DIAS report

April 2000

No. 28 • Plant Production

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– a modification of the qualitative spade diagnosis for scientific use

Ministry of Food, Agriculture and Fisheries
Danish Institute of Agricultural Sciences

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DIAS report Plant Production no. 28 • April 2000

Publisher:	Danish Institute of Agricultural Sciences Research Centre Foulum P.O. Box 50 DK-8830 Tjele	Tel. +45 89 99 19 00 Fax +45 89 99 19 19
Sale by copies: (incl. VAT)	up to 50 pages up to 100 pages more than100 pages	50,- DKK 75,- DKK 100,- DKK
Subscription:	Depending on the number of reports sent but equivalent to 75% of the price of sale by copies.	

Preface

In this report a modification of the qualitative classical spade diagnosis is presented. This work has been carried out within Project I.3 "Soil fertility and soil tilth as influenced by organic farming practices and soil tillage" operated under the Danish Research Centre for Organic Farming. In the project the soil tilth of differently managed soils has been investigated by the use of "holistic" field methods as well as specialised "reductionistic" laboratory methods. Wide ranges of soil physical, biological and chemical parameters have been measured in the differently managed soils. The spade analysis was the most integrating and holistic analytical method applied in the project.

In the process of developing the spade analysis manual a number of persons have given kind advice. At the initiation of the work Knud Suhr, Den Økologiske Landbrugsskole and my colleagues Susanne Elmholt and Karl J. Rasmussen, Danish Institute of Agricultural Sciences (DIAS) have contributed with hints and good ideas. Andrea Beste and Ulrich Hampl, Stiftung für Ökologie und Landbau, Germany have been very helpful and particularly given valuable information on where to find old hardly accessible literature. Lastly, Per Schjønning, DIAS has contributed with fruitful ideas and a critical review from the initial developing phase to the publication phase.
In the practical work Kresten Meyer, DIAS-Bygholm and Stig T. Rasmussen, DIAS-Foulum have assisted.

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November 1999
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Contents

Summary

Optimal soil fertility is of particular importance in organic farming where plant production relies heavily on the inherent properties and the accumulated effect of past and present soil management. The term "soil tilth" describes the desired soil structure in relation to plant growth. Assessing soil tilth in the field has been a challenge to scientists and practicians for centuries. Johan Görbing from Germany developed the descriptive spade diagnosis method in the years from 1920 to 1945. Another German, Gerhardt Preuschen, reintroduced the method in the early 1980s as a tool specifically applicable to evaluate soil tilth in organic farming. The key elements in the Preuschen spade diagnosis are an examination of soil structure, root growth, soil fauna, decomposition of organic matter and soil fragmentation.

The Preuschen spade diagnosis is a qualitative method that is highly dependent on the experience and skill of the operator. In this report a standardised "semi-quantitative" field method to evaluate soil tilth in the field is presented and evaluated.

Soil structure is described according to international standard methods. New guidelines are proposed where no clear and standardised methods of describing specific soil characteristics were found in the literature. This applies e.g. to the description of pore and root growth characteristics and degree of decomposition of applied organic matter.

The spade analysis method was tested on four groups of soils each consisting of two or three soils with contrasting long-term or short-term soil management. In all soils three characteristic layers were observed. At the top a 5-8 cm intensely cultivated layer was found, which had a crumb structure in most cases. In the middle (approximately 7-22 cm) a denser, granular or sub-angular structured layer was found in most cases. At the bottom a dense, coarse blocky or compact massive plough pan was found – except for the treatment with deep soil loosening. The occurrence of plough pans confirms the general finding of plough pans in cultivated Danish soils.

Root growth was restricted at the interface between all layers. A rather weak root restriction was observed at the interface between the loose, intensely cultivated top layer and the middle layer. A severe root growth restriction was in most cases detected at the transition to the plough pan layer.

Positive long-term effects of a versatile crop rotation and application of organic manure was found - except for the Group I soils. In that case negative short-term effects of intensive tillage and traffic may have overshadowed positive effects of long-term soil management. The significant effect of tillage and traffic on soil tilth was also evident from the tillage trial results. The deep soil loosening had successfully broken up the plough pan and resulted in an improved soil tilth in comparison with the traditionally ploughed soil.

The spade analysis was a useful tool to describe the present soil tilth status of the soil. On the background of comprehensive data material on soil management of the past years, it was possible to evaluate long and short-term effects of soil management. Good correlations to parameters measured by specialised quantitative methods in the field and in the laboratory have been found.

Sammendrag

Optimal frugtbarhed er i særlig grad af betydning i økologisk jordbrug, hvor planteproduktionen stærkt afhænger af jordens oprindelse og af dyrkningshistorien. Termen "soil tilth" er et begreb anvendt i den engelsksprogede verden til at beskrive den ønskede jordstruktur i relation til plantevækst. Det er svært at oversætte begrebet til dansk, men begrebet en "bekvem" jord kommer tættest på. Bedømmelse af "soil tilth" i marken har været en udfordring for agerdyrkeren gennem århundreder. Tyskeren Johan Görbing udviklede i årene 1920 til 1945 spadediagnosen til dette formål. Metoden blev taget op på ny i starten af 1980'erne af Gerhardt Preuschen, som en metode til at bedømme "soil tilth" i specielt økologisk jordbrug. I spadediagnosen er nøgleelementerne en beskrivelse af jordens struktur og smuldreevne, rodvækst, fauna aktivitet, omsætning af tilført organisk stof.

Spadediagnose metode er en beskrivende kvalitativ metode og derfor har operatørens uddannelse og erfaring stor betydning for resultatet af beskrivelsen. I denne rapport præsenteres og evalueres en "semi-kvantitativ" metode til bedømmelse af "soil tilth" i de øverste 30 cm af jorden.

I den foreslåede spade analyse manual er velbeskrevne internationale standardmetoder anvendt til beskrivelse af jordens struktur. Der er udviklet en vejledning til beskrivelse af egenskaber, hvor standardmetoder ikke kunne findes i litteraturen. Dette gælder bla. for beskrivelse af pore- og rodsystem samt for bedømmelse af omsætning af organisk stof.

Spade analysen blev evalueret på fire grupper af jorder, der hver indeholder to eller tre jorde med forskellig dyrkningsmæssig forhistorie. For alle jorderne fandtes tre karakteristiske lag. I de øverste 5-8 cm fandtes et intenst bearbejdet lag generelt med krummestruktur. I midten (omkring 7-22 cm) var der et mere kompakt lag med granulær eller subangulær blokstruktur i de fleste tilfælde. I bunden (22-30 cm) fandtes en kompakt pløjesål med grov blokstruktur eller kompakt massiv struktur – undtagen i en dybdeløsnet jord. Dette bekræfter, at pløjesål er meget udbredt i danske landbrugsjorde.

Rodvæksten var hæmmet ved overgangen mellem de ovennævnte lag. Ved overgang til midterzonen fandtes en svag hæmning af rodvæksten. En kraftig hæmning af rodvæksten fandtes i de fleste tilfælde ved overgang til pløjesålen.

Generelt var der en gunstig effekt af et alsidigt sædskifte og tilførsel af organisk stof på jordens "tilth". For Gruppe I jordene var tendensen dog modsat; hvilket kan forklares med, at den negative effekt af intens jordbearbejdning og trafik havde overskygget de positive langtidseffekter af et alsidigt sædskifte og tilførsel af organisk stof. Jordbearbejdningsforsøget viste også klart at jordbearbejdning er af stor betydning for jordens "tilth". Den "ikke-vendende" jordbearbejdning med dybdeløsning til 35 cm's dybde resulterede i forbedret "tilth" i forhold til den traditionelt behandlede jord med årlig pløjning til 20 cm's dybde.

Spadeanalysen var et anvendeligt redskab til at bedømme jordens aktuelle ”soil tilth” status. Et omfattende kendskab til jordenes dyrkningshistorie muliggjorde en evaluering af lang- og korttids virkninger af dyrkningshistorien på jordens ”tilth”. Der fandtes gode korrelationer til jordfysiske og –biologiske parametre målt med specialiserede kvantitative metoder i marken og i laboratoriet.

1. Introduction

Soil fertility and soil structure/plant interactions are areas in which interest is increasing world-wide. Terms like soil quality, soil fertility and soil tilth have become well-known among soil scientists as well as practicians in agriculture. One of the main reasons for this growing interest is the increased importance of optimal soil fertility. The use of mineral fertilisers and pesticides is increasingly being restricted in Denmark and other countries. This has reduced the farmer's options of compensating for sub-optimal plant growth by applying extra mineral fertilisers or pesticides. The growing interest in sustainable farming systems has possibly also caused more attention on the subject. In Denmark organic farming in particular has gained much attention and many farmers have converted to organic farming practices. Presently about 5% of the agricultural area is managed according to organic farming practices (Borgen, 1999). The need for optimal soil fertility and soil structure is particularly important in organic farming where plant production relies more heavily on the inherent properties (basic material and the accumulated effect of past and present soil management). Lastly, the fact that modern agricultural practices may cause soil degradation (erosion, compaction and depletion of organic matter) is probably also a reason the attention on the subject. In order to clarify what is meant by soil fertility and a desired structural state of the soil some broadly used terms are presented and defined below.

Soil fertility: The inherent soil fertility of the soil is a function of parent material, climate, the duration of soil forming processes acting on the soil and the vegetation that has evolved in response to soil properties and climate (King, 1990).

Bodengare: In Germany the term "Bodengare" has been used for centuries to describe a soil with an optimal soil structure. Sekera and Brunner (1943) defined "Bodengare" simply as the stability of an optimal soil structure. They considered a crumb structure as the desired soil structure in relation to plant growth. According to Görbing (1947 p. 112) "Bodengare" has a broader meaning – it cannot just be replaced by "crumb structure". By a "Gare" soil Görbing understands a biologically active soil that is the fundament for developing crumb structure in the upper 20 cm of the soil profile. "Gar ist ein Boden, dessen Krümelstruktur durch das Leben selbst gebildet wird, von den Wurzlen aller den Boden besiedelnden Pflanzen bis zu den Mikroorganismen, im harmonischen Kräftespiel mit allen physikalischen, chemischen und kolloidkemischen Vorgänge im Boden" (Görbing, 1947 p. 177).

Soil tilth: Soil tilth is a multifaceted characteristic. Several definitions have been proposed for this term. Yoder (1937) addressed the overall quality of soil as a medium for plant growth: *soil tilth is a blanket term describing all the conditions that determine the degree of fitness of a soil as an environment for the growth and development of a crop plant.* More recent approaches highlight the physical properties of the soil *the physical condition of soil as related to ease of tillage, fitness as a seedbed, and its impedance to seedling emergence and root penetration* (Karlen et al., 1990).

With the aim of developing a quantitative understanding of the concept of soil tilth Karlen *et al.* (1990) proposed a new definition and introduced a term called tilth-forming processes. Soil tilth was defined as *the physical condition of a soil described by its bulk density, porosity, structure, roughness, and aggregate characteristic as related to water, nutrient, heat and air transport; stimulation of microbial and microfauna populations and processes; and impedance to seedling emergence and root penetration.* Soil tilth forming processes were defined as *the combined action of physical, chemical, and biological processes that bond primary soil particles into simple and complex aggregates and aggregate associations that create specific structural or tilth conditions.* A comprehensive review on formation and stabilisation of soil tilth is given by Hadas (1997).

"Soil tilth" has been chosen as a general term to describe the desired structural state of the soil in this presentation. Assessing soil tilth in the field may be very difficult because it is a qualitative and multifaceted term. Despite that, some field methods have been proposed. The so-called "spade diagnosis" developed by Görbing in the 1930s (Görbing, 1947) and modified by Preuschen (Preuschen 1983, 1994) is an attempt to assess soil tilth by a simple qualitative field method.

In this report a standardised "semi-quantitative" field method to evaluate soil tilth in the field is presented and evaluated. The method is developed on the basis of the description of the Preuschen spade diagnosis. It is entitled "The spade analysis" to signal roots in the "spade diagnosis" combined with a new approach.

2. Background

2.1. The spade diagnosis

The spade diagnosis was developed in the years between 1920 and 1945 by Görbing (Görbing, 1947) as a simple tool for practicians (farmers, advisors etc.) to evaluate soil fertility in the field.
Görbing was originally educated as a chemist in food science. Just after the conclusion of the First World War he dedicated his life to teaching and research in agriculture. He had experienced famine in Palestine and Syria and hungers in Germany and wanted to make his contribution to avoid such catastrophes in the future by securing a larger and more stable food supply. He started by giving lectures about the proper use of especially mineral fertilisers in plant production. His work on developing the spade diagnosis was initiated on the background of questions asked by practicians in the field (e.g. "why does my winter barley grow poorly in this spot?" or "what is wrong with my winter rye?"). Such questions could not always be properly answered by nutrient deficiency only. An investigation of the soil was needed to give a more comprehensive explanation. Görbing gathered knowledge for 25 years before he published anything about the spade diagnosis. In that time he performed more than 50.000 single spade diagnoses. Actually, Sekera and Brunner (1943) were the first who rather briefly

described the Görbing spade diagnosis. The method was almost forgotten for decades until Preuschen and others reintroduced the method about 20 years ago (Diez, 1982; Preuschen, 1983). It was reintroduced especially as a tool in organic farming to evaluate soil tilth and soil fertility (Preuschen, 1983). In Denmark the spade diagnosis has been introduced by pioneers in organic farming (Suhr et al., 1995) and is still mainly used by organic farmers and advisors.

Görbing based his examination on the description and classification of soil structure (Görbing, 1947). He describes three fundamental elements in "Gare" (i.e. soil tilth) formation and stabilisation: 1. An adequate pH level (lime deficiency was a major problem at that time), 2. Proper management of applied organic matter and 3. Biologically suitable soil tillage.
He focused on an evaluation of the upper 30 cm of the soil profile unless there was a specific reason to include deeper layers (e.g. poor drainage or an assessment of the need for deep soil-loosening). A minimally disturbed soil block is taken out with a so-called Görbing spade and studied when it lies horizontally above ground. According to Görbing (1947) and Sekera and Brunner (1943) a crumb soil structure is the desired soil structure in relation to plant growth. The deeper down in the soil the crumb structure reaches the better.

Preuschen extended the spade diagnosis by a more comprehensive examination of root growth, faunal activity and decomposition of organic matter (Preuschen, 1983). The Preuschen spade diagnosis is developed to evaluate the connection between soil structure, soil faunal activity and root and plant growth in the field. Preuschen has given a detailed description on what to look for when performing the spade diagnosis. The key elements in the Preuschen spade diagnosis are an examination of 1. soil structure (layering, structural units, density, colour, moisture content), 2. root growth (number and distribution, abnormal root growth, root nodules (leguminous plants), 3. Soil fauna, 4. decomposition of organic matter and 5. soil fragmentation.
Soil structure: Soil texture is roughly estimated and the soil profile is divided into horizons that are markedly different from each other. Preuschen emphasises especially the need to note compacted layers (e.g. tillage pans) and anaerobic layers that might impede root growth.
For each layer soil colour, the structural units and the degree of compaction are described. Preuschen suggest that the basis of an optimal soil structure is the formation of soil crumbs. In accordance with Görbing, Preuschen considers a crumb structure as the desired soil structure for plant growth. The further down the profile a crumb structure is observed the better.
Preuschen defines "genuine" soil crumbs as spherical, porous aggregates with a rough surface. The "genuine" soil crumbs are mainly 2-4 mm and are seldom larger than 5 mm in diameter.
Root growth: Preuschen gives a thorough description of what to look for when describing the root system. Preuschen states that it is important to examine the root system of both the crop and weeds. The number, size distribution and branching of the roots must be described for each designated layer in the profile. It is of great importance to note abnormal root growth caused by e.g. compacted or anaerobic areas in the soil. Abnormal or sub-optimal root growth may appear as thickened roots and strongly bended/deflected roots. According to Preuschen

(1994), rhizosheath consisting of soil-organic matter material adhering to the roots is a sign of high biological activity in the soil. Rhizosheaths are mainly found on the roots of grasses. According to McCully (1995) most dicotyledons do not form rhizosheaths.
For leguminous plants Preuschen (1994) proposes to characterise the number and distribution of root nodules in the profile. Ideally, the root nodules should be relatively sparse but evenly distributed on the leguminous roots in the studied profile. The *Rhizobium* bacteria need well-aerated conditions to fixate nitrogen. Therefore minimal occurrence of root nodules in an area of the soil may indicate poor aeration.
Soil fauna: Preuschen stresses the importance of examining earthworm activity. The observed earthworms should be noted. Also the number and distribution of earthworm burrows must be noted as well as surface features in the earthworm burrows. He emphasises that surface features consisting of soil and organic matter should cover earthworm burrows, ideally. The occurrence of narrow straight burrows without surface features indicates a biological worthless area according to Preuschen (1994).
Decomposition of organic matter: The degree of decomposition of applied organic matter is examined. The consistence, smell and colour of the decomposing organic matter are evaluated. After some time the applied organic matter e.g. straw must be friable. If it remains firm and without sign of decomposition it indicates poor biological activity in the soil. If the material goes black and smells musty it signifies anaerobic decomposition.
Soil fragmentation: The Preuschen spade diagnosis is completed by lifting up the rest of the material on the spade and then dropping the soil on the ground. The degree of soil fragmentation is evaluated. Ideally, the soil should fragment into small pieces without any persistent major clods or soil layers.

The Preuschen spade diagnosis gives a comprehensive examination of soil features. It is a problem that the description of Preuschen lacks detailed guidelines. This implies that the spade diagnosis depends on the experience of the descriptor and therefore the results may be highly subjective.

Sobelius (1995) has suggested a modification of the spade diagnosis. The description of soil structure (layering, colour, grade, aggregate type and size, consistence, pore size and number of pores) follows the FAO guidelines for soil description (FAO, 1990). Also the description of number and size of roots follows the FAO guidelines. In addition, Sobelius has proposed a more detailed description of root growth. Root morphology (branching, thickening, bending, rhizosheaths) and root nodules on leguminous plants are described. Unfortunately, he has not included guidelines on how to evaluate biological activity in the soil – except for a key to determine earthworm species.

Recently, Beste (1999) has proposed an extended spade diagnosis that combines a qualitative description of soil structure in the 0-30 cm layer with a quantitative determination of some key physical parameters. Wet aggregate stability is determined by a simple method applied in the field. Shear strength is determined *in situ* in all layers with at vane shear apparatus. Core samples are taken for determination of water content and bulk density.

2.2 Other methods

2.2.1 Pedological soil profile descriptions

Many of the soil features described in the Preuschen spade diagnosis are also described when making a pedological description of the soil profile. A number of international guidelines for soil description have been worked out (e.g. FAO, 1990; Soil Survey Division Staff, 1993). Danish guidelines for soil description have been set up by e.g. Petersen and Møberg (1987) and Madsen and Jensen (1988) on the basis of the international guidelines. These guidelines may also be applied to the spade diagnosis as suggested by Sobelius (1995).

It is worth noting that there are significant differences between a spade diagnosis and an ordinary soil profile description – particularly in the objectives. The purpose of a soil profile description is commonly to learn about soil genesis and/or to be able to classify the soil. The objective of the spade diagnosis is to evaluate the present soil management strategy by studying the relation between the soil structure, root growth and biological activity in the upper part of the soil profile (Preuschen, 1983).

2.2.2 Numerical evaluation of soil tilth

<u>The Peerlkamp method</u>

In the Netherlands in the 1960s there was a lot of activity in the development and testing of descriptive soil evaluation field methods. Especially the Peerlkamp method (Peerlkamp, 1959) has been broadly used in the Netherlands and elsewhere (Boekel, 1963; Batey, 1975, 1988). In the Peerlkamp method the soil is assigned an "St" number (1-9); St 1 = poor, St 9 = optimal soil tilth. With an ordinary spade soil blocks are dug out from the soil (at least 10 samples). The assignment of the index is based on a visual evaluation of the structural units (type, shape, size, porosity and rupture energy in moist condition), soil porosity and root growth. Peerlkamp proposed a separate rating table for light and heavy soils. For heavy soils a poor soil (St 1) consists of large dense clods, with evidence of anaerobic conditions in some areas. The roots grow solely in the cracks between the clods. On the other hand a fine, loose crumb structure characterises an ideal heavy soil (St 9). A poor sandy soil is characterised by single-grain structure, whereas a soil consisting stable porous soil aggregates characterises an optimal sandy soil.

The Peerlkamp method has been broadly used in the Netherlands and in other countries as described by Batey (1975). Boekel (1982) used the method to study the development of soil tilth over several years (1960-1982) for some commercial and research station fields in the Netherlands. He found a general decrease in rating during the 22 years of study. This finding was explained by increased problems with soil compaction due to the use of increasingly heavier tractors and implements in modern agriculture. Boekel (1963) also found a positive effect of the content of organic matter on soil tilth (i.e. higher visual rating). Batey (1975) noted that visual scoring methods - equal or similar to the Peerlkamp method – were extensively used in Great Britain in advisory as well as in investigational work.

The Batey method

In a so-called practical guide to the use and management of soil Batey (1988) describes problems of soil structure in modern agriculture and presents a method of numerically evaluating soil structure in the field. The method resembles to a great extent the Peerlkamp method. A spadeful of soil is dug out and gently broken apart. The soil structural units, the grade and the consistence are assessed. The soil or soil layer is assigned a number according to a "soil structural key". The index goes from S1 to S7 where S1 is the best. S1 soils/soil layers are characterised by fine aggregates, 1-6 mm in diameter. S7 soils/soil layers are compact soils/layers with few or no component aggregates visible where anaerobic conditions may be detected.

3. The spade analysis method

The presented spade analysis method is developed on the basis of the spade diagnosis as described by Preuschen (1983, 1994) and Sobelius (1995). The purposes of the spade analysis are:

- to describe the present status of soil tilth
- to relate the present soil tilth status to past soil management practices
- to give a foundation for making decisions on improved soil management (e.g. altered tillage, crop rotation and fertilisation).
- to evaluate the effect of implemented initiatives.

Guidelines for spade analysis description are presented in Appendix B. The description of soil layering and boundaries is carried out according to the guidelines of Madsen and Jensen (1988) with slight modifications. Soil colour is described using the Munsell colour chart system (Munsell, 1975). Evaluation of soil texture, grades, and types of structural units follows the standard soil description methods (Madsen and Jensen, 1988). Assessment of aggregate size and soil consistence follows the FAO guidelines (FAO, 1990). Evaluation of macropores, surface features in macropores, and of number and size of earthworm burrows and roots is based on the description of Petersen and Møberg (1987) and Greve et al. (1999).

In order to get a more comprehensive characterisation of pore and root structure guidelines for evaluation of pore continuity, root branching and abnormal root growth have been worked out on the basis of the qualitative descriptions by Preuschen (1983, 1994) and Greve et al. (1999). Concerning the characterisation of root nodulation on leguminous plants the guidelines are based on Preuschen (1983, 1994) and Sobelius (1995). When describing soil faunal activity, earthworms are evaluated separately (numbers, species and earthworm casts). Other soil animals are assessed as well as possible. The guidelines for evaluation of the degree of decomposition of organic matter have been based on the descriptions of Preuschen (1983, 1994). In the enclosed manual (Appendix B), a description of sampling, and recommendations on when to perform the analysis, number of replicates etc.

3.1. How to use the spade analysis

The method is applicable for a number of purposes in practical agriculture as well as in agricultural research. The method may be used by practicians in many connections as described by Görbing (1947). The objective of the inspection may be general monitoring of soil-plant interactions. It may also be applied more actively as a tool at the operational level in the decision-making process in soil management. For instance the method may be applied to evaluate seedbed quality or the degree of decomposition of newly applied organic matter. It may also be used prior to tillage to determine the proper depth and/or intensity of soil tillage.

In agricultural research the method may be used as a first step in a hierarchical analysis of e.g. effects of soil management systems on soil tilth. In that case it may be supplemented by other qualitative and quantitative field and laboratory methods (Schjønning et al., 1999). The spade analysis may also be used more directly oriented to assess the proper depth of sampling or the proper depth and type of tillage action to be used in a tillage trial.

4. Materials and methods

4.1 Long-term soil management effects

Results from the spade analysis performed on sites with different soil management are presented below. Detailed scientific studies on the state of soil tilth have been conducted on the soils in Project I.3 operated under Danish Research Centre for Organic Farming. A detailed description of basic characteristics and the selection of the soils is given by Schjønning et al. *(In prep.)*. Soil type and parent material is comparable for soils within each of the four groups of soils presented. Soil management differs within each of the four groups. There is a difference in long-term soil management within each of the groups I-III and a difference in soil tillage within the Group IV (Table 1).

All soils in Group I-III are developed on till plains from the Weichselian glacial stage. The soils may all be classified as Oxyaquic Agriudolls according to Soil Taxonomy (Soil Survey Staff, 1998). The clay content was around 15% in the Group I soils, 20% in the Group II soils, and 18% in the Group III soils. The Group I soils are not neighbouring sites. There is about 2 km between Org-H(I) and Conv-H(I) and about 25 km between Conv-P(I) and the others. The Group II and III soils are located near each other (approx. 2 km distance). Within each of these groups the two sites are located around 250 meters from each other. The soils are labelled by 'Org' (Organic) or 'Conv' (Conventional) with an 'H' for 'Animal Husbandry' meaning a dairy fodder cropping system and a 'P' for 'Plant' meaning a cropping system for cash crop (primarily small grain cereals) production.

4.1.1 Group I

The soils labelled Org-H and Conv-H have for decades been managed in a forage crop rotation (Table 1). They have had a crop rotation with a mixture of annual and perennial crops and animal manure have regularly been applied. The Org-H soil has been dedicated to biodynamic farming practices for almost 50 years. The Conv-H soil has been cultivated mainly with cereals for the last 20 years before sampling. Animal manure has not been applied for at least 10 years but straw has been incorporated into the soil. In the year of sampling and field testing, spring barley with a grass/clover mixture undersown was grown on Org-H and Conv-H and peas on Conv-P.

For all Gr. I soils the tillage system included mouldboard ploughing in the autumn preceding all new crops The soils had received contrasting tillage and traffic intensity within the year of sampling and field testing. The traffic intensity was high on Org-H and Conv-H due to preparation of seedbed, sowing of the small grain cereal cover crop and the grass/clover ley, and rolling the soil afterwards: This resulted in a total of 8 tractor passes between the autumn ploughing and the sampling at plant germination in the spring (Table 1). On the Conv-P soil a single pass in the field after ploughing was carried out. Seedbed preparation and sowing were performed with a combined implement.

The soils had approximately similar soil texture and pH (Table 2). The content of organic matter and readily available K, Mg and P was very high for Conv-H. The content of extractable P (Olsen-P) was low for Conv-P (Olsen-P=15 mg kg^{-1} ~Pt=1.5) and very low for Org-H (Olsen-P=8 mg kg^{-1} ~ Pt=0.8).

4.1.2 Group II

The soil labelled Org-H has been managed according to organic farming practices with a forage crop rotation since 1951 (Table 1). The rotation has included annual as well as perennial crops. The reference soil, labelled Conv-H, has been managed conventionally with a simple four-course cash crop rotation. Quite high amounts of animal manure have been applied annually to this soil. The soils had similar textural compositions and both had a high level of readily available K, Mg and P (Table 2). The organic matter content and CEC were slightly higher for the Org-H soil than for the Conv-H soil, whereas the pH was highest for the Conv-H soil. In the year of analysis (1998) spelt *(Triticum spelta)* was grown on Org-H and winter wheat *(Triticum sativum)* on Conv-H.

4.1.3 Group III

The soil labelled Org-H has been managed according to organic farming practices with a forage crop rotation since 1958 (Table 1). The conventionally managed reference soil, labelled Conv-P, has been grown almost continuously with cereals for the last 20 years.

Animal manure was not applied and straw was removed in most years on the Conv-P soil. In 1998 Spelt *(Triticum spelta)* was grown on Org-H and winter wheat *(Triticum sativum)* was grown on Conv-H. The soils had comparable textural compositions (Table 2). The Org-H soil had a much higher content of organic matter and readily available K, Mg and P than the Conv-P soil. The CEC was also highest for the Org-H soil, whereas the pH was similar for the two soils.

4.2 Effects of soil tillage – Group IV

The tillage experiment was initiated under Project I.3 under Danish Research Centre for Organic Farming. The experiment was established in 1997 at the organically managed Rugballegård Experimental Station, Horsens where the fields were converted to organic farming practices in 1995. The soil is a sandy loam developed on diluvial clay, sand and gravel. Beets were grown in 1997 and spring barley/pea mix with grass/clover undersown in 1998 (Table 1). Four tillage treatments were carried out on plots in a randomised block design with four replicates. Spade analysis was carried out in two treatments. The field did not receive animal manure in 1998. Sampling and measurements took place in the spring barley/pea mix with grass/clover undersown.

The traditional tillage treatment, labelled TT, included mouldboard ploughing followed by secondary tillage and drilling in one pass by a combined implement. An implement composed of subsoiler tines combined with a rotovator and a drill was used for the non-inverting tillage. labelled NIT. The depth of subsoil loosening is flexible, but was set at approximately maximum depth (35 cm) in 1998. The texture and the general chemical characteristics are at the same level for both treatments (Table 2).

4.3 Analysis

Three replicates of the spade analysis were performed on Gr. I soils at the beginning of July 1997. For Gr. II and III soils two replicates of the spade analysis were carried out on each soil. The distance between sampling points on Gr. I-III soils was approximately 25. The spade analysis was performed at the end of June 1998 for Group II and at the beginning of July 1998 for Group III. In the tillage experiment four replicates were carried out for each treatment (i.e. one per replicate in the field trial) in the beginning of July 1998. There is a rather large spatial textural variation in the field. Before the trial was initiated the field was characterised in a 40*40 m grid (Rasmussen et al., 1995). Based on those results areas with similar texture were selected for sampling and also for performing the spade analysis. In all cases the same operator (*the author*) carried out the spade analyses.

5. Results and discussion

Detailed results are presented in appendix A. The presented results are averages of the two or three replicates at each site.

5.1 Long-term soil management effects

5.1.1 Group I

The soil profiles could be divided into three characteristic horizons in all soils. A loose and crumb-structured top layer (harrowed layer) was followed by a rather loose ploughed layer. Below 23-25 cm a plough pan was identified. The soils had similar soil colour and moisture content in all three horizons. Figure 1 shows photos of soil blocks from the Conv-P and Org-H soils.

For the Conv-P soil a crumb structure was identified down to the plough pan layer, whereas for the other two soils (Org-H and Conv-H) a crumb structure was found only in the harrowed top layer. For those soils the structure became denser with granular to sub-angular blocky units below the top layer. At the bottom a plough pan was identified. A plate-structured plough pan was noted for the Org-H soil. Characteristics of the plough pan were not described for Conv-P and Conv-H.

At all depths the soils had a sticky and plastic consistence when wet. When moist all the soils were characterised as friable in the top layer. A friable soil consistence when moist was also found for the middle layer of the Org-H and Conv-P soils. A slightly firmer soil was found in the middle layer of the Conv-H soil. When dry the Org-H soil was hard in the top and middle layer and very hard in the plough pan layer. In comparison, the Conv-P and Conv-H soils were less hard in the top layer. The Conv-P was also less hard in the middle layer.

The number of coarse macropores (>2 mm in diameter) decreased with depth for all soils from >5 pores dm^{-2} in the top layer to 1-5 pores dm^{-2} in the middle layer. The top and middle layers of all soils had approximately the same estimated number of macropores. A similar level of fine macropores (0.5-2 mm in diameter) was likewise estimated for the top layer of all soils. The Conv-P soil had more fine macropores in the middle layer than the other soils. A roughly equal number of earthworm burrows was observed in the top and middle layer of all soils (1-5 pores dm^{-2}). There was a tendency to a higher number in the top layer of the Conv-P soil and a lower number in the middle layer of the Conv-H soil. The continuity and orientation of macropores and earthworm burrows was difficult to evaluate. It was definitely impossible to evaluate these characteristics for the fine macropores. Nevertheless a "slight" pore continuity of the coarse macropores was estimated in the top layer for all soils. In the middle layer it was estimated as "high" for the Org-H and Conv-H and as "moderate" for the Conv-P soil. The continuity of earthworm burrows was estimated as "high" in the top and middle layer of the soils, except for the top layer of the Conv-P soil where it was estimated as "slight". The coarse macropores and the earthworm burrows were oriented diffusely in the top layer of the soils (except for the earthworm burrows in the Org-H soil). In the middle layer they were oriented mainly vertically.

A comparison in root growth characteristics between all soils is not possible, because pea was grown on the Conv-P soil and spring barley with grass/clover undersown was grown on the other soils. When comparing the Org-H and Conv-H soils a similar number of coarse and fine roots were found in the profiles. The number of coarse roots (>2 mm in diameter) was similar in the top and the middle layers, whereas the number of fine roots (0.5-2 mm in diameter) decreased with depth. This trend was also found for the Conv-P soil. The number of root nodules on the pea roots in the Conv-P soil also decreased with depth. A slight hampering of root growth was observed at the interface between the harrowed top layer and the middle layer below for especially the Conv-P soil. A more severe root growth restrain was observed at the interface between the middle layer and the plough pan at the bottom of the profile for Org-H and Conv-H soils.

The type of organic matter under decomposition differed between the soils. In the Org-H soil only root residues were observed, while in the Conv-H soil rather persistent root and stubble residues of the previous maize crop occurred. In the Conv-P soil a large number of straw residues from the previous cereal crop were present. Due to different types of organic matter being present in the soils it is very difficult to compare the ability of the soils to decompose the visible organic matter. This is expressed as the degree of decomposition characteristic and varied from moderate to good for the Conv-H and Conv-P soils to good for the Org-H soil.

Generally, the Conv-P soil had the most desirable soil tilth of the three studied soils. It had crumb structure to a greater depth, less hard consistence when dry and a larger macroporosity. This difference agrees with the difference in bulk density (Table 2). The two soils grown with forage crops had almost similar characteristics. There was a tendency to slightly poorer soil tilth for the Conv-H soil due to a blockier structure in the middle layer and a lower estimated macroporosity. The less desirable soil tilth found on the Org-H and Conv-H soils is very likely due to short-term effects of intensive soil tillage and traffic rather than long-term effects of soil management.

5.1.2 Group II

Three different soil layers were detected in both soils (Table 2, Appendix A). At the top a loose and crumb-structured top-layer was observed. In the middle down to the bottom of the ploughed layer a denser, blockier soil was noticed. At the bottom a denser but rather weak plough pan with a sub-angular blocky structure was observed. The soil colour and the moisture content were quite similar for the soils. A photo of a soil block from the Org-H soil is shown in Figure 2.

The two soils had a matching soil structure (structural units, grade and consistence) throughout the 30 cm deep soil profile. The soils were sticky and plastic in all layers when wet. When moist, both soils had a rupture resistance that increased from friable in the top layer to very firm in the bottom layer. The soils differed in number of macropores (especially earthworm burrows) in the lower parts of the soil profile and earthworm activity. There was an extremely high earthworm activity in Org-H. An abundance of coarse macropores and earthworm burrows (>5 pores dm^{-2}) was found at all depths in the Org-H soil. The soils had similar number of fine macropores in the top and middle layer (>5 pores dm^{-2}). A slightly lower number of fine macropores was found in the plough pan layer of the Org-H soil than in the Conv-H soil. In the plough pan layer a higher continuity of coarse macropores and burrows was estimated for the Org-H soil. Many different horizontally and vertically burrowing earthworm species were seen in the Org-H soil but not identified.

In both soils a slightly impeded root growth was found at the interface between the middle layer and the subsoil (weak plough pan). The branching of the roots was assessed equally for the top layers (moderate/strong). In the plough pan layer the roots was less branched for the Conv-H soil than for the Org-H soil. The abundance of earthworm burrows in Org-H may have caused a less restricted root growth in the bottom layer of Org-H. For both soils a good degree of decomposition of straw and stubble was observed.
In conclusion, the soils had a very similar and rather good soil tilth. They had mainly crumb structure in the ploughed layer and a rather weak plough pan. They differed mainly in earthworm activity, where an extremely high activity was observed in the Org-H soil.

5.1.3 Group III
In both soils three layers were detected (Table 3, Appendix A). The ploughed layer was divided into a 6-7 cm deep top layer with a mainly crumbly structure and a denser mainly blocky structured layer (7-20 cm). Below 20 cm depth a compact plough pan was found with a predominantly compact massive structure. The soils had matching soil colour in the ploughed layer. In the plough pan layer the soil was brighter in the Conv-P than in Org-H soil indicating a lower content of organic matter. A photo of a soil block from each soil is shown in Figure 3.

The Conv-P soil had a denser and less favourable soil structure in the whole 30 cm profile than Org-H. Even in the top layer a partially blocky structure was found in the Conv-P soil. In the Org-H soil a crumb structure was observed in the top layer and partially in the middle layer. A totally massive plough pan was detected in the Conv-P soil, whereas it was partially blocky in the Org-H soil. The unfavourable soil structure in especially Conv-P is also apparent from the grade and consistence of the soil. The Conv-P soil did not fracture into aggregates (i.e. grade = massive) in part of the middle and in the plough pan layer. On the other hand the Org-H soil fractured moderately into whole aggregates (i.e. grade = "moderate") in most of the profile in Org-H soil. The rupture resistance of moist soil increased from "firm" in the top layer to "extremely firm" in the plough pan in the Conv-P soil. For the Org-H soil the rupture resistance was classified as "friable" in the upper layer and "very firm" in the plough pan layer.

Concerning macropores and earthworm burrows, no significant difference was detected between the soils. Despite that, a higher number of especially horizontally burrowing earthworms was observed in the Conv-P soil compared to the Org-H soil. Root growth was severely hampered in both soils. Abnormal root growth was seen in form of bended/deflected and thickened roots at the interface between the upper and the middle layer and most severely at the crossing to the plough pan layer. The number of coarse roots was low in both soils. The number of fine roots decreased with depth in both soils – although most drastically in the Conv-P soil.

In both soils areas with poor decomposition (either slow or anaerobic decomposition) were found. Most of the applied organic matter (straw and stubble) was located at the bottom of the plough layer. Some of the material was either still tough (no sign of decomposition) or was black and smelled musty (anaerobic decomposition) Figure 4.

In general both soils had a rather poor soil tilth. A crumb structure was present only in the top harrowed layer and severe root restriction was observed at the interface between the three layers. Nevertheless the Org-H soil had a more desirable soil tilth than the compact and hard Conv-P soil.

5.2 Effect of soil tillage - Group IV

The soils were both divided into three characteristic layers (Table 4, Appendix A). An upper crumb structured layer was observed for both treatments on top of a denser layer that reached to the bottom of the ploughed or old ploughed layer. At the bottom a strongly compacted plough pan was observed in the TT treated soil and the remains of an old plough pan was detected in the NIT treated soil. The soils were "moist" in all layers and had similar soil colour within the specified layers. The differently treated soils were slightly plastic and slightly sticky when wet. When moist the soils were friable in the ploughed layer and firm in the bottom layer. Photos of a soil block from each soil are shown in Figure 5. An example of a compact plough pan is illustrated in Figure 6.

A large number of fine macropores (>5 pores dm^{-2}) was observed in all layers of the NIT treated soil. In the TT treated soil the number of fine macropores decreased from >5 pores dm^{-2} in the top layer to <1 or 1-5 pores dm^{-2} in the plough pan layer. The estimated continuity of coarse macropores improved from "slight" in the top layer to "moderate/high" in the bottom layer for both treatments. A difference between the treatments was found regarding the continuity of earthworm burrows. The highest continuity was estimated for the TT treated soil. In both treatments a hampered root growth was noticed - but most severely in the TT treated soil (Figure 7). Restricted root growth was noticed at the crossing to the middle layer and at the interface between the middle and plough pan layer. The number of root nodules seemed to be negatively affected by the poor soil structure in the plough pan layer of the TT treated soil. Fewer root nodules were observed in the TT treated soil than in the NIT treated soil (Figure 8).

Some horizontally and vertically burrowing earthworms were observed in the investigated soil blocks of the NIT treated soil. No earthworms were seen in the TT treated soil blocks. The degree of decomposition was assessed as "good" for both treatments.

In conclusion, both soils had a fairly good soil tilth down to the plough pan layer. The successful loosening of the plough pan in the NIT treated soil means that this soil had the most desirable soil structure.

5.3 General discussion

5.3.1 General findings

In the nine investigated soils the 30 cm soil profile could be divided into three characteristic layers reflecting the past and present tillage practices. At the top a 5-8 cm deep intensely cultivated layer was found, where the soil in most cases had a crumb structure. In the middle (approximately 7-22 cm) a denser crumb to blocky-structured layer was found. A dense, blocky to compact massive plough pan was found at the bottom of all soils except for the deep loosened soil (NIT) in the tillage experiment. An increase in rupture resistance and a decrease in macroporosity with depth also reflected the general increase in density with depth.

Root growth was restricted at the interface between all layers. A rather weak root restriction was observed at the interface between the loose, intensely cultivated top layer and the middle layer. On the other hand, severe root growth restriction was seen at the transition to the plough pan layer. This was especially the case for the Group III soils and the TT treated soil in the tillage experiment. In the plough pan roots grew mainly in macropores in the form of old root channels and earthworm burrows and only a few roots had grown into the bulk of the soil. The nodulation of pea roots seemed to be negatively affected by soil compaction (i.e. "few" root nodules on pea roots in the plough pan in the TT treated soil, whereas it was "common" for NIT treated soil).

Earthworm activity was evaluated on the basis of the number and characteristics of earthworm burrows and the number and species identified while excavating the soil block. An evaluation of earthworm activity should not rely solely on the latter. The soil block is too small a unit to give a representative sample of the number of earthworms present in the soil. Moreover some of the earthworms would have escaped while digging out the sample. Lastly, a significant number of vertically burrowing species like *Lumbricus terrestris* may be located below 30 cm depth.
In one case a clear difference in earthworm activity was noticed. The Org-H(II) soil had an extremely high activity compared to all the other soils including its counterpart (Conv-H(II)). The degree of decomposition of organic matter was assessed "good" in most soils except for the Group III soils. In these soils with a prominent plough pan, areas of poor decomposition were observed.

5.3.2 Compacted layers

In all soils plough pans occurred. This agrees with other recent studies in Denmark that subsoil compaction occurs extensively in many Danish soils (e.g. Schjønning, 1989; Schjønning and Rasmussen, 1989; Rasmussen et al. 1995). The development of plough pans is caused by the traffic of machinery on the soil surface and by the pressure and slippage of tractor tyres in the furrow when ploughing. Harmful soil compaction is not a new problem (see e.g. Soane and Van Ouwerkerk, 1994), but the problems have supposedly escalated during recent years because of a sharp increase in the size and weight of agricultural machinery. In the early work on the spade diagnosis the problem of compacted plough pans is highlighted (Görbing, 1947 and Teipel, 1952 a, b). According to Teipel (1952a) Görbing assessed that plough pans were present in about 80% of the many soils that he had investigated throughout the years (1920-1947). Teipel found plough pans in more than 60% of the 140 soils from Thüringen, Germany that were investigated by the spade diagnosis. The soils ranged from heavy clay soils to sandy soils. In recent years Preuschen (1994) has emphasised the negative impact of tillage pans on soil tilth.

As a measure of remedying and avoiding the formation of plough pans Görbing proposed that primary cultivation was performed with a plough that combines an inverting tillage of the upper 10-15 cm of the soil with deep non-inverting soil loosening to more than 30 cm depth. Hampl et al. (1995) advocates a similar primary tillage system as being particularly suitable in organic farming.

5.3.3 Long-term and short-term effects

There was no clear trend in the results of the spade analysis concerning long-term effects of different soil management. The application of organic matter and a versatile crop rotation were expected to result in improved soil tilth as found by e.g. Reganold (1988). The results from the Group II and III soils support this hypothesis. Conversely, the results from the Group I soils show the opposite trend. The beneficial effects of application of organic manure and a forage crop rotation for the Org-H(I) and Conv-H(I) soils have probably been blurred by negative effects of soil compaction in the plough layer. This finding agrees with e.g. Munkholm et al. (1999a) who found that heavy soil compaction in early spring on wet soil after primary cultivation had a marked negative effect on soil structure in the seedbed (i.e. increased penetration resistance and strength of soil aggregates, and decreased soil friability).

Soil compaction of the plough layer may be especially critical on the Org-H(I) soil, which has a very low Olsen-P content. On this soil, optimal growth conditions are needed to be able to extract the strongly bound P. This is the case for both the plant roots and the arbiscular mycorrhizal fungi. The latter may take up a considerable part of the P associated with the plant roots (George et al., 1995). The combination of a compact and a soil low in plant available P may be one of the main reasons for the generally low yield level recorded on the farm with the Org-H(I) soil (Jensen and Kristensen, 1998).

Clear differences were observed between and within groups. The Group III soils had in general a poorer soil tilth than Group II soils. A serious root-restricting plough pan was detected in both Group III soils. The Conv-P(III) soil with almost continuous small grain production without application of animal manure had the poorest soil tilth. Only minor differences are seen between Group II soils that primarily differed in crop rotation. The main difference was in earthworm activity. The marked effect of tillage on soil tilth was confirmed in the tillage experiment. The non-inverting soil-loosening system had a positive effect on soil tilth – mainly due to the break up of the plough pan.
Also when evaluating the top 20 cm of the soil by the Peerlkamp method clear differences between the soils appear. The soils were applied the following St numbers: *St 7*: Conv-P(I), *St 6*: Org-H(I), NIT, *St 5*: TT, Conv-H(I) Conv-H(II) and Org-H(II), *St 4*: Org(III) and *St 3*: Conv-P(III). This evaluation is solely based on the soil structure and root growth characteristics.

There was a trend to stronger and blockier structure with increasing clay content as could be expected. However, it is very interesting that the two conventionally managed soils grown mainly with cereals and no addition of organic manure are ranged as the soils with the best and poorest soil tilth.

The contradicting results from this investigation concerning long-term effects of soil management give rise to some questions that need to be answered. There is a need to investigate the interactions between expected positive effects of proper long-term soil management and harmful "short-term" effects of especially intensive traffic on wet soil. To what extent do the harmful effects of intense soil tillage and traffic negate the positive effects of appropriate long-term soil management? For how long will these harmful effects persist?

5.3.4 Evaluation of the spade analysis method

When performing the spade analysis a good "holistic" description of the actual state of soil tilth is obtained. When using the spade analysis the present soil properties are described. Based on historical data on soil management conclusions may be draw on the effect of soil management of the past. The classical spade diagnosis is a qualitative method and the results depend on the experience of the operator. Minimisation of operator dependency has been one of the main objectives of this work. Using well-known standardised methods for describing e.g. soil colour, structural units and consistence should minimise this dependency. Where no clear and standardised methods were found in the literature, guidelines for describing characteristics have been proposed. This applies e.g. to the description of pore and root growth characteristics and degree of decomposition of applied organic matter. These guidelines may need further specification and clarification. Especially the description of root nodulation on leguminous plants requires further clarification.

Fine correlations to parameters measured by specialised quantitative methods in the field and in the laboratory have been found (Schjønning et al. 1999). Many different parameters have been measured especially in the 6-13 cm layer of the soils (Jensen et al. (submitted); Munkholm et al., 1998 and Schjønning et al. (in prep.)). For instance the increase in density and strength by depth found in most soils by the spade analysis was reflected by an increase in penetration resistance with depth (Munkholm et al., 1998, Schjønning et al. (in prep.)). Also the difference in root growth characteristics found between the treatments in the tillage trial was confirmed by quantitative root counting methods (Munkholm et al., 1999b). The extremely high earthworm activity in the Org-H(II) soil was probably the reason for a very large saturated hydraulic conductivity, K_{sat}, measured at the soil surface in this soil (K_{sat}=445 mm h^{-1}) (Schjønning and Munkholm, in prep). For the three other Group II and III soils, K_{sat} varied between 40 and 60 mm h^{-1}.

6. Conclusions

A positive effect of long-term versatile crop rotation and application of organic manure was clearly found for the Group III soils and to some extent also for the Group II soils. For the Group I soils an reverse trend was detected. Negative short-term effects of intensive tillage and traffic may explain this. The significant effect of tillage and traffic was also evident from the tillage trial results. The deep soil loosening had successfully broken up the plough pan and resulted in an improved soil tilth in comparison with the traditionally ploughed soil.

The spade analysis was a useful tool for describing actual soil tilth status of the soil. Based on historical data on the soil it was possible to evaluate long and short-term effects of soil management on soil tilth. Although the proposed spade analysis method is a comprehensive method it should not be taken as a final description of how to perform such a visual evaluation of soil tilth in the field. The method may be too comprehensive in many circumstances where the purpose of the investigation is to evaluate specific soil properties. In other situations the method may fall short where a more detailed and clearer description of e.g. faunal activity is needed.

7. Literature

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Table 1. General information about the soil groups.

	Group I			Group II		Group III		Group IV	
	Org-H	Conv-H	Conv-P	Org-H	Conv-H	Org-H	Conv-P	TT	NIT
	Høng	Torpe, v. Høng	Flakkebjerg	Sj.Odde	Sj.Odde	Sj.Odde	Sj.Odde	Bygholm	Bygholm
UTM E	644101	642850	651721	648213	647800	646425	646525	555221	555221
UTM N	6157194	6155440	6133708	6204333	6204525	6205875	6205675	9471170	9471170
Farming system	Organic	Conventional	Conventional	Organic	Conventional	Organic	Conventional	Organic	Organic
Conversion to organic farming	1951	-	-	1951	-	1958	-	1996	1996
Crop rotation									
Year of sampling	Barley with grass/clover	Barley with grass/clover	Peas	Spelt	Winter wheat	Spelt	Winter wheat	Barley/peas with grass/clover	Barley/peas with grass/clover
Previous year	Beetroots	Maize	Spring barley	Winter wheat	Spring barley	Winter wheat	Winter wheat	Beetroots	Beetroots
2nd year prior to sampling	Grass/clover	Grass/clover	Winter wheat	Grass/clover	Beetroots	Grass/clover	Winter rape	Oats followed by radish	Oats followed by radish
3nd year prior to sampling	Grass/clover	Grass/clover	Winter rape	Grass/clover	Winter wheat	Barley/peas with grass/clover	Winter barley	Spring barley	Spring barley
4th year prior to sampling	Oats with grass/clover	Grass/clover	Winter barley	Potatoes followed by grass/clover	Winter wheat	Spring barley	Spring barley	Winter barley	Winter barley
5th year prior to sampling	Winter wheat	Grass/clover	Winter wheat	Potatoes	Spring barley	Grass/clover	Winter wheat	Spring barley	Spring barley
6 to about 12 years	Cereals, grass/clover, lucerne, beetroots	Cereals, maize, grass/clover	Cereals, peas	Cereals, grass/clover, vegetables	Cereals, beetroots	Cereals, grass/clover, potatoes	Mainly cereals	Cereals, ryegrass, beetroots	Cereals, ryegrass, beetroots
Ploughing	Y	Y	Y	Y	Y	Y	Y	Y	N
PTO-machinery	N	N	Y	Y	Y	Y	Y	N	Y
No of passes after primary cultivation	8	8	1	1	1	1	1	1	0

Table 2. Texture and chemical data of soil sampled from the 6-13 cm layer.

		Group I			Group II		Group III		Group IV	
		Org-H	Conv-H	Conv-P	Org-H	Conv-H	Org-H	Conv-P	TT	NIT
Organic matter	g 100 g^{-1}	2.4	2.8	2.5	3.9	3.5	3.5	2.4	3.3	3.0
Clay (<2 µm)	g 100 g^{-1}	16	15	14	20	21	17	19	13	14
Silt (2-20 µm)	g 100 g^{-1}	17	14	21	15	20	17	14	14	13
F. sand (20-200 µm)	g 100 g^{-1}	40	42	40	43	39	38	45	37	38
C. sand (200-2000 µm)	g 100 g^{-1}	25	27	22	18	17	24	20	33	32
pH ($CaCl_2$)		6.7	6.7	6.4	6.7	7.1	6.2	6.1	5.9	5.7
Extractable K	mg kg^{-1}	80	346	102	390	325	380	185	226	222
Extractable Mg	mg kg^{-1}	59	120	39	207	149	163	93	75	69
Extr. P (Olsen P)	mg kg^{-1}	8	50	15	39	47	46	23	30	29
CEC[1]	meq 100 g^{-1}	13.2	11.0	12.6	17.8	16.0	13.8	12.3	12.2	12.4
Bulk density	g cm^{-3}	1.54	1.54	1.44	1.35	1.35	1.36	1.49	1.41	1.46
Water content (sampling)	m^3 100 m^{-3}	n.d.	n.d.	n.d.	17.7	20.0	19.5	16.9	21.8	21.6
Water content, -100 hPa	m^3 100 m^{-3}	30.2	31.3	30.7	34.9	32.7	31.4	31.9	30.6	30.5
Water content, -300 hPa	m^3 100 m^{-3}	23.3	23.6	24.1	28.8	26.6	26.6	27.7	20.5	19.9

[1]Cation exchange capacity

Figure 1. Soil samples from the Group I soils. Org-H(I) *(top)* and Conv-P(I) *(bottom)*.

Figure 2. Soil sample from Org-H(II) soil.

Figure 3. Soil samples from the Group III soils. Org-H(III) *(top)* and Conv-P(III) *(bottom)*.

Figure 4. Poorly decomposed straw and stubble residues from the bottom of the ploughed layer of the Conv-P(II) soil. The material incorporated September 1997 was still tough and poorly decomposed in July 1998.

Figure 5. Soil samples from the Group IV soils. Traditional tillage (TT) *(top)* and non-inverting tillage (NIT) *(bottom)*.

Figure 6. A compact plough pan from the TT treated soil. After excavation of the loose topsoil a very compact massive plough pan – almost like a brick – ramain standing.

Figure 7. Root restriction caused by a plough pan (TT treatment). Top: Photo shows horizontal root growth on top of a plough pan and root clustering at the entrance to vertical earthworm burrows.
Bottom: A plough pan seen from below (30 cm depth). Remark the dense structure and roots mainly growing in earthworm burrows or old root channels.

Figure 8. Root nodulation on pea roots in the NIT treated soil. Remark, the relatively high number of nodules on pea roots at the bottom of the 30 cm deep profile (old plough pan region).

Appendix A

Table 1. Group I results[1]

Soil	Org-H(I)	Conv-H(I)	Conv-P(I)
Generally			
Described by	Lars J. Munkholm	Lars J. Munkholm	Lars J. Munkholm
Position, UTM	644101 E 6157194 N	642850 E 6155440 E	651721 E 6133708 N
Date	July 7, 1997	July 7, 1997	July 8, 1997
Vegetation	Arable	Arable	Arable
Ground cover	Spring barley (*Hordeum vulgare*) Lucerne (*Medicago sativa*) undersown	Spring barley (*Hordeum vulgare*) Grass/clover undersown	Peas (*Pisum sativum*)
Growth stage cover crop	79 (Barley)	79 (Barley)	72
Layers[2]	**a. 0-10 cm harrowed layer** **b. 10-25 cm ploughed layer** **c. 25-30 cm plough pan**	**a. 0-9 cm harrowed layer** **b. 9-23 cm ploughed layer** **c. 23-30 cm plough pan**	**a. 0-10 cm harrowed layer** **b. 10-25 cm ploughed layer** **c. 25-30 cm plough pan**
Boundaries[3]	a/b. N.E.[4] b/c. N.E.	a/b. N.E. b/c. N.E.	a/b. N.E. b/c. Sharp
Colour, dry	a. 10 YR 5/2 b. 10 YR 5/2 c. 10 YR 6/3	a. 10 YR 5/2 b. 10 YR 5/2 c. N.E.	a. 10 YR 5/2 b. 10 YR 5/2 c. N.E.
Colour, moist	a. 10 YR 4/2 b. 10 YR 4/2 c. 10 YR 4/3	a. 10 YR 4/2 b. 10 YR 4/2 c. N.E.	a. 10 YR 5/2 b. 10 YR 4/2 c. N.E.
Moisture	a. Dry b. Dry c. Dry	a. Dry b. Dry c. Dry	a. Dry b. Dry c. N.E.
Texture[5]	Sandy loam	Sandy loam	Sandy loam
Structure			
Type	a. Crumb b. Granular c. Platy	a. Crumb b. Granular / sub. blocky c. N.E.	a. Crumb b. Crumb c. N.E.
Size	a. Fine b. Coarse c. Very coarse	a. Medium b. Medium / coarse c. N.E.	a. Medium b. Medium c. N.E.
Grade	a. Moderate / strong b. Strong c. Strong	a. Moderate b. Moderate c. N.E.	a. Moderate b. Moderate c. N.E.
Consistence *Wet* Stickiness	a. Sticky b. Sticky c. Sticky	a. Sticky b. Sticky c. N.E.	a. Sticky b. Sticky c. N.E.
Wet Plasticity	a. Plastic b. Plastic c. Plastic	a. Plastic b. Plastic c. N.E.	a. Plastic b. Plastic c. N.E.
Moist Rupture resistance	a. Friable b. Friable c. Firm	a. Friable b. Friable / firm c. N.E.	a. Friable b. Friable c. N.E.
Dry Rupture resistance	a. Hard b. Hard c. Very hard	a. Slightly hard b. Hard c. N.E.	a. Slightly hard b. Slightly hard / hard c. N.E.

Table 1. *Continued*

Soil	Org-H(I)	Conv-H(I)	Conv-P(I)
Macropores			
Number fine (cm^{-2})	a. >5 b. 1-5 c. 1-5	a. 1-5 / >5 b. 1-5 c. N.E.	a. >5 b. >5 c. N.E.
Number coarse (dm^{-2})	a. >5 b. 1-5 c. 1-5	a. 1-5 / >5 b. 1-5 c. N.E.	a. 1-5 / >5 b. 1-5 c. N.E.
Number earthw. burrows (dm^{-2})	a. 1-5 b. 1-5 c. 1-5	a. 1-5 b. <1 / 1-5 c. N.E.	a. 1-5 / >5 b. 1-5 c. N.E.
Distribution	N.E.	N.E.	N.E.
Continuity Coarse	a. Slight b. High c. High	a. Slight b. High c. N.E.	a. Slight b. Moderate c. N.E.
Continuity earthw. burrows	a. High b. High c. High	a. High b. High c. High	a. Slight b. High c. N.E.
Orientation coarse	a. Diffuse b. Mainly vertical c. Mainly vertical	a. Diffuse b. Mainly vertical c. N.E.	a. Diffuse b. Mainly vertical c. N.E.
Orientation earthw. burrows	a. Mainly horizontal b. Mainly vertical c. Mainly vertical	a. Diffuse b. Mainly vertical c. N.E.	a. Diffuse b. Mainly vertical c. N.E.
Internal surface features			
Type	N.E.	N.E.	Clay and humus
Quantity	N.E.	N.E.	In earthworm burrows
Concentrations			
Type	N.E.	N.E.	N.E.
Quantity	N.E.	N.E.	N.E.
Roots[6]			
Number fine (cm^{-2})	a. >5 b. 1-5 c. 1-5	a. >5 b. 1-5 c. N.E.	a. 1-5 / >5 b. <1 c. N.E.
Number coarse (dm^{-2})	a. 1-5 b. 1-5 c. 1-5	a. 1-5 b. 1-5 / >5 c. N.E.	a. 1-5 b. 1-5 c. 1-5
Branching	a. Moderate b. Slight c. Slight	a. Strong b. Slight / moderate c. N.E.	a. Moderate b. Moderate c. N.E.
Distribution	N.E.	N.E.	N.E.
Impediments	a/b. Compact layer (weak) b/c. Compact layer	a/b. Not observed b/c. Compact layer	a/b. Compact layer (weak) b/c. N.E.
Thickened roots	a/b. Not observed b/c. Common (comp. layer)	a/b. Not observed b/c. Common (comp. l.)	a/b. Common (c. l.,weak) b/c. N.E.
Degree of bending	N.E.	N.E.	N.E.
Root nodulation Number	a. Common b. N.E. c. N.E.	a. No leguminous plants b. No leguminous plants c. No leguminous plants	a. Many b. Common c. N.E.
Distribution	a. Good b. N.E. c. N.E.	a. No leguminous plants b. No leguminous plants c. No leguminous plants	a. Good b. N.E. c. N.E.

Table 1. *Continued*

Soil	Org-H(I)	Conv-H(I)	Conv-P(I)
Soil fauna			
Earthworms	N.E.	N.E.	N.E.
Others	N.E.	N.E.	N.E.
Decomposition of organic matter			
Type	a. Root residue b. Root residue c. N.E.	a. Root and stubble residue b. Root and stubble residue c. N.E.	a. Straw residue b. Straw residue c. N.E.
Degree of decomposition	a. Good b. Good c. N.E.	a. Moderate / good b. Moderate / good c. N.E.	a. Moderate / good b. Moderate / good c. N.E.

[1] The soils were described in 1997 when the method was under development. Therefore, N.E. (not evaluated) occurs frequently in this table.
[2] Layers: Figures mentioned below refer to figures stated for each detected layer.
[3] "a/b" denote interface between layer a and b. "b/c" denotes interface between layer b and c.
[4] N.E.: not evaluated.
[5] Texture was not evaluated in the field. Lab. data from the 7-15 cm layer is stated.
[6] Not possible to compare root growth characteristics for Conv-P(I) with the other soils – different crops grown in the fields.

Table 2. Group II results

Soil	Org-H(II)	Conv-H(II)
Generally		
Described by	Lars J. Munkholm	Lars J. Munkholm
Position, UTM	648213 E 6204333 N	647800 E 6204525 N
Date	June 30, 1998	June 30, 1998
Vegetation	Arable	Arable
Ground cover	Spelt (*Triticum spelta*)	Winter wheat (*Triticum sativum*)
Growth stage cover crop	77	75
Layers[1]	**a. 0-6 cm harrowed layer** **b. 6-22 cm ploughed layer** **c. 22-30 cm plough pan**	**a. 0-6 cm harrowed layer** **b. 6-21 cm ploughed layer** **c. 21-30 cm plough pan**
Boundaries[2]	a/b. Clear b/c. Sharp	a/b. Clear b/c. Clear
Colour, dry[3]	a. N.E.[4] b. N.E. c. N.E.	a. N.E. b. N.E. c. N.E.
Colour, moist	a. 10 YR 3/3 or 4/3 b. 10 YR 3/3 or 4/4 c. 10 YR 4/3 or 4/4	a. 10 YR 3/2 b. 10 YR 3/3 or 4/2 c. 10 YR 3/3 or 4/3
Moisture	a. Moist b. Moist c. Moist	a. Moist b. Moist c. Moist
Texture[5]	Sandy clay loam	Sandy clay loam
Structure		
Type	a. Crumb b. Crumb and sub. blocky c. Sub. blocky	a. Crumb b. Crumb and sub. blocky c. Sub. blocky
Size	a. Medium b. Fine / medium (blocks) c. Coarse	a. Medium b. Medium (blocks) c. Coarse
Grade	a. Moderate b. Moderate c. Moderate	a. Moderate b. Moderate c. Weak / moderate
Consistence *Wet* Stickiness	a. Sticky b. Sticky c. Sticky	a. Sticky b. Sticky c. Sticky
Wet Plasticity	a. Plastic b. Plastic c. Plastic	a. Plastic b. Plastic c. Plastic
Moist Rupture resistance	a. Friable b. Friable / firm c. Very firm	a. Slightly friable / friable b. Firm c. Very firm
Dry[6] Rupture resistance	a. N.E. b. N.E. c. N.E.	a. N.E. b. N.E. c. N.E.

Table 2. *Continued*

Soil	Org-H(II)	Conv-H(II)
Macropores		
Number fine (cm^{-2})	a. >5 b. >5 c. 1-5	a. >5 b. >5 c. >5
Number coarse (dm^{-2})	a. >5 b. >5 c. >5	a. >5 b. 1-5 / >5 c. 1-5
Number earthw. burrows (dm^{-2})	a. >5 b. >5 c. >5	a. >5 b. 1-5 c. 1-5
Distribution	N.E.	N.E.
Continuity Coarse	a. Moderate b. Moderate / high c. High	a. Moderate b. Moderate c. Moderate
Continuity earthworm burrows	a. Moderate b. Moderate / high c. High	a. Moderate b. Moderate c. Moderate
Orientation coarse	a. Diffuse b. Diffuse c. Mainly vertical	a. Diffuse b. Diffuse c. Mainly vertical
Orientation earthw. burrows	a. Mainly horizontal b. Diffuse c. Mainly vertical	a. Mainly horizontal b. Diffuse c. Mainly vertical
Internal surface features		
Type	Earthworm excrements	Earthworm excrements
Quantity	In earthworm borrows	In earthworm borrows
Concentrations		
Type	N.E.	N.E.
Quantity	N.E.	N.E.
Roots[7]		
Number fine (cm^{-2})	a. >5 b. 1-5 / >5 c. 1-5	a. >5 b. 1-5 c. 1-5
Number coarse (dm^{-2})	a. <1 / 1-5 b. <1 / 1-5 c. <1	a. <1 / 1-5 b. <1 c. <1
Branching	a. Strong b. Moderate c. Moderate	a. Strong b. Moderate c. Slight
Distribution	N.E.	N.E.
Impediments	b/c. Compact layer	b/c. Compact layer (weak)
Thickened roots	b/c. Common (Compact layer)	b/c. Common (compact layer)
Degree of bending	b/c. Weak	b/c. Weak
Root nodulation Number	a. N.E. b. N.E. c. N.E.	a. N.E. b. N.E. c. N.E.
Distribution	a. N.E. b. N.E. c. N.E.	a. N.E. b. N.E. c. N.E.

Table 2. *Continued*

Soil	Org-H(II)	Conv-H(II)
Soil fauna		
Earthworms	Extremely many most in 0-10 cm many species	Common most in layer a by straw residue
Others	No observed	N.E.
Decomposition of organic matter		
Type	Straw and stubble primarily in layer b	Straw and stubble in all the ploughed layer (layer a & b)
Degree of decomposition	Good	Good

1 Layers: Figures mentioned below refer to figures stated for each detected layer.
2 "a/b" denote interface between layer a and b. "b/c" denotes interface between layer b and c.
3 Colour and consistence was not evaluated in dry condition because the soil was too wet at testing.
4 N.E.: not evaluated.
5 Texture was not evaluated in the field. Lab. data from the 7-15 cm layer is stated.
6 Soil was too wet to evaluate rupture resistance when dry.
7 The Number of roots is difficult to compare between the two soils – not the same crop.

Table 3. Group III results

Soil	Org-H(III)	Conv-P(III)
Generally		
Described by	Lars J. Munkholm	Lars J. Munkholm
Position, UTM	646425 E 6205875 N	646525 E 6205675 N
Date	July 10, 1998	July 10, 1998
Vegetation	Arable	Arable
Ground cover	Spelt (Triticum spelta)	Winter wheat (Triticum sativum)
Growth stage cover crop	81	79
Layers[1]	**a. 0-7 cm harrowed layer** **b. 7-20 cm ploughed layer** **c. 20-30 cm plough pan**	**a. 0-6 cm harrowed layer** **b. 6-20 cm ploughed layer** **c. 20-30 cm plough pan**
Boundaries[2]	a/b. Clear b/c. Sharp	a/b. Clear b/c. Sharp
Colour, dry[3]	a. N.E.[4] b. N.E. c. N.E.	a. N.E. b. N.E. c. N.E.
Colour, moist	a. 10 YR 3/2 b. 10 YR 3/3 c. 10 YR 3/3	a. 10 YR 3/2 b. 10 YR 3/3 c. 10 YR 4/2
Moisture	a. Moist b. Moist c. Moist	a. Moist b. Moist c. Moist
Texture[5]	Sandy loam	Sandy loam
Structure		
Type	a. Crumb b. Sub. blocky and crumb c. Compact massive and sub. blocky	a. Crumb and sub. block b. Sub. blocky c. Compact massive
Size	a. Medium b. Medium (blocks) c. Coarse (blocks)	a. Medium (crumbs.); fine (blocks) b. Medium / coarse (blocks) c. -
Grade	a. Moderate b. Moderate c. Massive / moderate	a. Moderate b. Moderate / massive c. Massive
Consistence *Wet* Stickiness	a. Sticky b. Sticky c. Sticky	a. Sticky b. Sticky c. Sticky
Wet Plasticity	a. Plastic b. Plastic c. Plastic	a. Plastic b. Plastic c. Plastic
Moist Rupture resistance	a. Friable b. Firm / very firm c. Very firm	a. Firm b. Very firm c. Extremely firm
Dry[6] Rupture resistance	a. N.E. b. N.E. c. N.E.	a. N.E. b. N.E. c. N.E.

Table 3. *Continued*

Soil	Org-H(III)	Conv-P(III)
Macropores		
Number fine (cm^{-2})	a. >5 b. >5 c. 1-5	a. >5 b. >5 c. 1-5
Number coarse (dm^{-2})	a. >5 b. >5 c. 1-5	a. >5 b. >5 c. 1-5 / >5
Number earthw. burrows (dm^{-2})	a. >5 b. 1-5 / >5 c. 1-5	a. >5 b. >5 c. 1-5 / >5
Distribution	N.E.	N.E.
Continuity Coarse	a. Moderate b. Moderate c. Moderate / high	a. Weak / moderate b. Moderate c. High
Continuity earthworm burrows	a. Moderate b. Moderate / high c. Moderate / high	a. Moderate b. High c. High
Orientation coarse	a. Diffuse / mainly horizontal b. Mainly vertical c. Mainly vertical	a. Diffuse / mainly horizontal b. Mainly vertical c. Mainly vertical
Orientation earthw. burrows	a. Mainly horizontal b. Mainly vertical c. Mainly vertical	a. Diffuse b. Mainly vertical c. Mainly vertical
Internal surface features		
Type	Earthworm excrements	Earthworm excrements
Quantity	In earthworm borrows	In earthworm borrows
Concentrations		
Type	N.E.	N.E.
Quantity	N.E.	N.E.
Roots[7]		
Number fine (cm^{-2})	a. >5 b. >5 c. <1 / 1-5	a. >5 b. 1-5 c. <1
Number coarse (dm^{-2})	a. <1 b. <1 c. <1	a. <1 b. <1 c. <1
Branching	a. Strong b. Moderate / strong c. Slight / moderate	a. Strong b. Moderate c. Slight
Distribution	N.E.	N.E.
Impediments	a/b. Compact layer (only 1 test) b/c. Compact layer	a/b. Compact layer b/c. Compact layer
Thickened roots	a/b. Common (compact layer, 1 test) b/c. Common (compact layer)	a/b. Common (compact layer) b/c. Common (compact layer)
Degree of bending	a/b. Weak / strong (1 test) b/c. Strong	a/b. Weak b/c. Weak / strong
Root nodulation Number	a. N.E. b. N.E. c. N.E.	a. N.E. b. N.E. c. N.E.
Distribution	a. N.E. b. N.E. c. N.E.	a. N.E. b. N.E. c. N.E.

Table 3. *Continued*

Soil	Org-H(III)	Conv-P(III)
Soil fauna		
Earthworms	2 observed 1 *Lumbricus terrestris* 1 *Aporrectodea calignosa*	Many horizontally burrowing earthworms (layer a) (*Aporrectodea rosea; Octolasion cyaneum)* Some in layer b by decomposing straw *(Aporrectodea calignosa)*
Others	Bug larva	No observed
Decomposition of organic matter		
Type	Straw residues in the bottom of the plough layer	Straw and stubble residues in the plough layer
Degree of decomposition	Poor / good	Poor / good

[1] Layers: Figures mentioned below refer to figures stated for each detected layer.
[2] "a/b" denote interface between layer a and b. "b/c" denotes interface between layer b and c.
[3] Colour and consistence was not evaluated in dry condition because the soil was too wet at testing.
[4] N.E.: not evaluated.
[5] Texture was not evaluated in the field. Lab. data from the 7-15 cm layer is stated.
[6] Soil was too wet to evaluate rupture resistance when dry.
[7] The Number of roots is difficult to compare between the two soils – not the same crop.

Table 4. Group IV results

Soil	TT	NIT
Generally		
Described by	Lars J. Munkholm	Lars J. Munkholm
Position, UTM	555221 E 9471170 N	555221 E 9471170 N
Date	July 7/8, 1998	July 7/8, 1998
Vegetation	Arable	Arable
Ground cover	Spring barley/pea mixture with grass/clover undersown	Spring barley/pea mixture with grass/clover undersown
Growth stage cover crop	71 (Spring barley) 68 (Pea)	71 (Spring barley) 68 (Pea)
Layers[1]	**a. 0-7 cm harrowed layer** **b. 7-22 cm ploughed layer** **c. 22-30 cm plough pan**	**a. 0-6 cm harrowed layer** **b. 6-22 cm old ploughed layer** **c. 22-30 cm old plough pan region**
Boundaries[2]	a/b. Clear b/c. Sharp	a/b. Clear b/c. Clear
Colour, dry[3]	a. N.E.[4] b. N.E. c. N.E.	a. N.E. b. N.E. c. N.E.
Colour, moist	a. 10 YR 3/3 b. 10 YR 3/3 c. 10 YR 4/3	a. 10 YR 3/2 b. 10 YR 3/3 c. 10 YR 4/3
Moisture	a. Moist b. Moist c. Moist	a. Moist b. Moist c. Moist
Texture[5]	Sandy loam	Sandy loam
Structure		
Type	a. Crumb b. Granular and sub. blocky c. Sub. blocky and platy	a. Crumb b. Crumb and sub. blocky c. Sub. blocky
Size	a. Fine / medium b. Medium (blocks) c. Coarse (blocks)	a. Fine / medium b. Fine / Medium (blocks) c. Medium
Grade	a. Moderate b. Weak / moderate c. Weak	a. Weak / moderate b. Weak / moderate c. Weak
Consistence *Wet* Stickiness	a. Slightly sticky b. Slightly sticky c. Slightly sticky	a. Slightly sticky b. Slightly sticky c. Slightly sticky
Wet Plasticity	a. Slightly plastic b. Slightly plastic c. Slightly plastic	a. Slightly plastic b. Slightly plastic c. Slightly plastic
Moist Rupture resistance	a. Friable b. Friable / firm c. Firm	a. Friable b. Friable c. Firm
Dry[6] Rupture resistance	a. N.E. b. N.E. c. N.E.	a. N.E. b. N.E. c. N.E.

Table 4. *Continued*

Soil	TT	NIT
Macropores		
Number fine (cm^{-2})	a. >5 b. 1-5 / >5 c. <1 / 1-5	a. >5 b. >5 c. >5
Number coarse (dm^{-2})	a. >5 b. 1-5 / >5 c. 1-5	a. >5 b. 1-5 c. >5
Number earthw. burrows (dm^{-2})	a. >5 b. 1-5 / >5 c. <1 / 1-5	a. >5 b. 1-5 c. 1-5
Distribution	N.E.	N.E.
Continuity Coarse	a. Slight b. Moderate c. Moderate / high	a. Slight / moderate b. Moderate c. Moderate / high
Continuity earthworm burrows	a. Moderate / high b. Moderate / high c. High	a. Slight / moderate b. High c. Moderate / high
Orientation coarse	a. Diffuse b. Mainly vertical c. Mainly vertical	a. Diffuse b. Mainly vertical c. Mainly vertical
Orientation earthw. burrows	a. Mainly horizontal b. Mainly vertical c. Mainly vertical	a. Diffuse b. Mainly vertical c. Mainly vertical
Internal surface features		
Type	Earthworm excrements	Earthworm excrements
Quantity	In earthworm borrows (only 1 test)	In earthworm borrows
Concentrations		
Type	N.E.	N.E.
Quantity	N.E.	N.E.
Roots		
Number fine (cm^{-2})	a. >5 b. 1-5 c. <1	a. >5 b. 1-5 c. 1-5
Number coarse (dm^{-2})	a. >5 b. 1-5 c. <1	a. >5 b. 1-5 c. <1 / 1-5
Branching	a. Strong b. Moderate / strong c. Slight	a. Strong b. Moderate / strong c. Moderate
Distribution	N.E.	N.E.
Impediments	a/b. Compact layer (weak) b/c. Compact layer	a/b. Compact layer (weak), not in all tests b/c. Compact layer (weak), not in all tests
Thickened roots	a/b. Common (compact layer, weak) b/c. Common (compact layer)	a/b. Common (c. l., weak), not in all tests b/c. Common (c. l., weak), not in all tests
Degree of bending	a/b. Weak b/c. Weak / strong	a/b. No / weak b/c. No / weak
Root nodulation Number	a. Many b. Common c. Few	a. Many b. Common c. Common
Distribution	a. Good b. Moderate / good c. N.E.	a. Good b. Good c. Moderate / good

Table 4. *Continued*

Soil	TT	NIT
Soil fauna		
Earthworms	No observed	a. Some small horizontally burrowing earthworms observed e.g. *Octolasion cyaneum* b. Some *Lumbricus terrestris* c. Some *Lumbricus terrestris*
Others	Mosquito larva	Some mosquito larvae
Decomposition of organic matter		
Type	Straw residues in the bottom of the plough layer	Straw and stubble residues in the bottom of the plough layer
Degree of decomposition	Good	Good

[1] Layers: Figures mentioned below refer to figures stated for each detected layer.
[2] "a/b" denote interface between layer a and b. "b/c" denotes interface between layer b and c.
[3] Colour and consistence was not evaluated in dry condition because the soil was too wet at testing.
[4] N.E.: not evaluated.
[5] Texture was not evaluated in the field. Lab. data from the 7-15 cm layer is stated.
[6] Soil was too wet to evaluate rupture resistance when dry.

Appendix B

The spade analysis manual

Contents

1. Introduction

In this manual guidelines for describing a number of soil characteristics are presented. The following text is related to the forms presented at the end of this document. The forms may be used when performing a spade analysis in the field.

1.1 Sampling

With a flat Görbing spade (length 30 cm, width 20 cm) a 30x20x10 cm minimally disturbed soil block is taken out (Figure 1). The soil block is taken out as gently as possible. The soil is kept on the spade that is subsequently placed on two holders; thus the soil block lies horizontally. The sample is then placed at a proper height for examination. The soil surfaces may be cleaned with a knife and the sample is then ready for examination according to the guidelines presented.

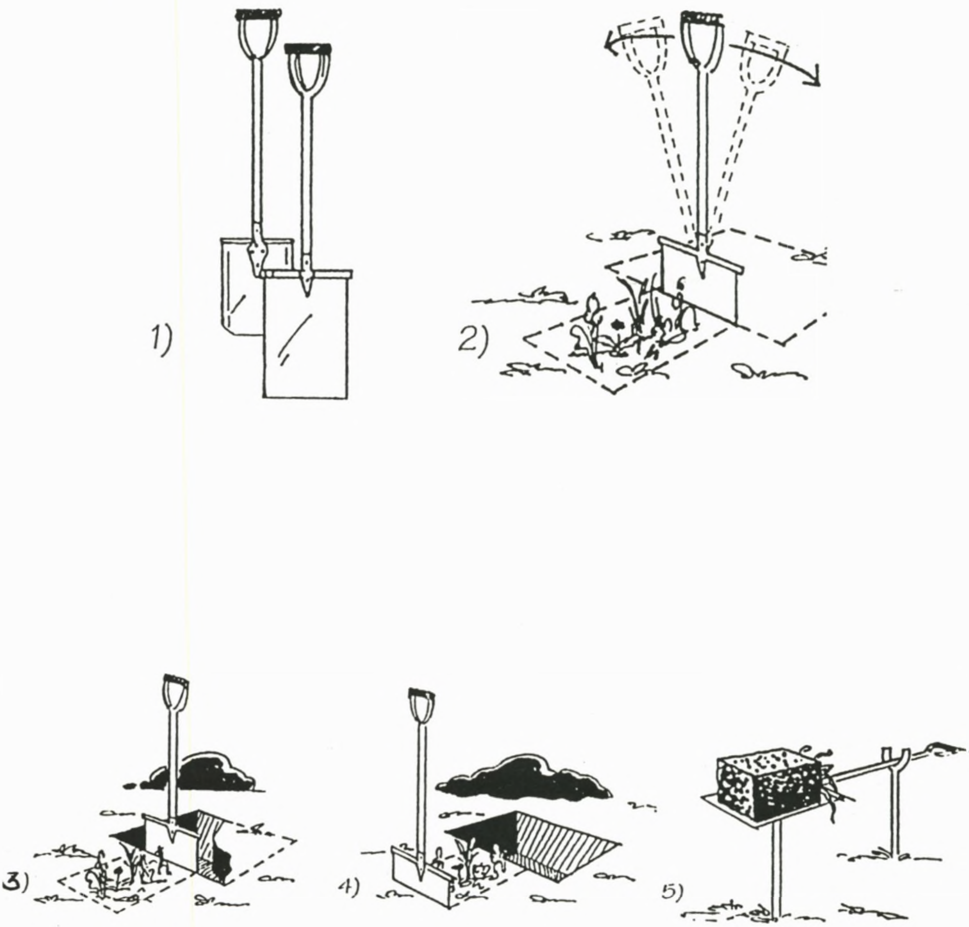

Figure 1. An outline of how to take out a sample for spade analysis (After Suhr et al., 1995).

1.2 When to perform the spade analysis

The spade analysis can be carried out at all times of the year – except when the soil is frozen. The optimal time for examining the soil depends on the purpose of the inspection. If the purpose is to evaluate soil-plant interactions, it is recommended to examine the soil regularly throughout the growing season, e.g. fortnightly or monthly.

The best time for a single examination of the soil-plant interrelations is when the plant root system is at its maximum. For many annual crops (cereals: Russell, 1977; peas: Salter and Drew, 1965) this occurs at the time of flowering. Preuschen (1994) suggests that the best time for examining the soil is three weeks before harvest for cereals, in the middle of august for sugar beets and late potatoes and shortly before the second cut in a grass field.

If the purpose is to assess e.g. the appropriate loosening depth in a tillage operation, the spade analysis may be carried out shortly before the planned tillage operation. In other cases the purpose may be to examine the degree of decomposition of applied organic matter and then the optimal time for examining the soil may be a few weeks after application.

The spade analysis can also be used as a tool to find out why there is a problem in a certain field or in minor area of a field. For instance to determine whether a wet area in a field is caused by soil compaction.

1.3 Replicates, time consumption

The number of replicates needed depends on the purpose of the inspection, soil variability and the precision needed. When a comprehensive description of a specific field is required, soil micro- meso- and macro-variation should be considered. The latter may be taken account of by dividing the field into soil units of similar soil type. Within these soil units it is recommended to select at least 3-5 sampling points. For each sampling point the spade analysis must be repeated once or twice to take account of micro-variation. The spade analysis is a time-consuming method – you can expect to use 1-2 hours to perform one test.

Because a full description is time-consuming, a simpler and quicker analytical procedure may be appropriate for practicians (farmers, advisors, etc). At least one full description must be performed per soil unit in representative areas. This should be supplemented by a number of simplified descriptions in order to obtain knowledge on soil variability. To get started using the spade analysis is the most important thing for many practicians. It is far better to carry out a number of simplified and quick spade analyses than doing nothing at all.

2. Equipment

The following equipment is recommended for the analysis:

Manual + forms to fill in
Notebook
Görbing spade plus holders
Regular spade
Hammer
Munsell Color Chart
Decimal scale to determine growth state
Magnifying glass
Water
Camera

3. Generally

General information on date, name of the descriptor, position of the pit in the landscape and the actual slope on the spot are noted. Basic information on past soil management is very useful and should be described as far as possible. This includes a description of crop rotation, tillage practice, fertilisation, use of pesticides etc. As a minimum, information on preceding crop(s), incorporation of straw, application of animal manure and soil tillage is noted. The present crop is registered and the growth stage is determined using the decimal scale. Features of the soil surface are described (e.g. surface roughness and amount of earthworm cast).

3.1 Layers

Note the layers and draw lines on the form where the layers separate. Note especially surface crust and compacted layers e.g. tillage pans. In many cases the transition to the upper part of an E or B-horizon might be observed at the bottom of the profile.

3.2 Boundaries

The boundary to the underlying layer is described by the sharpness of the transition (modified after Madsen and Jensen, 1988).

0. *Not described*
1. *Sharp*: less than <2 cm
2. *Clear*: 2-5 cm
3. *Gradual or diffuse*: >5 cm

3.3 Soil colour

For topsoils, soil colour may primarily give information on the content of organic matter and the degree of water saturation. For each layer soil colour in wet, moist and/or dry condition is determined according to the Munsell notation (Munsell, 1975). Most important is to determine soil colour on moist soil. If necessary moisten the soil with water before the assessment.

3.4 Soil moisture

The soil moisture state is evaluated and may give information on soil drainage and water availability for crops.

0. *Not described*
1. *Dry*
   Below wilting point (pF 4.2), the soil feels dry, water located in unavailable pores.
2. *Slightly moist*
   The soil is slightly moist, water located in fine pores (pF 3.5-4.2).
3. *Moist*
   The soil feels moist, but is not sticky (only loam and clay soils) (pF 2-3.5).
4. *Wet*
   The soil is wet, clay gets sticky, water content above field water capacity (> pF 2).

3.5 Soil texture

If the texture is known in advance, a further assessment of the texture is not necessary except where the texture changes with depth in the profile. Otherwise a raw estimate of clay content may be obtained by the following method that is applicable under Danish soil conditions (Madsen and Jensen, 1988).

Roll a moist soil sample of the size of a pea into a thin roll. The diameter of the roll when it begins to crack and break is related to clay content.

	Diameter	Clay content
1.	>2.5 mm	0-5%
2.	2.0-2.5 mm	5-15%
3.	1.5-2.0 mm	15-25%
4.	<1.5 mm	>25%

4. Soil structure

4.1 Aggregate type and size

The type and size of the dominant soil structural units are assessed according to Madsen and Jensen (1988) and FAO (1990). In plough layers a porous crumb structure is desirable. When a mixture of soil unit types is present, the dominant soil unit types are noted. Please note the relative distribution of the different types in the studied soil layer.

0. *Not described*
1. *Crumb*
   Rounded, porous, rather small aggregates.
   (Ordinary in loamy and clayey topsoils)
2. *Granular*
   Rounded, but relatively massive.
   (Ordinary in loamy and clayey topsoils)
3. *Blocky*
   Polyhedral aggregates. Is subdivided into sub-angular blocky (rounded edges) and angular blocky (sharp edges).
   (Ordinary in topsoil and subsoil)
4. *Prismatic*
   Prismatic aggregates with sharp edges and flat to rounded vertical faces.
   Oriented in a vertical direction.
   (Is usually found in compacted layers in the subsoil)
5. *Columnar*
   Prismatic aggregates with rounded edges and flat to rounded vertical faces.
   Oriented in a vertical direction.
   (Usually found in compacted layers in the subsoil)
6. *Platy*
   Aggregates oriented horizontally in the soil.
   (Usually found in compacted layers, e.g. plough pans)

Table 1. Aggregate size for different aggregate types.

	Crumb or granular	Blocky	Prismatic	Platy
1. Very fine	<1 mm	<5 mm	<10 mm	<1 mm
2. Fine	1-2 mm	5-10 mm	10-20 mm	1-2 mm
3. Medium	2-5 mm	10-20 mm	20-50 mm	2-5 mm
4. Coarse	5-10 mm	20-50 mm	50-100 mm	5-10 mm
5. Very coarse	>10 mm	>50 mm	>100 mm	>10 mm

4.2 Grade

The grade describes the ratio of aggregated material in relation to total material. Should be determined on moist soil according to Madsen and Jensen (1988) – otherwise the moisture condition must be noted. A block of undisturbed soil is taken out and dropped and on the basis of the resulting disturbed soil the grade is assessed.

0. *Not described*
1. *Structureless*
   Single grain structure
   (Prevalent in sandy soils)
2. *Very weak*
   A few weak aggregates can be seen among much unaggregated material.
   (Ordinary in coarse sandy and gravel rich soil)
3. *Weak*
   Weak aggregates are seen among some unaggregated material.
   (Ordinary on sandy soils)
4. *Moderate*
   A lot of rather strong well-formed whole aggregates among some broken aggregates and unaggregated material.
5. *Strong*
   Strong, whole and evident aggregates among a few broken units and almost no unaggregated material. The aggregates are distinct in undisturbed soil.
   (Ordinary in strongly developed Bt horizons)
6. *Very strong*
   Practically only whole and undisturbed aggregates are seen. The aggregates do not stick together.
   This is normally only found in very clayey soil that is exposed to strong periodical wetting and drying cycles.
7. *Massive*
   A structureless soil, which when dropped fractures into large clods that cannot be characterised as aggregate faces.
   (Can be found in e.g. heavily compacted clay-rich soil)

4.3 Consistence

Soil consistence gives information on the soil mechanical properties, which can be related to soil workability and friability. Especially the rupture resistance determined on moist and if possible on dry soil may be related to soil workability. Soil consistence when wet (stickiness and plasticity) is mainly related to clay content and clay mineralogy. Stickiness and plasticity increases in general with clay content and with increasing prevalence of expanding clay minerals in the clay fraction. The assessment of soil consistence follows the guidelines of Petersen and Møberg (1987) and FAO, (1990).

When wet

Stickiness:

The stickiness is determined by noting the adherence of soil material when it is pressed between thumb and finger.

0. *Not described*
1. *Non-sticky*
   Practically no material adheres to thumb or finger.
2. *Slightly sticky*
   Some material adheres to thumb or finger but comes off one or the other rather cleanly.
3. *Sticky*
   Some material adheres to thumb and finger and the soil material tends to stretch somewhat when pulling thumb and finger apart.
4. *Very Sticky*
   Some soil material adheres to both thumb and finger and the soil material is decidedly stretched when the fingers are pulled apart.

Plasticity:

The plasticity is determined on thoroughly puddled soil material. The soil material is rolled in the hand and a 3-mm thick roll is formed.

0. *Not described*
1. *Non-plastic*
   Not possible to form a 3-mm thick roll.
2. *Weakly plastic*
   Possible to form a 3-mm thick roll, soil deforms easily.
3. *Plastic*
   Possible to form a 3-mm thick roll, soil needs moderate pressure to deform.
4. *Very plastic*
   Possible to form a 3-mm thick roll, soil needs heavy pressure to deform.

When moist

Rupture resistance:

The rupture resistance is determined by crushing moist block-like specimens in the hand.

0. *Not described*
1. *Loose*
   The soil material is non-coherent.

2. *Slightly friable*
   The soil material fails under very slight applied pressure.
   (Common in sandy soils)
3. *Friable*
   The soil material fails under slight pressure.
4. *Firm*
   The soil material fails under moderate pressure between the thumb and finger - clear resistance against failure.
   (Common for loamy Danish moraine soils)
5. *Very firm*
   The soil material fails under strong pressure between thumb and finger.
6. *Extremely firm*
   The soil material cannot be crushed between thumb and finger.

When dry

Rupture resistance:

0. *Not described*
1. *Loose*
   The soil material is non-coherent.
2. *Slightly hard*
   Fails under slight pressure between the thumb and finger.
3. *Hard*
   Difficult to break between the thumb and finger - fails easily in the hand.
4. *Very hard*
   Can be broken in the hand with difficulty.
   (Common for Danish soils developed on loamy moraine)
5. *Extremely hard*
   Can be broken by the use of both hands with difficulty.

At the same time as evaluation of consistence in moist and dry condition, the degree of aggregation of the broken soil material may be assessed as described above for *grade*.

5. Macropores

The pore system is characterised with regards to number and sizes of macropores and earthworm burrows, and regarding the continuity, orientation and distribution of the pores in the soil. Also the characteristics of the macropore system are of particular of importance in relation to soil drainage, aeration and root growth. The number of earthworm burrows is an indicator of earthworm activity. It is important to distinguish between burrows made by primarily horizontally or vertically burrowing species. The description is performed according to Petersen and Møberg (1987) and Greve et al. (1999). Characteristics of fine and coarse macropores are described with earthworm burrows included. Moreover, earthworm burrows are evaluated separately.

5.1 Number and size

The number and size of pores are evaluated by studying approximately 5 squares on the soil block surfaces.

Table 2. Number and size classes of macropores and earthworm burrows.

	Fine (0.5-2mm)	Coarse (>2 mm)
1. Few	<1 cm^{-2}	<1 dm^{-2}
2. Common	1-5 cm^{-2}	1-5 dm^{-2}
3. Many	>5 cm^{-2}	>5 dm^{-2}

If possible please note whether the pores are e.g. mainly root-channels or cracks.

5.2 Pore distribution

0. *Not described*
1. *Inter aggregate*
   Pores are mainly located within aggregates.
2. *Intra aggregate*
   Pores are mainly located between aggregates.
3. *Inter/intra aggregate*
   Pores are located within and between aggregates.

5.3 Pore continuity

This characteristic may be difficult to assess – especially for the fine macropores.

0. *Not described*
1. *High*
   Most of the macropores can be followed over a fair distance (several cm).
2. *Moderate*
   Some of the macropores can be followed over a fair distance.
3. *Slight*
   No more than a few macropores can be followed over fair distance.

5.4 Pore orientation

The orientation of coarse macropores and earthworm burrows is assessed

0. *Not described*
1. *Mainly vertical*
   Most of the pores are oriented vertically.
2. *Mainly horizontal*
   Most of the pores are oriented horizontally.
3. *Random*
   No clear general orientation.

6. Internal surface features

In the topsoil surface features may be located within macropores and on structural units. Coatings of clay and organic matter in earthworm burrows are very common in Danish topsoils. The description is modified after Petersen and Møberg (1987).

6.1 Type

0. *Not described*
1. *Clay*
2. *Organic matter*
3. *Iron and aluminium oxides*
4. *Clay and organic matter*

6.2 Quantity

0. *Not described*
1. *Sparse*
   Spots on aggregate or pore surfaces.
2. *Disconnective*
   Coatings cover many aggregate and pore surfaces.
3. *Connective*
   Coatings covers all aggregate and pore surfaces.

7. Concentrations

Concentrations in the form of nodules or concretions may be observed in the topsoil. Red concentrations of iron-oxyhydroxides are commonly observed in the topsoil – especially in plough pans. Black concentrations of iron-manganese oxyhydroxides and white concentrations of lime (calcium carbonate) are also commonly observed. The description is modified after Petersen and Møberg (1987) and Soil Survey Division Staff (1993).

7.1 Type

0. *Not described*
1. *Iron oxyhydroxides (red)*
2. *Iron-manganese oxyhydroxides (black)*
3. *Lime (calcium carbonate) (white)*
4. *Others*

7.2 Quantity

0. *Not described*
1. *Few*
   Constitute less than 2 percent of soil volume.
2. *Common*
   Constitute more than 2 percent of soil volume.

8. Roots

A description of the soil root system is a key element in the spade analysis. First of all, look for signs of abnormal or impeded root growth. Root growth may be impeded due to e.g. acid soil, poor aeration or high penetration resistance. The number and size of roots are described together with a more detailed characterisation of the root system (branching, distribution, thickening and bending). If a leguminous crop is grown, root nodulation is described. The description of the root system is modified after the descriptions of Preuschen (1983, 1994), Petersen and Møberg (1987), Sobelius (1995) and Greve et al. (1999).

8.1 Numbers and size-classes

The number and size of roots are evaluated by studying a number of vertical and horizontal soil surfaces. It may also be determined using the core break method (Drew and Saker, 1980). Soil cores are retrieved in metal cylinders, broken into halves and subsequently the number of root ends is counted on the core surfaces.

	Fine (0.5-2 mm)	Coarse (>2 mm)
1. Few	<1 cm^{-2}	<1 dm^{-2}
2. Common	1-5 cm^{-2}	1-5 dm^{-2}
3. Many	>5 cm^{-2}	>5 dm^{-2}

8.2 Root branching

0. *Not described*
1. *Slight*
   Most main roots have none or just a few lateral roots.
2. *Moderate*
   Intermediary.
3. *Strong*
   Most main roots have many lateral roots.

8.3 Root distribution

0. *Not described*
1. *Random*
   Roots are randomly distributed.
2. *Cracks and pores*
   Roots are mainly located in cracks and pores (between aggregates).
3. *Layer interface*
   Roots are located at the interface between soil layers.

8.4 Root impediments

0. *Not described*
1. *Compact layer*
2. *Anaerobic layer*
3. *Others*
   (Please note the character).
4. *None*

8.5 Deformed roots

The extent of deformed roots in the form of thickened and bended roots is noted. The cause of thickened roots is noted e.g. compact layers or acidic soil.

Thickened roots:

0. *Not described*
1. *None*
2. *Common*

Cause:

A. *Acidic soil*
B. *Compact layer*
C. *Others*
   (Please note the cause if possible).

Degree of bending:

The degree of abnormal root bending is assessed. Be especially aware of root deflection at the transition to a compact or anaerobic layer.

0. *Not described*
1. *None*
2. *Weak*
3. *Strong*

   Many roots are deflected; a total change of direction of growth is common.
   In most cases a change in vertical direction is changed to growth in a horizontal direction.

8.6 Root nodulation

The number and distribution of root nodules on leguminous plant roots gives information on the condition of the crop and is affected by soil structure. Usually there are many root nodules on the leguminous roots at the top of the profile. The number of root nodules may be determined relatively to the length of leguminous plant roots.

Number of root nodules:

0. *Not described*
1. *Few:* <1
2. *Common:* 1-5
3. *Many:* >5

Distribution:

0. *Not described*
1. *Poor*

   Very heterogeneous distribution.
2. *Moderate*

   Rather heterogeneous distribution.
3. *Good*

   Homogeneous distribution.

9. Soil Fauna

The spade test is only applicable for a very rough estimate of soil faunal activity. The sample is very small and earthworms as well as other soil animals will try to escape when the sample is dug up. However, the observed earthworms are as far as possible identified at species level. The location and the distribution of the earthworms are noted. See e.g. Greve et al. (1999) for a comprehensive identification key.

Other soil animals are described and identified as far as possible.

10. Decomposition of organic matter

The type of organic matter is noted and the degree of decomposition of organic matter is assessed.
The degree of decomposition should be related to the type of material and to the time of application and/or incorporation. The climate highly affects the rate of decomposition of organic matter in the soil. The classification presented below is aimed at a humid temperate climate and is based on the description of Preuschen (1983, 1994).

10.1 Type

0. *Not described*
1. *Straw and stubble*
2. *Roots*
3. *Farmyard manure*
4. *Others*
   (Please note which type).

10.2 Degree of decomposition

0. *Not described*
1. *Poor*
   Poorly decomposed plant material remains tough for a long time. The colour is either yellow/bright (i.e. very slow decomposition) or black (i.e. anaerobic decomposition). The latter is also characterised by a smell of decay.
2. *Moderate*
   Intermediary.
3. *Good*
   In the summer half applied plant material decomposes to a large extent within 3-4 weeks after application. Straw and stubble incorporated into the soil immediately after harvest becomes darkish brown during October. In the following spring the material has become friable.

11. Literature

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Generally

Described by: ______________________________ Date: ______________

Location: __________________________________ Position: __________

Plot/treatment: _____________________________

Vegetation:

Crop: _____________________________________ Growth stage:_______

Preceding crop: _____________________________

Tillage:

Ploughing: _________________________________ Date: ______________

Seedbed preparation: _________________________ Date: ______________

Others: ___________________________________ Date: ______________

Application of organic matter *(type and amount)*:

Straw incorporation: _________________________ Date: ______________

Animal manure (1): __________________________ Date: ______________

Animal manure (2): __________________________ Date: ______________

Others: ___________________________________ Date: ______________

Application of mineral fertilisers *(type and amount)*:

Fertiliser (1): _______________________________ Date: ______________

Fertiliser (2): _______________________________ Date: ______________

Features of the soil surface:
Roughness:___________________________ Earthworm casts: ______________

	Generally				Structure							Macropores								
cm	Layer descr.& Bound.	Colour	Moist-ure	Texture	Type	Size	Grade	Consistence				Number			Distribution		Continuity		Orientation	
								Wet		Moist	Dry	Fine 0.5-2mm	Coarse >2mm	Earthw. burrows						
								Stic.[1]	Plas.[2]	R. res.[3]	R. res.[3]	cm^{-2}	dm^{-2}	dm^{-2}	Coar.[4]	Bur[5]	Coar.[4]	Bur[5]	Coar.[4]	Bur[5]
0																				
5																				
10																				
15																				
20																				
25																				
30																				

[1] Stickiness, [2] Plasticity, [3] Rupture resistance, [4] Coarse pores and [5] Earthworm burrows.

cm	Surface features & Concentrations		Roots									Fauna		Organic matter	
	Type	Quantity	Number		Branching	Distribution	Impediments	Deformed		Root nodulation		Earthworms	Others	Type	Degree of decomp.
			Fine 0.5-2mm	Coarse >2mm				Thickened	Degree of bending	Number	Distrib.	Species and numbers	Species and numbers		
0															
5															
10															
15															
20															
25															
30															

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ISSN 1397-9876