14 cm layer. Measurements were carried out in May at the time of sampling when the soil water content was close to field capacity (Table 1). Twenty replicate measurements were carried out in each investigated plot.

Shear strength

In situ shear strength was determined in September with a 10.0 cm diameter torsional shear box operated at five normal loads ranging from 7.3 to 32.3 kPa (Payne and Fountaine, 1952). The box was placed on the soil surface after removal of the 0-7 cm soil layer and forced to a depth of about 12 cm below the original surface. The soil surrounding the metal box was carefully removed before shearing. For all soils one series of determinations (five normal loads) was performed at sampling surface 1 and 3 in each plot, i.e. eight determinations for each combination of normal load and tillage treatment.

Laboratory Methods

Aggregate tensile strength

Aggregate tensile strength was measured on air-dried aggregates according to the method described by Dexter and Kroesbergen (1985). For each sampling time, ten aggregates were chosen at random from each box (i.e. 40 per combinations of time, tillage treatment and size-class, in total 1280 aggregates). The aggregates were crushed individually between two flat parallel plates at constant strain rate, 2 mm min^{-1}. The compressive force was measured by a load cell (0-100 N +/- 0.03 N) and recorded automatically by an adapted computer. The aggregate tensile strength (Y, kPa) was calculated from the equation (Braunack et al., 1979)

$$Y = 0.576 \frac{F}{d^2} \quad [1]$$

where F (N) is the polar force required to fracture the aggregate and d (m) is the mean aggregate diameter. In this study d was estimated from “method 1”, described by Dexter and Kroesbergen (1985).

Friability, *k,* was estimated from the equation (Utomo and Dexter, 1981)

$$\log Y = -k \log V + A \quad [2]$$

where A (kPa) is the normalised strength of 1 m^3 soil and V (m^3) the aggregate volume.

Annulus shear strength

Before analysis, the soil cores were wetted slowly from beneath to saturation on sandboxes and thereafter the soil cores were drained to –300 hPa matric potential. The samples were subsequently moved to the shearing apparatus, exposed to a specific load and then sheared immediately (Schjønning, 1986). Shear strength was determined at 18 normal loads in the interval 30-270 kPa. One replicate soil core from each plot was sheared for each combination of normal load and tillage treatment (i.e. four replicates per combination of treatment and normal load). The shear test is a torque measurement during a rotational shearing action of a grousered shear annulus. The maximum shear strength, τ_{max}, was calculated from the shear strength-strain relationship as detailed by Schjønning (1986). Estimates of apparent soil cohesion and angle of internal friction was calculated from the Coulomb model using normal load as effective stress.

Statistical Analysis

All parameters were analysed for normal distribution or transformed to yield normality. Averages were calculated for each plot and using these averages F-tests was carried out (PROC GLM procedure, SAS-Institute, 1996) for testing significant difference between tillage treatments.

RESULTS

Soil Bulk Density and Water Content

There was a tendency of a higher bulk density of the NINV treated soil in the 7-11 cm depth (Table 1). For both sampling times the soil water content was highest in the NINV treated soil, although the difference was significant only for the May sampling. There was no significant difference in water content at the adjusted matric potentials in the laboratory. The water retention results suggest that soil sampling and field measurements were performed at matric potentials between –100 and –1000 hPa with the highest at sampling in May.

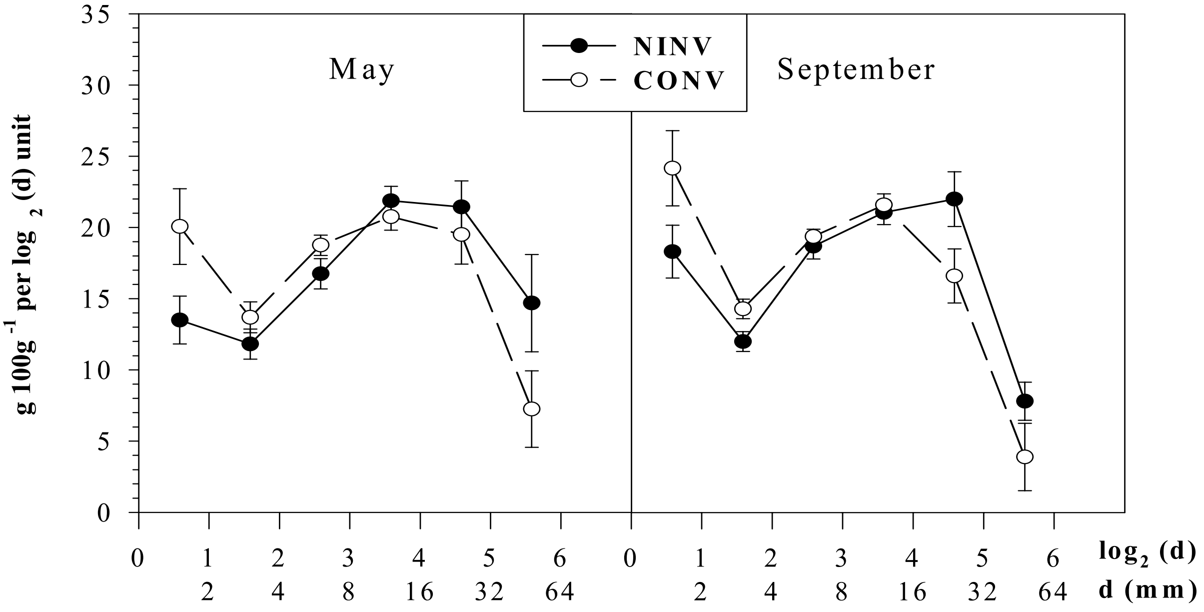
Table 1. Bulk density and water content at sampling and at controlled matric potentials determined on soil from the 7-14 cm depth. Figures followed by the same letter are not significantly different at the P=0.05 level.

			Volumetric water content			
		Bulk density	Sampling	-100 hPa	-300 hPa	-1000 hPa
Time	Treatment	Mg m^{-3}	m^3 100 m^{-3}			
May	CONV	1.417 a	23.5 a			
	NINV	1.496 a	25.1 b			
September	CONV	1.418 a	21.4 a	30.5 a	22.6 a	20.5 a
	NINV	1.450 a	21.6 a	30.5 a	22.4 a	19.9 a

Visual Evaluation and Soil Fragmentation

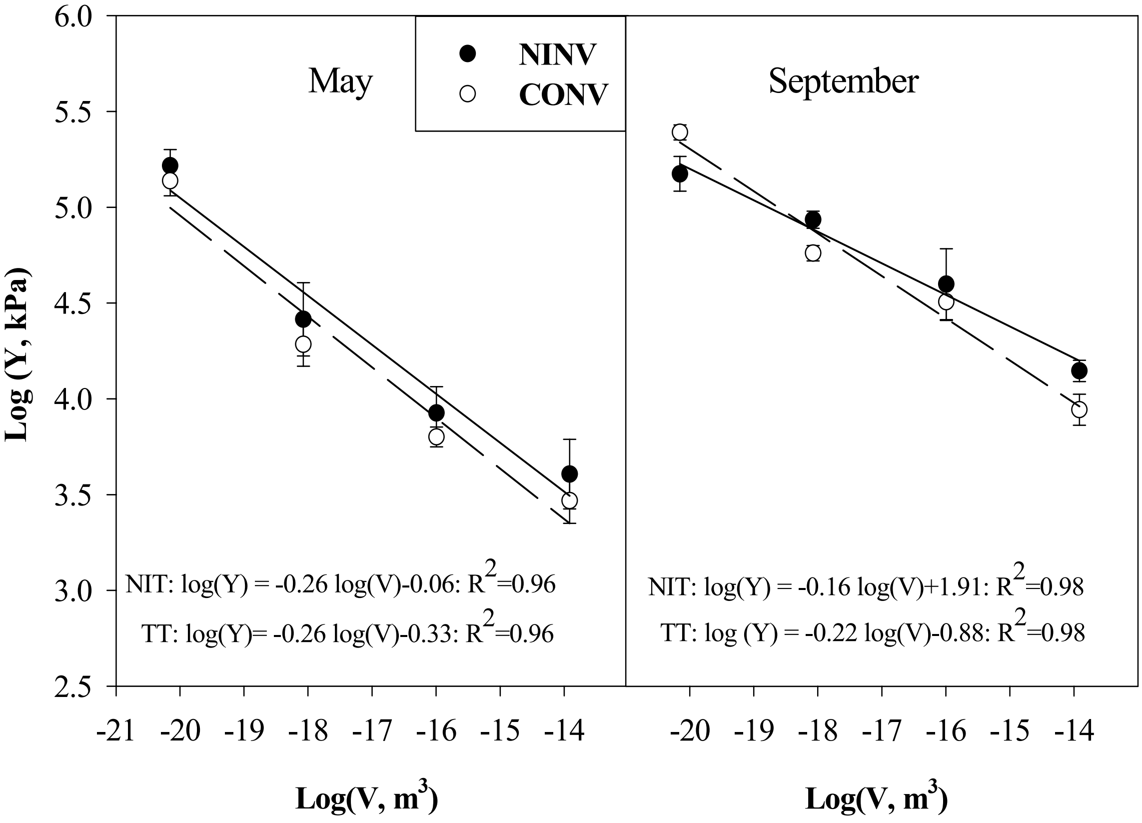
The visual evaluation did not reveal clear differences between the soils in the 7-14 cm layer. Both soils contained a mixture of granular and sub-angular blocky structural units and the soils were evaluated as “friable” (Munkholm, 2000). At both times of performing the soil drop test, there was a tendency to a higher ease of fragmentation for the CONV treated soil (Figure 1). The difference for the dropped samples had developed due to the energy input when dropping the samples, as there was no difference for the reference treated samples (results not shown). Apparently, there is an effect of sampling time, i.e. a larger fragmentation in September than in May. It cannot be concluded whether this is related to difference in water contents at measurement or due to a change in soil characteristics over time.

Figure 1. Aggregate size distribution of dropped cubic samples (soil drop test) determined in May and in September. Bars indicate +/- 1 standard error of mean.



Also the tensile strength measurements indicate that it was more difficult to fragment the NINV treated soil (Figure 2). Generally, the NINV treated soil had stronger air-dry aggregates. Moreover, the NINV treated soil had the smallest friability index for the September sampled soil (i.e. friability index, *k*= 0.16 and.0.22, respectively for the NINV and CONV treated soils) (Figure 2). For the May sampling, there was no difference between the treatments. However, both soils would be classified as “very friable” for the May sampling (i.e. friability index, *k*= 0.26 for both treatments) according to the friability classes proposed by Utomo and Dexter (1981). For the September sampling, both soils would be classified as “friable”.

Figure 2. The relationship between aggregate tensile strength, *Y* (kPa) and aggregate size, *V* (m^3) in a log-log presentation. Index of soil friability, *k* = (-1)*slope of linear regression lines. Solid and broken lines denote linear regression lines for NINV and CONV, respectively. Bars indicate +/-1 standard error of mean.



Soil Strength

The non-inverting tillage did not loosen the topsoil as effectively as the CONV treatment. The cone index tended to be highest for the NINV treated soil in the 7-14 cm layer (Table 2). Furthermore, the NINV soil had the largest shear strength when measured at –300 hPa in the laboratory (data not shown). When differentiating the shear strength into an apparent soil cohesion and angle of internal friction component, the NINV treated soil turned out to exhibit significantly higher apparent soil cohesion than the CONV treatment (Table 2). On the other hand the *in situ* measurements of shear strength revealed no difference between the treatments.

Table 2. Cone index and estimates of apparent soil cohesion and angle of internal friction from shear strength measurements. Cone index was measured in the 7-14 cm layer. Torsional shear strength determined *in situ* in the 7-12 cm layer. Annulus shear strength was determined in the laboratory at – 300 hPa matric potential on core samples taken in the 7-11 cm layer. Figures with the same lettering within each soil group and sampling time are not significantly different at the P=0.05 level.

		Torsional shear box		Annulus shear	
	Cone index	Cohesion	Int. friction	Cohesion	Int. friction
Treatment	kPa	kPa	tan ϕ	kPa	tan ϕ
CONV	786 a	24.5 a	0.78 a	32.8 a	0.71 a
NINV	891 a	24.5 a	0.83 a	35.6 b	0.73 a

DISCUSSION

Optimal soil tilth is of paramount importance in organic farming systems. The finding of poorer soil tilth in the non-inverting tillage treated soil questions the applicability of the tested non-inverting tillage system in organic farming systems. The NINV treated soil tended to exhibit a higher soil strength and a lower soil friability. However, the non-inverting soil tillage system successfully loosened a compacted plough pan (data not shown) that occurred in the conventionally treated soil. Furthermore, the reported results in this paper must be viewed in a time perspective. The measurements were carried out at an early stage in a conversion from conventional to non-inverting tillage. The completion of at least one crop rotation is needed before an evaluation of long-term effects is possible.

The stronger and less friable soil in the 7-14 cm layer of the NINV treatment most probably is due to a less effective soil loosening of this layer by the non-inverting deep loosening. Moreover, it could also be caused by a compacting effect of the rotovator. A tillage pan developed under a rotovated soil has been reported in a number studies (e.g. Schjønning, 1989).

Interestingly, the soil aggregates had become stronger and the soil less friable during the growing season. The meliorating action of repeated cycles of drying and wetting and biological activity was supposed to decrease the tensile strength and increase friability (e.g. Utomo and Dexter, 1981, Kay and Dexter, 1992). Generally, tillage is expected to increase aggregate tensile strength and decrease friability due to breakdown of primarily the weakest aggregates (Watts et. al., 1996). Watts and Dexter (1997) found that tillage-induced differences decreased with time but were still measurable three weeks after tillage. The results in the present investigation clearly show that the meliorating actions during the growing season (wet-dry cycles, biological activity) were not able to eliminate the differences between the tillage treatments.

CONCLUSIONS

- The conversion to non-inverting tillage resulted in a poorer soil tilth in the former plough-layer (i.e. a higher soil strength and a lower ease of fragmentation and friability index).
- The poorer soil tilth condition in the NINV treated soil was not eliminated due to soil meliorating actions in one growing season.

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LITERATURE

Bennie, A.T.P. 1996. Growth and mechanical impedance. In: Waisel, Y., Eshel, A and Kafkafi, U. (Eds.). Plant Roots – The Hidden Half. Marcel Dekker, Inc. New York, Basel, Hong Kong. 1002 pp.

Braunack, M.V., Hewitt, J.S. and Dexter, A.R. 1979. Brittle fracture of soil aggregates and the compaction of aggregate beds. Journal of Soil Science 30: 653-667.

Chan, K.Y. 1989. Friability of a hardsetting soil under different tillage and land use practices. Soil and Tillage Research 13: 287-298.

Dexter, A.R. and Kroesbergen, B., 1985. Methodology for determination of tensile strength of soil aggregates. Journal of Agricultural Engineering Research 31: 139-147.

Douglas, J.T., and Goss, M.J., 1987. Modification of porespace by tillage in two stagnogley soils with contrasting management histories. Soil and Tillage Research 10: 303-317.

Douglas, J.T., Goss, M.J., and Hill, D., 1980. Measurements of pore characteristics in a clay soil under ploughing and direct drilling, including use of a radioactive tracer (^{144}Ce) technique. Soil & Tillage Research 1: 11-18.

Hampl, U., Hoffmann, M., Kaiser-Heydenreich, B., Kress, W. and Markl, J., 1995. Ökologische Bodenbearbeitung und Beikrautregulierung. Deukalion Verlag, Holm, Germany, 128pp.

Kay, B.D. and Dexter, A.R. 1992. The influence of dispersible clay and wetting/drying cycles on the tensile strength of a red-brown earth. Australian Journal of Soil Research 30: 297-310.

Lampkin, N. 1990. Organic Farming. Farming Press, UK. 701 pp.

Macks, S.P., Murphy, B.W., Cresswell, H.P. and Koen, T.B. 1996. Soil friability in relation to management history and suitability for direct drilling. Australian Journal of Soil Research 34, 343-360.

Munkholm, L.J., 2000. The spade analysis – a modification of the qualitative spade diagnosis for scientific use. DIAS-report. Danish Institute of Agricultural Sciences (*in press*).

Olsen, H.J., 1988. Electronic penetrometer for field tests. Journal of Terramechanics 25: 287-293.

Payne, P.C.J. and Fountaine, E.R., 1952. A field method of measuring the shear strength of soils. Journal of Soil Science 3: 136-144.

Perfect, E. and Kay, B.D. 1994. Influence of corn management on dry aggregate tensile strength: Weibull analysis. Soil and Tillage Research 32: 149-161.

Preuschen, G., 1983. Die Spatendiagnose und ihre Auswertung. p. 355-368. *In* Böhm, W., Kutschera, L. and Lichtenegger, E., (eds). Root ecology and its pracitical application, International Symposium Gumpenstein, 1982. Bundesanstalt Gumpenstein, Irdning.

Rasmussen, K.J., Nielsen, O.H., Olesen, S.E. and Schjønning, P. 1995. Karakterisering af jordarealer ved Forskningscenter Bygholm. SP-rapport nr. 30. Landbrugs- og Fiskeriministeriet, Statens Planteavlsforsøg. 70pp.

Rydberg, T., 1987. Studies in ploughless tillage in Sweden 1975-86. Div. of Soil Management Uppsala, Sweden, Rep. No. 76, 35 pp.

SAS, 1996. SAS Institute SAS/STAT™ Software: changes and enhancements through Release 6.11. SAS Institute, Cary, NC, 1104 pp.

Schjønning, P., 1986. Shear strength determination in undisturbed soil at controlled water potential. Soil & Tillage Research 8: 171-179.

Schjønning, P. 1989. Long-term reduced cultivation. II. soil pore characteristics as shown by gas diffusivities and permeabilities and air-filled porosities. Soil & Tillage Research 15: 91-103.

Schjønning, P., Elmholt, S.E., Munkholm, L.J. and Debosz, K. Physical and biological characteristics in paired organically and conventionally managed soils. (Submitted to: Agriculture, Ecosystem & Environment).

Soil Science Society of America, SSSA, 1996. Glossary of soil science terms. Am. Soc. Agron. Madison, WI, p. 137.

Sommer, C. and Zach, M., 1992. Managing traffic-induced soil compaction by using conservation tillage. Soil & Tillage Research 24: 319-336.

Utomo, W.H. and Dexter, A.R., 1981. Soil friability. Journal of Soil Science 32: 203-213.

Watts, C.W., Dexter, A.R. and Longstaff, D.J. 1996. An assesment of the vulnerability of soil structure to destabilisation during tillage. Part II. Field trials. Soil & Tillage Research 37: 175-190.

Watts, C.W. and Dexter, A.R. 1997. Intensity of tillage of wet soil and the effects on soil structural condition. p. 669-672. *In* Fragmenta Agronomica TOM 2B. Proceedings 14th ISTRO conference, July 27- August 1, 1997, Pulawy, Poland.

Weichel, E. 1984. Unkrautbekämpfung durch vereinfachung und verbesserung der Bodenbearbeitung. Zeitschrift für Pflanzenkrankheit und Pflanzenschutz, Sonderheft 10: 259-267.