LONG- AND SHORT-TERM EFFECTS OF FIELD MANAGEMENT ON SOIL QUALITY

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Preface

This thesis is submitted in partial fulfilment of the requirements for the Doctor of Philosophy degree (PhD) at the Faculty of Science and Technology, Aarhus University. The thesis is based on my research carried out at the Department of Agroecology between March 2011 and March 2014. The study was part of the OptiPlant project financed by the Danish Ministry of Food, Agriculture and Fisheries. The PhD life expenses in Denmark were financially supported by Iranian government. The fulfilment of this work would not have been possible without the constant support of my supervisors, Lars Juhl Munkholm, Per Schjønning and Mogens Humlekrog Greve. They provided me with scientific, moral and even financial supports. They gave me the opportunity to work freely at my own pace and in the right direction toward achieving the success in my PhD life. I will not forget the help and support from Lars and especially Mogens in solving my financial problems which occurred several times during the PhD period.

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During my staying abroad I had a wonderful and productive time at Cranfield University in England. I had the opportunity to work focused on my all papers at the same time. Jane Rickson provided me with a nice research environment and gave me the chance to visit Rothamsted, the longest running agricultural research station in the world. Thank you so much, Jane.

I am also thankful to my family in Denmark and my mother and brother back home for all the support I needed during my PhD life.

Summary

Producing food, fibre and other essential goods for the ever-increasing world population is based on the multifunctional performance of the soil system. The significant role of soil in delivering ecosystem services highlights the crucial need for the development of field management strategies to combat the accelerated human-induced soil degradation and for the sustenance or enhancement of the functioning capacity of the soil system. Knowledge of how management activities influence soil quality helps to develop new management systems to improve the quality and sustainability of soil. Soil quality, which is defined as “fitness for purpose”, may be evaluated by selecting and measuring a minimum data set of soil quality indicators which are related to essential soil functions. The output of measuring soil quality indicators will help to detect how management strategies affect soils. This knowledge will be helpful for making decisions on selecting and implementing appropriate management systems.

This thesis aimed to quantify the mid- and long-term effects of different management systems including organic matter amendment, intensive tillage and traffic, reduced tillage, crop rotations and cover crops on soil quality indicators on sandy loam soils. An overall soil quality assessment method was also implemented to assess the productivity function of soil in the study area.

The field experiments were carried out in Danish long-term field experiments. The first experiment located at Research Centre Foulum was used to evaluate the effect of organic amendment (13-14 years of treating the soil with mineral fertiliser, animal manure and straw incorporation (treatment ORG), or fertilisation with only mineral fertiliser and with all straw removed (treatment MIN)), and with mechanical energy input (two years before sampling the soil was rotovated (treatment ROT), compacted (treatment PAC) or left undisturbed (treatment REF)) on the soil system. In this experiment organic matter treatments were the main plots and mechanical energy inputs were the subplots of the split-plot design of the experiment.

In field experiment two, the effects of crop rotation (rotation 2 (R2: W. rape, W. wheat, W. wheat and W. barley), rotation 3 (R3: W. barley, Oat, W. wheat and S. barley) and rotation 4 (R4: W. barley, Oat, W. wheat and S. barley), tillage systems (mouldboard ploughing (MP), harrowing to a depth of 8-10 cm (H) and direct drilling (D) and cover crop (plots with cover crop (+CC) and plots without cover crop (-CC)) on soil quality were investigated in a split-split-plot design. This experiment was located at both Research Centre Foulum and Research Centre Flakkebjerg. However, the effect of cover crop was only studied at Research Centre Foulum. An overall assessment of soil quality (Muencheberg soil quality rating method) was used to assess the effect of rotation and tillage on the soil productivity function including

results from both locations.

A number of soil physical, chemical and biological indicators (field and laboratory measurements) were used to evaluate the short- and long-term effects of the above-mentioned management systems on the quality of the studied soils.

To assess the productivity potential of soil (soil productivity function) an overall soil quality assessment method (Muencheberg Soil Quality Ratio (M-SQR)) was employed. The M-SQR uses both inherent and management-induced soil quality indicators and climate data, including thermal and moisture regimes of soil. Using scoring tables, two types of indicators including "basic soil indicators" and "soil hazard indicators" are scored, weighted and summarised to yield a final score in the range of 0 (worst) to 100 (best). These scores can later be used for assessing soil productivity potential.

The long-term application of organic matter boosted the soil organic matter fractions and resulted in a more friable soil with a less cloddy structure and better soil tilth condition. The larger amount of polysaccharide C in ORG-treated soil was shown to play an important role in the aggregation process and its influence in this process was more important than fungal hyphae.

Data from the long-term experiment indicated a clear detrimental effect of intensive tillage (ROT) and compaction (PAC) on soil friability, structural strength and tilth condition. However, application of OM modified the soil responses to compressive and tensile stresses. In un-manured soil the reaction to compressive stress was less affected by differences in initial bulk density than in OM-amended soil. This indicates a more rigid soil structure for the un-manured soil.

Results from the rotation and tillage experiment showed that conventional tillage (MP) produced a more friable soil with larger amounts of total and air-filled porosity and lower penetration resistance in the topsoil layer. Its soil structure (as evaluated visually) also appeared to be better compared to the reduced tillage systems (H and D). The reduced tillage systems produced the poorest topsoil structure with greater soil strength.

Five-year application of a cover crop indicated that it has potential to alleviate soil compaction by reducing penetration resistance in the plough pan layer and creating continuous macropores (biopores) to facilitate water and gas transport and root growth in the soil system. Our results also highlighted the potential use of cover crops in combination with direct drilling to overcome the limitations of poorer topsoil structure following the utilisation of reduced tillage systems.

The Muencheberg soil quality rating method was able to differentiate the potential crop productivity of two different locations with the same soil type (sandy loam soil) but different water budgets. Significant correlations were found in most cases between soil quality indices and relative yield. This highlights the influence of soil quality and soil structure in particular on crop yield potential.

Sammendrag (Danish summary)

Produktion af fødevarer, foder og bioenergi til en voksende befolkning er været baseret på dyrkningsjordens multifunktionalitet. Dyrkningsjordens rolle som leverandør af essentielle økosystem ydelser understreger behovet for at udvikle bæredygtige dyrkningsstrategier til at imødegå den accelererende menneskeskabte forringelse af dyrkningsjordens kvalitet og bibeholde eller forøge jordens funktion. Viden om dyrkningseffekter på jordens kvalitet kan bidrage til at udvikle nye bæredygtige dyrkningssystemer. Jordens kvalitet kan defineres som "fitness for purpose", dvs. egnethed til et givet formål. Denne kan beskrives ved at udvælge og måle et minimums datasæt af jordkvalitets parametre relateret til essentielle funktioner i jord. Resultatet heraf vil give nyttig viden om, hvordan dyrkningsfaktorer påvirker jorden og kan således bidrage til udvikling af bæredygtige dyrkningssystemer.

I denne afhandling sættes tal på medium til langtidseffekter af dyrkningsfaktorer på en række jordkvalitetsindikatorer. De undersøgte dyrkningsfaktorer var tilførsel af organisk stof, intensiv jordbearbejdning og trafik, reduceret jordbearbejdning, sædskifte samt efterafgrøder.

De eksperimentelle aktiviteter inkluderede to langvarige markforsøg: 1. et systemforsøg beliggende på Forskningscenter Foulum (JB4) og 2. et sædskifte og jordbearbejdningsforsøg beliggende på Forskningscenter Foulum (JB4) og Forskningscenter Flakkebjerg (JB6). Forsøgsbehandlingerne i systemforsøget inkluderede 13-14 års behandling med høj tildeling af organisk stof (husdyrgødning og halmnedmuldning), ORG, versus lille tilførsel af organisk stof (kunstgødning og halm fjernelse), MIN. Som underbehandlinger i ORG og MIN storparcellerne blev en reference sammenlignet med intensiv rotorharvning (ROT) og pakning (PAC). I det 10-årige sædskifte og jordbearbejdningsforsøg med et split-split-plot design blev der sat tal på effekten af 1. sædskifte (R2 (halm nedmuldet): vinterraps, vinterhvede, vinterhvede, vinterbyg; R3(halm fjernet): vinterbyg/olieræddike, havre, vinterhvede/olieræddike, vårbyg; R4 (halm nedmuldet): vinterbyg/olieræddike, havre, vinterhvede/olieræddike, vårbyg), 2. jordbearbejdning (pløjet (MP), reduceret jordbearbejdning med harvning til 8-10 cm (H) og direkte såning (D) samt 3. efterafgrøde (+/- olieræddike). Effekten af efterafgrøde blev kun undersøgt i forsøget på Forskningscenter Foulum, hvor der blev lavet målinger efter fem års behandling med +/- efterafgrøde i et ensidigt sædskifte med vårbyg.

I forsøgene blev fysiske, biologiske og kemiske jordkvalitets indikatorer anvendt til at kvantificere effekten af forskellige dyrkningsmetoder. Disse blev bestemt ved brug af en række felt- og laboratoriemetoder.

Den overordnede ”The Muencheberg Soil Quality Rating” metode (M-SQR) blev anvendt til at vurdere dyrkningspotentialet for lokaliteterne og behandlingerne, som indgik i sædskifte og jordbearbejdningsforsøgene. I dette arbejde blev udbyttemålinger samt jordkvalitets- og klimadata fra begge lokaliteter anvendt. Jordkvalitetsparametrene omfattede både statiske (tekstur) og dyrkningsafhængige faktorer (strukturvurdering, penetreringsmodstand, kulstofindhold). I M-SQR metoden blev to typer af indikatorer anvendt: 1. ”basic soil indicators” (basale jordparametre) og 2. ”soil hazard indicators” (trusler mod jordens frugtbarhed). Disse blev bestemt, vægtet og sammenvejet til at give en karakter på mellem 0 (dårligst) og 100 (bedst).

Langvarig tilførsel af organisk stof via husdyrgødning og halmnedmuldning gav forøget indhold af levende og dødt kulstof i jord og resulturede i en mindre knoldet og mere bekvem jord. Resultaterne tyder på, at klisterstoffer (polysakkarider) udskilt af rødder og mikroorganismer spillede en større rolle for strukturdannelsen end svampehyfer i den undersøgte JB4 jord.

I det langvarige forsøg med organisk stof tilførsel var der en klar negativ effekt af intensiv rotorharvning (ROT) og pakning (PAC) på jordens struktur – herunder smuldreevne og strukturstabilitet. Ved lave volumenvægte pakkede ORG lettere end MIN, mens det modsatte var tilfældet ved relativt høje volumenvægte. Dette indikerer en mere stiv struktur i MIN jorden.

Resultaterne fra sædskifte og jordbearbejdningsforsøget viste, at pløjning (MP) gav den mest fordelagtige jordstruktur i pløjelaget set i forhold til planteproduktion (bedre smuldreevne, større porøsitet og mindre penetreringsmodstand, bedre visuel strukturkvalitet) sammenlignet med reduceret jordbearbejdning (H) og direkte såning (D).
Fem års årlig anvendelse af olieræddike som efterafgrøde forbedrede især jordens struktur lige under pløjelaget. Der blev målt mindre penetreringsmodstand og flere gennemgående porer i efterafgrøde behandling end i referencen. Dette vil alt andet lige forbedre betingelserne for rodvækst samt vandafledning og iltskifte i jorden. I pløjelaget var der en signifikant vekselvirkning mellem jordbearbejdning og efterafgrøde i forhold til smuldreevne. Resultaterne tydede på en positiv effekt af efterafgrøden i den direkte sået jord.

Ved brug af M-SQR metoden blev Foulum vurderet signifikant bedre end Flakkebjerg hvilket stemmer overens med et højere relativt udbytte for Foulum end for Flakkebjerg. Lokaliteterne har relativt ens jordtype men adskiller sig ved større for tørke for Flakkebjerg end for Foulum. De overordnede jordkvalitets indekser (M-SQR m. fl.) kunne også i nogen grad anvendes til at forklare variationen i relativt udbytte mellem sædskifter og jordbearbejdningsstrategier. For hver lokalitet var der var i mange tilfælde en signifikant positiv sammenhæng mellem relativt udbytte og M-SQR indenfor for sædskifte og jordbearbejdning.

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Acronyms/Abbreviations

+CC	Plots with cover crop
−CC	Plots without cover crop
CENTS	Crop management and Economic on Non-inversion Tillage Systems
CT	Computed tomography
D	Direct drilling
d_B	effective pore diameter for gas flow
DS/DO	Relative gas diffusivity
E	Rupture energy
H	Harrowing to a depth of 8 to 10 cm
HWSOC	Hot-water extractable C (Polysaccharide C)
k_a	Air permeability
kPa	Kilo Pascal
k_Y	Friability index
LAM	Level of Animal Manure
MBC	Microbial biomass carbon
MDS	Minimum data set
MIN	Fertilisation with only mineral fertilisers and with all crop residues removed
MP	Mouldboard ploughing to a depth of 20 cm
M-SQR	Muencheberg Soil Quality Ratio
MWD	Mean weight diameter
MWD	Mean weight diameter
n_B	The number of air-filled pores in a soil transect
OC	Organic carbon
OM	Organic matter
ORG	Fertilisation with slurried pig manure and straw incorporation
OVS	Overall visual structure
OSS	Overall soil structure
PAW	Profile available water

PCA	Principal component analysis
PO	Pore organization
PR	penetration resistance
R2	Rotation 2
R3	Rotation 3
R4	Rotation 4
REF	Undisturbed soil (reference plot in mechanical treratments)
RY	Relative yield
SOC	Soil organic carbon
VESS	Visual evaluation of soil structure
WSA	Water stable aggregates.
ε	Strain, The ratio of the deformation, s and the height of the soil core
ε_a	Air-filled porosity

List of supporting papers

This dissertation is based on 3 published papers and one unpublished paper which are referred to in the text by their Roman numerals.

1. **Abdollahi, L.,** Schjønning, P., Elmholt, S., and Munkholm, L. J. (**2014**). The effects of organic matter application and intensive tillage and traffic on soil structure formation and stability. Soil and Tillage Research 136, 28-37.

2. **Abdollahi, L.,** and Munkholm, L. J. (**2014**). Tillage System and Cover Crop Effects on Soil Quality:I. Chemical, Mechanical, and Biological Properties. Soil Sci. Soc. Am. J. 78, 262-270.

3. **Abdollahi, L**., Munkholm, L. J., and Garbout, A. (**2014**). Tillage System and Cover Crop Effects on Soil Quality: II. Pore Characteristics. Soil Sci. Soc. Am. J. 78, 271-279.

4. **Abdollahi, L**., Hansen, E.M., Rickson R.J. and Munkholm, J. L. (**submitted**). Overall assessment of soil quality on humid sandy loams: Effects of climate, rotation and tillage. Soil and Tillage Research.

1. Introduction

1.1. Soil: importance, functions and threats

Soil is an invaluable and non-renewable resource which supports and sustains life on our planet. It is a medium for plant growth, a habitat for animals and billions of macro- and micro-organisms that play a key role in human health and wellbeing (Robinson et al., 2012). Soil is also the basis of our terrestrial ecosystem on which we depend for our procurement of food, fibre and fuel. Of the total global land area, 40-50% is used for agricultural purposes (Smith et al., 2007). Producing food, fibre and other essential goods for the ever-increasing world population has been based on the multifunctional performance of soil (Hillel, 2009). According to recent studies (Cassman et al., 2003; Richter et al., 2007), the increase in food production (cereal grains) is not keeping pace with the increasing food demands. To produce more food you either have to extend cultivation to previously non-agricultural land or intensify the production on the currently available agricultural land (Oldeman, 1998). However, overexploitation and mismanagement of soil resources accelerates soil degradation (Lal, 2008, 2009; Oldeman, 1998). According to the Chinese Academy of Science, there are five types of soil degradation that lead to a reduction in soil quantity and quality. These include soil erosion, soil properties deterioration, salinisation, pollution, desertification and non-agricultural uses of soils (Jie et al., 2002). Houghton et al. (1983) also cited the conversion of grasslands and forests to arable land, mechanical agriculture and development of row crop production system as prime agents of physical soil loss and organic matter decline. According to the Soil Framework Directive (SFD) proposal, which is based on the "EU Soil Thematic Strategy", European soils are suffering from six major threats including erosion, compaction, organic matter depletion, acidification, landslides and salinisation (Van-Camp. L. et al., 2004). In a review of existing knowledge in the context of the EU Soil Thematic Strategy, Schjønning et al. (2009) reported soil organic matter decline, erosion by water and tillage, and compaction as the most important threats to soils in Denmark.

Soil itself has the ability to resist imposed threats to its system using a number of functions. With the aid of buffering, filtering and other inherent properties soil is able to keep its chemical, physical and biological factors stable and balanced. This also helps to sustain plant productivity, natural resources and environmental quality (Herrick, 2000). Thus, soil performs multiple functions to sustain agricultural ecosystems and promote human health. Scientists have grouped these functions into different categories: protecting water and air quality, protecting soil biodiversity, resisting soil erosion, supporting plant productivity and quality, animal productivity and quality, nutrient cycling, filtering and buffering (Arshad and

Martin, 2002; Karlen et al., 1997; Karlen and Stott, 1994; Larson and Pierce, 1994). The above-mentioned functions of a soil system signify that soil is a main contributor in providing "ecosystem services" and supporting the life system on the Earth as part of a world ecosystem (Robinson et al., 2012). Ecosystem services are defined as the benefits that an ecosystem delivers to people. These include provisioning services (e.g. delivering food, fibre and water), regulating services (e.g. services that affect climate, waste recycling and water filtering), cultural services (e.g. preserving our heritage and cultural resources) and supporting services (e.g. nutrient cycling and photosynthesis) (Reid et al., 2005; Robinson et al., 2012). Despite its significant contribution to the Earth's life support system and ecosystem services, soil has not been considered as much in need of protection in terms of sustainability as water and air have. Understanding the significance of soil in the broader context of terrestrial ecosystem services highlights the crucial need for developing protective management practices to combat the accelerated human-induced soil degradation and sustain the maximum functioning capacity of soil. In other words, the extent of implementing these soil functions (services) depends on how well a land user maintains and enhances these soil functions.

1.2. Sustainable agriculture

Concerns about the stability of soil functions for the maintenance and enhancement of soil productivity for present and future generations motivated the emergence of the "*sustainable agriculture*" concept (Hatfield and Karlen, 1994; Richter and Markewitz, 2001; Treitz, 1991). Sustainable agriculture represents the development of improved management practices and conservation agricultural operations to protect natural resources for long-term agriculture and food production (CGIAR, 1985; Lal, 2008; LAL, 1995; Pezzey, 1992; Treitz, 1991). According to European commission strategies on soil protection, the "biomass production" (productivity function of soil) is regarded as a main soil function which must be sustained in agricultural systems (EC, 2006; Tóth G. et al., 2007). According to Liebig`s law of the minimum, crop yields occur only at the rate permitted by the most limited nutrient element available for plant growth. The law also states that it is not the total amount of available resources that controls plant growth, but rather the most limited resource (element) determines the growth rate (Jørgensen, 2008; Mengel, 2008; van der Ploeg et al., 2005). This concept was introduced when observations did not confirm an increase in plant growth following the application of fertiliser elements to soils with sufficient supply of those nutrient elements.

1.2.1. Natural factors

The minimum law of Liebig was, however, regarded as an inadequate law by Sinclair and

Wayne (1993). They stressed that this law ignores the great flexibility of plants in coping with changing environmental conditions via their morphological and physiological potentials. Consequently, they suggested that plant yield levels are constrained by input levels of a broader range of natural resources including solar radiation, soil and water and nutrients. Nevertheless, the principle of Liebig's law of the minimum still remains authentic because the plant cannot overcome a nutrient deficiency with its flexibility potential. Consequently, there is a need for modification/expansion of the factors affecting plant yield potential. Mueller et al. (2010) also emphasised that soil productivity is controlled by natural factors and anthropogenic activities. They classified natural factors into three groups: (1) thermal and moisture regimes which are crucial factors for plant growth, (2) soil substrate (soil texture) which impacts rooting and nutrition of plants and (3) topography which affects soil erosion and human and machinery access to the land. Optimal plant growth requires an appropriate soil temperature and adequate soil moisture content (Lavalle et al., 2009; Murray et al., 1983). Soil substrate and texture (soil inherent properties), on the other hand, provide a medium for root growth and water and nutrient uptake and control the water movement through the soil profile. This soil substrate may also suffer from adverse effects of acidification, salinity, sodicity or hardpans which, in turn, affect plant growth.

1.2.2. Anthropogenic activities

In the process of food and biomass production, a number of human activities affect the soil system and its functions. These effects occur during soil management practices including irrigation, fertilisation, liming, conservation tillage and a variety of other field management strategies (Blevins et al., 1983; Campbell et al., 1984; Lal et al., 1990; Pouyat et al., 2007). These may elevate levels of micro- and macro-nutrients, pH and soil moisture content and provide better soil conditions for plant growth.

Soil structure is defined as the spatial arrangement and size of soil particles and porosity (Oades, 1984). According to Oades (1984), the most desirable structure for plant growth has appropriate fractions of pores involved in water storage, water and air transport, and plant root growth. Soil structure is regarded as a complex entity that governs the chemical, physical and biological processes in the soil system (Carter, 2002; Mueller et al., 2010; Munkholm and Schjønning, 2004; Watts et al., 1996a; Watts et al., 1996c). This structure is susceptible to management-induced changes in the soil system, and therefore maintaining soil structure is a key element in sustainable agriculture and is why management strategies should aim at producing an optimum soil structure to enhance plant growth and agricultural production (Hulugalle et al., 2007). However, in agricultural practices, using heavy machinery and intensive tillage and traffic imposes adverse impacts on soil system especially on soil structure (Munkholm and Schjønning, 2004; Schjønning et al., 2007; Watts et al., 1996a,b), which consequently influences soil functions (Carter, 2002) due to the huge mechanical energy input.

Concerns about the sustainability of agricultural production has led to the development of a wide range of management strategies including "*conservation agriculture*" (Torres et al., 2001) and other land-use-dependent managements such as the use of cover crops, organic farming, manure application, mineral fertilisation, liming and water management (Berc, 2005; Carter, 2002; Govaerts et al., 2009; Karlen et al., 1992; Komatsuzaki and Ohta, 2007; Motta et al., 2007; Pleasant, 1992; Wienhold et al., 2005b) to avert the detrimental effects of human activities (da Silva et al., 1997; Govaerts et al., 2009; Karlen et al., 1992; Schjønning et al., 2002). Conservation agriculture basically focuses on a combination of the following managements: a) Reduction in tillage, b) retention of crop residues and c) use of crop rotations and cover crops (Motta et al., 2007; Verhulst et al., 2010).

The aim of reduced tillage (conservation tillage) is to avoid full disturbance of the soil surface and to maximise the coverage of the soil surface by residues (Van den Putte et al., 2012; Verhulst et al., 2010). Conservation tillage such as direct drilling has been reported as a useful management strategy to protect the soil against erosion and structural degradation (Comia et al., 1994; Munkholm and Hansen, 2012; Schjønning et al., 2011; Triplett and Dick, 2008).

The objective of leaving the plant residues on the soil is to preserve the soil surface from wind and water erosion, to enhance water use efficiency and to improve physical, chemical and biological soil properties through managing the soil organic matter (SOM) content. Management of soil organic matter has been suggested as a way of averting the detrimental impacts of intensive tillage and traffic (da Silva et al., 1997; Govaerts et al., 2009; Karlen et al., 1992; Schjønning et al., 2002).

The justifications for utilising crop rotations are as follows:: a) they protect against harmful weeds, pests and diseases, b) there are positive effects of some crops on soil quality and yield production of the succeeding crop and c) crop diversification minimises the economic risk in case of unforeseeable problems (Govaerts et al., 2009; Verhulst et al., 2010).

Using cover crops helps the soil to compensate for the lack of C input and crop residues (Mutegi et al., 2013; Thomsen and Christensen, 2004; Weil and Kremen, 2007). In addition, cover crops are able to absorb nutrients during the growing season and recycle them into the soil through incorporation of their residues (Dabney et al., 2001; Ewing et al., 1991; Fageria et al., 2005). The positive effect of cover crops on soil structural properties is also reported in many studies (Chen and Weil, 2010; Keisling et al., 1994; Latif et al., 1992; Villamil et al., 2006; Williams and Weil, 2004). Winter cover crops have been used to alleviate soil compaction problems and then been offered as an alternative to extensive tillage operations (Stirzaker and White, 1995). Cover crops are commonly used for winter ground cover and in combination with reduced tillage strategy or conservation tillage (Hargrove, 1991; Motta et al., 2007; Reeves, 1994).

The application of different management systems raises the question of which management strategy will be able to increase soil productivity while maintaining or enhancing soil conditions and reducing soil resource vulnerability. Therefore, the need for assessing the direct and indirect effects of utilised management systems to sustain the soil inventory was highlighted. Consequently, the "*soil quality*" concept was suggested for evaluating the impacts of different soil management strategies and provides a link between agricultural protective strategies and the attainment of sustainable agricultural aims (Acton and Padbury, 1993; Doran, 2002; Karlen et al., 1992; Karlen et al., 1997; Karlen and Stott, 1994)

1.3. Soil quality: concept and assessment

The adverse effects of human activities on the quality of air and water have long been recognised and relevant policies and regulations are well documented. However, concerns about the adverse effects of human impacts on the quality of soil emerged following the definition of soil quality in the 1970s (Bone et al., 2010; Karlen and Stott, 1994; Wienhold et al., 2004). Development of the soil quality concept is stimulated by the awareness of the vital importance of soil to produce food and fibre for an ever-increasing population (Doran and Parkin, 1994; Doran and Zeiss, 2000; Karlen et al., 1994a). Nevertheless, defining and quantifying soil quality is difficult due to the connectivity with external factors such as soil use and management, environmental impacts and ecosystem interactions (Doran and Parkin, 1994, 1996). The attempt to define "soil quality" has involved scientists and conservationists in extensive discussions. Doran and Parkin (1994) listed a number of soil quality definitions and proposed their own definition as, "*the capacity of a soil to function within ecosystem boundaries to sustain biological productivity, maintain environmental quality, and promote plant and animal health*". Discussions on how to define soil quality and the challenge of addressing complex soil functions in this definition led the Soil Science Society of America to appoint a committee for definition of the soil quality concept (Wienhold et al., 2004). The committee's definition of soil quality was "*the capacity of a specific kind of soil to function, within natural and managed boundaries, to sustain plant and animal productivity, maintain or enhance water and air quality, and support human health and* *habitation*" (Karlen et al., 1997).

The knowledge of how management activities influence soil quality helps to develop new management systems to improve the quality and sustainability of soil (Fig. 1). Therefore, to assess the effects of each management system on intended soil functions and soil quality it is essential to monitor changes in soil quality indicators associated with each function (e.g. we may measure nutrient levels, OM content, porosity, pH and water relations to check the management effects on the soil function of "sustaining plant growth") (Arshad and Martin, 2002; Karlen et al., 2001; Karlen and Stott, 1994). Assessment of changes in soil quality can be made by measuring proper indicators and comparing them with critical limits (or threshold levels). The critical limit is the eligible value of a soil quality indicator which must be kept in a specific range to allow normal functioning of the soil within the agro-ecosystem. For example, a desirable range of soil pH for most crops is 6.5-7.0. However, selecting these critical limits for each soil quality indicator is not that easy due to interactions between different soil parameters and the variability in requirements of the specific crops of interest (Arshad and Martin, 2002). Gomez et al. (1996) proposed threshold values for some sustainability indicators to evaluate sustainability at the farm level based on the work from (Smyth et al., 1993). Threshold values were tentatively set, based on the average values of soil indicators in local conditions, to differentiate between sustainable and unsustainable indicator values. Schjønning et al. (2004a) combined the common knowledge on soil functions and indicator thresholds with the outcomes from studies on specific soil management effects and introduced "management thresholds". They defined the management threshold as: "*the most severe disturbance any management may accomplish without inducing significant changes towards unsustainable conditions*".

The first step in evaluating soil quality is to determine the management goals and to identify the associated soil functions involved in achieving them (Larson and Pierce, 1991; Wienhold et al., 2005b). The term soil quality has commonly been used in relation to the two important soil functions of productivity and protection of environmental quality (Acton and Padbury, 1993; Wander et al., 2002). This means that soil quality is considered as the capacity of a soil to support crop production in a sustainable manner without negative impact on the environment. In this consideration, soil plays an important role in providing essential services for plant growth, for partitioning and balancing the movement of water and gases in the soil media and environment and as an effective buffer for the environment (Acton and Padbury, 1993; Karlen et al., 1994b; Larson and Pierce, 1991).

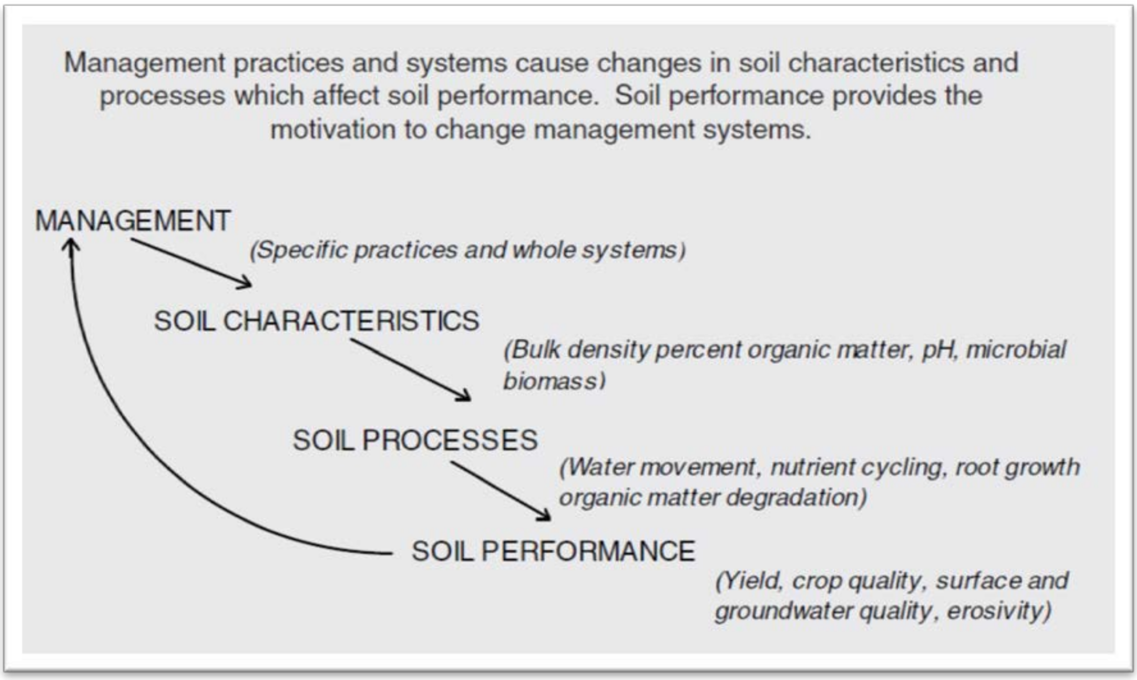

Fig. 1. The soil quality research framework, adapted from (Lewandowski and Zumwinkle, 1999).

In agriculture, management practices focus particularly on improvement of soil properties (physical, chemical and biological properties) which have a paramount impact on soil production ability. Thus, functions associated with providing essential nutrients and suitable soil tilth conditions are very important (Larson and Pierce, 1991; Wienhold et al., 2004; Wienhold et al., 2005a). As it is impossible to describe soil quality in terms of all existing soil quality indicators (e.g. physical, chemical and biological soil properties), the next step is determining, selecting and measuring soil properties affecting the intended soil functions. These selected soil properties will provide a minimum data set (MDS) (Larson and Pierce, 1991, 1994). Monitoring changes in this MDS would help as an overall indicator of changes in the overall soil quality condition. Soil properties that are sensitive to short-term management practices are appropriate as indicators in a MDS. (Larson and Pierce, 1991, 1994) proposed the following indicators for their MDS: nutrient supply (N, P), total and labile organic carbon, texture, plant-available water-holding capacity, soil structure parameters (bulk density, macro-porosity and saturated hydraulic conductivity), rooting depth, pH and EC. They also suggested using pedotransfer functions to extend the efficacy of the MDS. Moreover, they proposed a quantitative assessment of soil quality using quantitative expressions. Later evolutions in the concept of soil quality led to the development of soil quality test kits (Liebig et al., 1996), scorecards and various soil quality indexing methods (Karlen et al., 2001; Mueller et al., 2007). These soil quality rating methods are focused mostly on management-induced changes in the soil system which appear mostly in the soil structure. However, as inherent soil properties (e.g. plant-available water) and the natural genetic constitution of soils are also of crucial importance to soil functioning and soil quality, Mueller et al. (2007) introduced a field method for rating soil quality that takes into consideration the inherent soil quality. This method (Muencheberg Soil Quality Rating) has been developed for the quantification of cropland and grassland productivity based on the rating of indicators relevant to soil productivity and has proved to yield reliable, transferable and universally acceptable results (Mueller et al., 2012; Richter et al., 2009).

Measuring a range of soil quality indicators is the key approach in all methods of soil quality assessment. Although there is controversy regarding the applicability of different methods of soil quality assessment, the output of measuring these soil properties can help us identify the properties that are outside the acceptable range. In these instances, appropriate management strategies can then be recommended to enhance or restore deteriorated soil functions (Fig. 1). Where we have multiple management systems on a specific soil type and location, this measurement of soil properties enables us to determine the effect of different managements on soil quality. This is called "*comparative assessment*" of soil quality (Larson and Pierce, 1994; Reganold, 1988). Comparative assessment is a beneficial way of assessing the effect of long-term management practices on soil functions and soil attributes (Wienhold et al., 2004). Another effective way of assessing soil quality is "*dynamic assessment*" (Larson and Pierce, 1994). In dynamic assessment, the effect of management practices over time is evaluated after collection of data from a system. Implementing a dynamic assessment is useful for determining the trend and magnitude of changes in soil quality due to a specific management system (Arshad and Martin, 2002; Wienhold et al., 2004). To ascertain the effect of a specific land-use and management system on changes in soil quality, monitoring the changes in the key soil quality indicators (SQI) over time is necessary. This monitoring can serve to determine if the quality of a soil is improving, stable or declining and detect whether the quality of soil is changing due to anthropogenic activities or natural variations. This allows the land manager to make appropriate adjustments to the management system currently in place, if any are needed (Fig. 1) (Wienhold et al., 2005a). If current management system leads to no significant changes in soil quality, no alternative management system is required. On the other hand, a decline in soil quality or any sign of degradation would be a reason to implement an alternative management system to restore soil quality and prevent soil from further degradation. In this process, a first step would be to determine the impaired function(s) of soil quality and then decide on the appropriate remedial management system. As an example, if the water-holding capacity and infiltration rate of a soil has been diminished by compaction, it may be advisable to alter the type and timing of mechanical operations. Likewise, the loss of soil organic matter due to erosion may necessitate the adoption of conservation tillage practices (Harris et al., 1996).

1.4. Effects of management practices on soil quality and soil functions

Field management activities can affect soil quality negatively or positively. For instance, Karlen et al. (1992) in a review of previous soil and crop management practices drew attention to the positive effects of conservation tillage and management of crop residues as well as crop rotations and cover crops on soil quality. They emphasised that high priority must be given to soil organic matter management due to its significant effects on soil structural properties, particularly aggregate stability which, in turn, affects the water infiltration rate, water-holding capacity and other important soil properties. Govaerts et al. (2009) studied the feasibility of conservation agriculture in a long-term trial in the tropical highlands of central Mexico. He suggested zero tillage with residue retention to improve dry aggregate size distribution and water-stable aggregates compared to conventional tillage. In their conclusion they recommended using zero tillage with residue retention as a part of management strategies to enhance water use efficiency and reduce soil erosion. Comia et al. (1994) investigated the effects of two tillage systems (ploughing and ploughless systems) in combination with two seedbed preparation methods on a range of chemical and physical soil properties in an eight-year study. They reported a denser soil layer (higher bulk density, higher penetration resistance and lower root density) at 13-25 cm depth of the ploughless system compared to ploughed soil. However, for the 25-30 cm layer they recorded higher saturated hydraulic conductivity, air permeability and volume of pores with equivalent diameter >100 µm for the ploughless soil than for conventional tillage. Unploughed soil at 0-13 cm depth also had a higher concentration of organic carbon and potassium. The distribution of phosphorus, pH and yield were, however, not affected by tillage systems in their study. Verhulst et al. (2010) found positive effects of conservation agriculture on a number of soil quality indicators including soil physical (structure and aggregation, porosity, water balance, hydraulic conductivity and water-holding capacity), chemical (organic carbon, nutrient availability, acidity and salinity) and biological (microfauna, microflora, mesofauna and macrofauna) properties. Munkholm et al., (2013) studied the combined effects of two tillage treatments and three different rotations (including cover crops) in a 30-year long-term experiment in Canada. They concluded that diverse rotation under no tillage treatment promoted soil quality. They therefore recommended a combination of conservation tillage with residue management, diverse rotation and cover crops as the constituent parts of conservation agriculture. Schjønning et al. (2002) studied the effects of two long-term organic and conventional cultivation systems on a range of physical, chemical and biological soil characteristics. They highlighted the positive effects of organic manures and diverse rotations on soil quality indicators. They also reported the highly detrimental impacts of tillage and traffic in agriculture. Their results further indicate that the contribution of various biotic mechanisms for macro-aggregation differs from soil to soil. In another study, Schjønning et al. (2007) investigated the effects of three different cereal cropping systems in a crop rotation experiment in Denmark on a number of soil parameters. The first system was a cereal system with continuous small grain cereals and without any addition of manure, as a common reference soil. The next system was cereals with continuous animal manure addition and the third system received no manure but had continuous use of catch crops. Moreover, a section of each plot in the field received a mechanical energy input and compaction using a tractor. They reported noticeable effects after only five-six years of different management systems on the carbon contents of the soils. Animal manure and/or diversified crop rotation boosted the carbon content of whole-soil samples and aggregates, stabilised the clay particles, increased the tortuous network of soil pores and resulted in a better resistance to compaction.

Mueller et al. (2012) studied the applicability of the Muencheberg Soil Quality Rating method for characterising crop yield potentials (soil productivity function) based on the overall assessment of agricultural soil at more than 20 locations with different management systems and crop rotations. Based on the field manual, they rated soils (ranging from 0 (worst) to 100 (best)) at different locations taking into account soil structure, soil texture, climate and topography. The overall soil quality scores were well correlated with crop yield of small grain cereals. The method was able to differentiate between locations with different management intensity and different agrochemical inputs. Crop yield was shown to be a measure of productivity and a result of different soil qualities and the impact of management strategies. Consequently, they concluded that this method could be used for ranking and controlling soil quality in agricultural lands on a global scale.

From the above it is evident that different long- and short-term agricultural management systems have clear impacts on soil quality indicators, especially indicators related to the productivity function of a soil such as soil structural stability, organic matter components, reaction, water retention capacity, nutrient supply, porosity, friability, penetration resistance and soil resilience. In order to improve soil quality and achieve the sustainable use of soil resources, assessment of the long- and short-term impacts of different management strategies on major soil types and climate conditions is essential.

Increased concerns about the sustainability of production systems in Denmark and Northern Europe, especially the continued use of soil organic matter depleted soils and using heavy machinery for harvesting and slurry application, have sparked long-term studies on the quantification of conservation tillage systems and traffic impacts on arable farming systems. Adoption of conservation tillage systems such as no-tillage and shallow tillage in Northern Europe is reported to be low. This is partly due to poor topsoil structure (Soane et al., 2012) resulting from the application of these management systems. Recent studies in Denmark highlighted the potential use of cover crops, especially fodder radish (*Raphamus sativus* L.), for increasing soil biological activities and improving soil and air quality (Kristensen and Thorup-Kristensen, 2004; Munkholm and Hansen, 2012; Mutegi et al., 2011). This is attributed to its significant above- and below-ground biomass production which was reported to be 1.8 Mg ha^{-1} (Munkholm and Hansen, 2012). Cover crops are therefore expected to have a positive impact on the soil system and reduce the need for intensive tillage.

1.5. Objectives

This dissertation covers the following objectives:

The general objective of the PhD study was: "to quantify the mid- and long-term effects of different field management practices including organic matter amendment, intensive tillage and traffic, reduced tillage, crop rotation and cover crop on soil quality indicators and soil tilth condition".

The specific aims were:

(i) to quantify the long-term effects of organic matter application (comparing soils dressed only with mineral fertilisers with soil amended with animal slurry and plant residues) and intensive tillage and traffic (either wheel-by-wheel traffic or intensive pto-harrowing of topsoil) on soil structure formation and soil structural stability (Paper I);

(ii) to quantify the impacts of three different tillage treatments including direct drilling (D), harrowing to a depth of 8-10 cm (H) and mouldboard ploughing to a depth of 20 cm in combination with cover crop use on soil quality indicators (Papers II & III); and

(iii) to quantify the "productivity function" of soils following the application of different tillage and crop rotation systems using a soil quality assessment method (Paper IV),

and

We hypothesised that:

a) different soil management strategies would affect the dynamics of soil structure formation (Tisdall and Oades, 1982), soil tilth condition (Karlen et al., 1990) and aggregate formation (Oades, 1984; Tisdall and Oades, 1982) by affecting the interaction between the mechanisms involved in these processes (Fig. 2). Figure 2 presents an overview of the overall hypothesis used in the first experiment (Paper I),

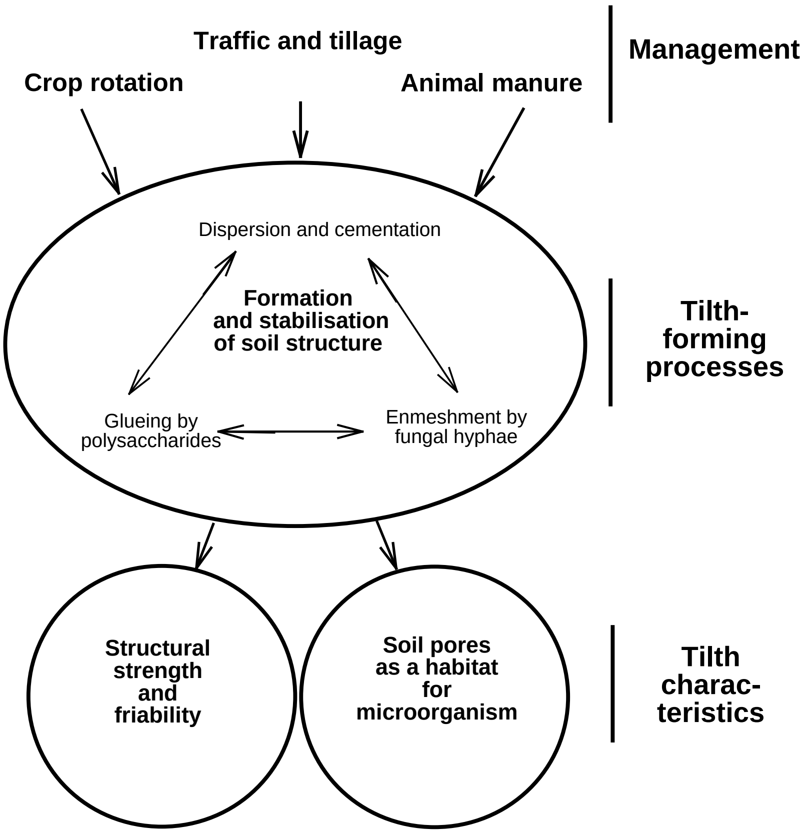

Fig. 2. A conceptual framework for use in the present study, relating management effects on the tilth-forming processes and the soil tilth characteristics (adapted from Schjønning et al. (2007), Fig. 1).

b) organic matter application (manure, residues) would lessen the adverse impacts of mechanical inputs,

c) the use of a cover crop improves the soil nutrient status and soil structure and thereby reduces the need for intensive tillage and

d) it is possible to assess the soil productivity function of different locations under various management systems using inherent and dynamic soil properties and climatic data.

2. Materials and Methods

2.1. Soil type and field trial

The field experiments were carried out in two long-term field experiments (Level of Animal Manure (LAM) and Crop management and Economic on Non-inversion Tillage Systems (CENTS)) located at two research centres in Denmark (Foulum, (56°30′N, 9°34′E) and Flakkebjerg (55°19′ N, 11°23′ E). Mean annual temperature and precipitation (1961–1990) at Foulum and Flakkebjerg were 7.3 °C and 626 mm and 7.7 °C and 558 mm, respectively. The soil is a sandy loam (a Mollic Luvisol according to the WRB (FAO system at Foulum and a Glossic Phaeozem at Flakkebjerg)) (Krogh and Greve, 1999). The clay (<2 μm), silt (2-20 μm), fine sand (20-200 μm) and coarse sand (200-2000 μm) contents of the soil (0-25 cm) were 92, 126, 444 and 307 g kg^{-1} and 147, 137, 426 and 270 g kg^{-1} for Foulum and Flakkebjerg, respectively.

The first experimental site (LAM) was used to evaluate the effect of organic amendment and mechanical energy input on the soil system. More details about this field trial are presented in Paper I. The experiment was initiated 13-14 years prior to sampling. It comprises four adjoining fields, two of which were used for this experiment. The experiment was a split-plot in three replications with two factors: organic matter as main plot and mechanical treatments as subplot. In each field, two different management strategies were applied: fertilisation with slurried pig manure and straw incorporation (treatment ORG), or fertilisation with only mineral fertilisers and with all crop residues removed (treatment MIN). Two years prior to the sampling, subplots with different mechanical treatments were added to each main plot (Paper I, Fig. 1). The soil was rotovated (treatment ROT), compacted (treatment PAC) or left undisturbed (treatment REF) as split-plot treatments in the main plots (Paper I, Fig. 1). The ROT treatment did not include wheeled traffic on the test soil. The six combinations of treatments are labelled MIN-REF, MIN-ROT, MIN-PAC, ORG-REF, ORG-ROT and ORG-PAC.

In field experiment two (CENTS), a long-term tillage and rotation trial (initiated in 2002, 10 years prior to sampling) was used to evaluate the effect of different crop rotation and tillage systems in combination with cover crops on soil quality indicators (Papers II, III & IV). The main experimental design was a split-split-plot in four replications with three factors: four crop rotation systems as main plot and four tillage systems as subplot (Hansen et al., 2010). From 2007 the cover crop was added to the experiment as a sub-sub-plot factor in a spring barley rotation at Foulum to quantify the effect of cover crop (fodder radish) in combination with tillage systems on soil quality and crop yield. This PhD study (papers II & III) made use of part of this experiment (tillage and cover crop subplots). This was a split-plot design in three replications with two factors: tillage as main plot and cover crop as subplot. The tillage systems included in this study were direct drilling (D), harrowing to a depth of 8–10 cm (H) and mouldboard ploughing to a depth of 20 cm (MP). A chisel coulter was used in the H and D treatments and a traditional Nordsten seed drill was used in the MP treatment. The main crop was spring barley (*Hordeum vulgare* L.) in every experimental year. Paired subplots (13.7×3m) with (+CC) or without (-CC) a fodder radish (*Raphanus sativus* L.) cover crop were used for this study and the CC treatments were placed in the same subplots every year during the period of cover crop application (i.e. 2007-2011). Fodder radish was established in the +CC subplots by the surface broadcasting of seeds, two weeks before harvesting of spring barley. The six combinations of treatments were labelled D+CC, D-CC, H+CC, H-CC, MP+CC and MP-CC.

For the purpose of Paper IV, three crop rotation systems were selected as main plot and three tillage systems as sub-plot from the main experimental design (at both Foulum and Flakkebjerg). Crop rotation systems were cereal-dominated rotations including W. rape, W. wheat, W. wheat and W. barley in rotation 2 (R2), W. barley, Oat, W. wheat and S. barley in rotation 3 (R3) and W. barley, Oat, W. wheat and S. barley in rotation 4 (R4) (further details in Paper IV, Table 1) and tillage systems were the same as used in papers II & III. After harvest, the straw was left in the field in R2 and R4, but removed in R3.

2.2. Indicator selection

In the selection of indicators our aim was to select appropriate indicators to be able to detect short- and long-term management-induced changes in the soil system. Hence, a range of soil quality indicators sensitive to short- and long-term management strategies were selected. These indicators included most of soil properties suggested for a minimum data set (MDS) (e.g. Larson and Pierce, 1991, which was mentioened in the introduction section as well) and supplemented by other field and laboratory measurements related to overall soil quality assessment (e.g. mean weight diameter following a drop-shatter test (MWD), visual evaluation of soil structure (VESS), penetration resistance (PR) and other lab measurements as listed in tables 1-3).

2.3. Soil sampling

Selected soil properties were measured in the field and soil samples were collected for laboratory studies. Minimally-disturbed soil cubes (7 cm × 8 cm × 11.5 cm ~650 cm^3) were sampled from the 6-13 cm layer (Paper I) and the 0-10 and 10-20 cm layers (Papers II & III) as described by Schjønning et al. (2002). Undisturbed soil cores were taken from the 6-10 cm layer (Paper I) and from 4-8, 12-16 and 18-27 cm (Papers II & III) by gently pushing steel cylinders into the soil. In a similar way, we sampled undisturbed soil cores (6-11 cm) in unified two-piece cylinders as described by Munkholm et al. (2002). Cubes and cores were taken to the laboratory and stored at 2 °C until analyses could take place. Bulk soil was sampled from the ~6-15 (Paper I) layer as well. Minimally disturbed bulk soil was also sampled from the 0-10 and 10-20 cm layers for the measurement of aggregate tensile strength (Papers II & III). A small auger was used to take a composite sample from 10 sampling points from each subplot for the measurement of chemical properties (Papers II & III). Eighteen topsoil core samples (~1257 cm^3) were taken for X-ray CT scanning.

2.4. Field measurements

In the field, a drop-shatter test was performed as described by Schjønning et al. (2002). Soil fragmentation was quantified as the mean weight diameter (MWD) of the aggregate size distribution from sieves with apertures of 2, 4, 8, 16 and 32 mm (Fig. 3). *In-situ* soil shear strength was quantified by rotating a 10-cm diameter torsional shear box as described by Munkholm et al. (2002) following in principle the method of Payne and Fountaine (1952). Soil cohesion and internal friction were taken as the intercept and slope, respectively, from a regression of the shear stress and the normal load (Paper I).

Fig. 3. Determination of aggregate size distribution (MWD) after a drop shatter test for soil taken from 10-20 cm depth.

The VESS method described by Ball et al. (2007) was used for a holistic semi-quantitative evaluation of the topsoil structural quality in the field at near-field-capacity water content (Fig. 4). In short, considering the aggregation, root growth, strength and porosity, the topsoil (a block of soil profile dug out with a flat-faced spade from 0-20 cm depth) is evaluated and graded on a scale from Sq1 to Sq5 where Sq1 is the best (Papers II & IV). For the purpose of Paper IV, these scores were converted to their counterpart in the M-SQR method according to table 2 in Paper IV.

Fig. 4. Assessing structural quality using a visual method (Ball et al. 2007).

Soil penetration resistance was measured to a depth of 60 cm at field-capacity soil water content using an automated cone penetrometer (Olsen, 1988) (Papers II & IV) (Fig. 5). Bulk density and rooting depth data were available from a previous study (Munkholm et al., 2008) (Paper IV). A-horizon depth had been measured at the beginning of the experimental set up I 2002. Profile available water (PAW) was calculated using existing data on retention curve (more details in Paper IV).

Water infiltration rate was measured at two different water tensions in the near-saturated range (~-3 and ~-10 cm) using a tension infiltrometer (UGT, IL-2007) (Ankeny et al., 1991). The results were then adjusted (interpolated) to a middle point -4 cm water tension using log-log X-Y axes for plotting infiltration rate (Y axis) against water tension (X axis) (Paper III).

Fig. 5. Measuring soil penetration resistance using an automated cone penetrometer.

2.5. Laboratory analyses

2.5.1. Chemical, physical and biological properties

In the present study we have measured and calculated a large number of soil properties. Details of measurement procedures of chemical, physical and biological properties have been presented in associated papers (I-IV) and here a brief description of measurements is presented in three tables including references to more detailed descriptions of the measurement procedure (Table 1).

2.5.2. Water retention and CT scanning characteristics

Pore size distribution and retention characteristics were measured by adjusting the core samples to different matric potentials. The soil cores were capillary wetted to saturation and then drained to matric potentials of -1, -3 and -10 kPa using tension tables and drained to -30 and -100 kPa using ceramic plates. The weight of each sample was recorded at each matric potential and after oven-drying at 105 °C for 24 h.

Table 1. Measured chemical and biological soil properties and associated methods.

Soil attribute	**Method used/ or instrument of measurement**	**Applied in paper**
SOC	Dry combustion method (Gordon Jr and Sutcliffe Jr, 1973)	I, III & IV
K	According to Kalra and Maynard (1991)	II
P	According to Olsen and Sommers (1982)	II
pH	Determined in 0.01 M $CaCl_2$ using a glass electrode	II, IV
Total nitrogen	According to Hansen (1989)	II
MBC	Fumigation–extraction method (Vance et al., 1987)	I & II
Hot water extractable carbon (HWSOC)	According to Elmholt et al. (2008)	I
Length of soil mycelial hyphae	Analysed by direct microscopy, described by Elmholt et al. (2008)	I

For Paper I, SOC and HWSOC were measured on 1–2 mm aggregate size samples as well.

Table 2. Measured physical and mechanical soil properties and associated methods.

Soil attribute	Method used/ or instrument of measurement	Applied in paper
Soil texture	A combination of the hydrometer and sieve methods	I, II, III & IV
Dry bulk density	Calculated from the soil core samples used in retention curve measurements	I, III & IV
Particle density	Calculated from the soil core samples used by (Eden et al., 2011)	I & III
Aggregate stability	Yoder-type sieving (Pojasok and Kay, 1990)	I & II
Clay dispersibility	End-over-end method (Pojasok and Kay, 1990)	I & II
Tensile strength of aggregates, Y	Described by (Dexter and Kroesbergen, 1985), involves crushing the aggregates between two parallel plates	I & II
Rupture energy, *E*	Derived by calculating the area under the stress-strain curve (Kirkham et al., 1959)	II
Soil friability index	Calculated based on aggregate tensile strength using the equation of Utomo and Dexter (1981)	I
Another indicator of aggregate strength, Y_4	The strength of a 4-mm ($\log_e (V)$ = -17.2 m^3) aggregate was calculated from the linear regressions obtained in (Arthur et al., 2014)	I
Direct tensile strength	Using an automatically operated mechanical press as described in detail by Munkholm et al. (2002)	I
Soil shear strength	The annulus shear method developed by Schjønning (1986) was used in lab; torsional shear	I
Soil cohesion	The interception of a regression of maximum shear stress and normal load	I
Strain, ε	The ratio of the deformation, s and the height of the soil core, H: $\varepsilon = s/H$	I
Internal friction	The slope of a regression of maximum shear stress and normal load	I

Table 3. Measured and estimated soil properties (from water retention characteristics and CT scanning) and associated methods.

Soil attribute	Method used/or instrument of measurement	Applied in paper#
Soil porosity	Estimated from bulk density and particle density	III
Volumetric water content,	Calculated from weight loss at specific drainage conditions and at oven-drying	III & IV
Air-filled porosity, ε_a	Calculated as the difference between total porosity and volumetric water content	III
Air permeability, k_a	Measured on the same cores according to the steady-state method described by (Iversen, 2001)	III
Gas diffusivity	Measured at -10 kPa matric potential by the non-steady state method Taylor (1949) using the one chamber technique described by Schjønning et al. (2013)	III
CT scanning	Samples were scanned using a medical computed tomography scanner. The following soil attributes were extracted using ImageJ software: degree of anisotropy (DA), pore total volume (PV), total surface area (PS), number (N) of networks, N of junctions, N of branches, N of end points and the mean branch length for each network	III
Estimation of soil pore characteristics from water retention, air permeability and gas diffusivity measurements	Empirical index of pore continuity (pore organization) (PO, μm^2) (Groenevelt et al., 1984) : $PO = k_a/\varepsilon_a$	III
	The simple exponential model of Ball et al. (1988) was used to relate k_a to ε_a: k_a = M ε_a^N, where M and N are model constants reflecting soil characteristics.	III
	Blocked air-filled porosity, ε_b, which does not take part in the transport of air by convection: $\varepsilon_b = 10^{-\log M/N}$	III
	The tube model of Ball (1981) was used to calculate equivalent pore diameter (d_B, μm) and the number of air-filled pores in a soil transect (n_B). $d_B = 2\left[\frac{8k_a}{(Ds/Do)}\right]^{1/2}$ $n_B = \left(\varepsilon_a^{1/2}\left(\frac{Ds}{(Do)}\right)^{3/2}\right)/(8\pi k_a)$	III

For the LAM experiment (Paper I), water retention characteristics were studied earlier by Eden et al. (2011)

2.6. Soil quality scoring procedure (Paper IV)

As a rating method of soil quality, the Muencheberg Soil Quality Rating (M-SQR) method was employed using its field manual (Mueller et al., 2007). This method focuses on the quantification of soil productivity potential based on the ratings of indicators relevant for soil productivity function. Two types of indicators (i.e. “basic” and “hazard”) are used in the quantification method. Basic indicators relate mainly to soil substrate (texture) and structural properties of soil. Hazard indicators relate to climate and field conditions that severely restrict soil functioning (for more details about basic and hazard indicators, see Fig. 1 in Paper IV). Each indicator is rated on a scale ranging from 0 (worst condition) to 2 (best condition). The scores of basic indicators are multiplied by a weighting factor according to its importance for plant growth and productivity (Fig. 1, Paper IV) to yield the final basic soil score (ranging from 0 to 34). The score of a hazard soil indicator is used as a multiplier for the basic soil score to yield the overall soil quality score (M-SQR) ranging from 0 (worst soil quality) to 100 (best soil quality). This was calculated according to the most severe hazard(s) in the study area. Based on the monthly climate data derived from an existing data set in Denmark the only detected hazard indicator (and only at Flakkebjerg) was drought risk. This hazard indicator was scored according to Table 3.3.7.-1 in the field manual and the multiplier value was calculated according to Table 3.3.7.-2. The multiplier was 3.0 and 2.8 for Foulum and Flakkebjerg sites, respectively.

2.7. Crop yield data

A plot combine was used to harvest the crop yield. Yield data were converted to dry matter, based on the water content of fresh yield and using near-infrared spectroscopy. As the crops were different in the crop rotation systems, the proportional yield was calculated for each plot (proportion of measured yield/region average yield for a specific crop) (Andrews et al., 2002). To enhance the accuracy of crop yield data the average of crop yield was calculated for four consecutive years (2009-2012) and used in the statistical analysis.

3. Management effects on soil quality

Since a large number of indicators have been measured in this study and used in the discussion part of the thesis, a brief overview of the trends and magnitude of changes to some important indicators would help the reader to achieve a better comprehension of the thesis (Table 4). This table is referred to frequently in the text so including it here obviates the need for frequent recourse to referred papers.

Table 4. Overall trends of treatment effects on measured indicators in two experiments (LAM and CENTS).

Soil property	Treatment				
	ORG vs. MIN	ROT vs. REF	PAC vs. REF	Reduced tillage vs. MP	+CC vs. -CC
Water stable aggregates	↗ #	↓	↙	↑	—
Clay dispersion	↓	↑	↑	—	—
Overal soil friability	↑	↙	↓	↓	—
Aggregate strength	—	↑	—	↑	—
Direct tensile strength	↓	↓	↑	—	—
Bulk density	↓	↓	↑	↑	—
Soil organic carbon	↑	—	—	—	—
Hot-water extractable C, (HWSOC)	↑	—	—	nd†	nd
Microbial biomass C	—	—	—	—	—
Fungal hyphae lengths	—	↙	↙	nd	nd
Total N	nd	nd	nd	—	—
Available K	nd	nd	nd	↑	↑
Available P	nd	nd	nd	↑	—
pH	nd	nd	nd	↑	—
PR	nd	nd	nd	↑	↓
Pore organisation (PO) #	—	—	↓	—	↑
Air permeability	↗	—	↓	↓	↑
Gas diffusivity	—	—	↓	—	—

No effect, —; significant decrease, ↓; significant increase, ↑; increasing trend, ↗; decreasing trend, ↙.

† Not defined

Pore characteristics data for LAM project (i.e. retention data for OM, ROT and PAC treatments) adapted from Eden et al. (2011).

3.1. Organic matter effects (Papers I & II)

3.1.1. The enrichment of carbon fractions (SOC, MBC and HWSOC)

Medium to long-term effects (5-14 years) of organic matter amendment were reported in **Papers I** and **II**. In **Paper I,** the amendment consisted of slurried pig manure and straw incorporation (treatment ORG) over a 13-14 year period and in **Paper II** the significant above- and belowground biomass production of a fodder radish (*Raphanus sativus* L.) cover crop (Mutegi et al., 2011) was regarded as an organic matter (OM) amendment strategy (Alabouvette et al., 2004). In **Paper I**, OM application increased soil organic carbon (SOC) levels in the plough layer from 16 g kg^{-1} in MIN to 17 g kg^{-1} in ORG-treated soil (Table 4 and Paper I, Table 4). This is consistent with the findings of other researchers (e.g. Schjønning et al., 2007; Six et al., 2002; Zhang and Peng, 2006) who also reported an increase in SOC after the application of OM amendment strategies. The higher C concentration and HWSOC in soil aggregates (1-2 mm size) compared to bulk SOC indicated the bonding effect in the aggregation process (Oades, 1984; Zhang and Peng, 2006).

However, in this study, microbial C was more variable than SOC and HWSOC, and OM amendment increased (not significantly) microbial biomass C by 8.7% compared to the MIN soil (P=0.28, Table 4 and Paper I, Table 4).

In the CENTS experiment, the five-year application of a cover crop did not affect SOC levels (Table 4 and Paper II, Table 2). This is consistent with the results of Mendes et al. (1999) and Steele et al. (2012) (13 years) who reported no increasing effect of cover crops on SOC. Despite the lack of effect on SOC, the cover crop tended to increase MBC at 10-20 cm depth (p=0.08). This weak increase in the labile fraction of carbon (MBC) could be interpreted as an early indication of SOC due to the short-term effect of organic matter amendment (five years of adding cover crop residues) (Powlson et al., 1987). However, positive long-term effects of a ryegrass cover crop on SOC have been reported in Denmark by other researchers. Hansen et al. (2000) and Mutegi et al. (2013) predicted (using a model) a potential carbon sequestration of up to 4.9 Mg C ha^{-1} over a 30-year period with a fodder radish cover crop.

3.1.2. Effects of OM on soil structure formation

The formation and stabilisation of soil particles into aggregates are of vital importance to achieving an optimal soil structure and supporting soil functions. OM fractions play important roles in these processes (Degens, 1997; Karlen, 2005; Tisdall and Oades, 1982). The gluing effect of polysaccharide C (HWSOC) on mineral particles and its correlation to the stability of soil structure have been highlighted in many studies (Ball et al., 1996; Chaney and Swift, 1984; Elmholt et al., 2008; Haynes and Beare, 1997; Haynes and Swift, 1990; Haynes et al., 1991). In this study, OM application (ORG-treatment in Paper I) increased SOC and HWSOC of aggregates (Table 4 and Paper I, Table 4) and indicated the bonding effect of these fractions in the aggregation process. This bonding effect resulted in a higher proportion of water-stable aggregates and lower proportion of dispersed clay in the ORG-treated soil compared to the MIN-treated soil (Table 4 and Paper I, Table 5). Testing the correlation between MWD and HWSOC revealed the pronounced effect of HWSOC on MWD and suggested polysaccharide C as an important driver of aggregation among the OM fractions (Paper I, Fig. 5). Moreover, we observed a significant positive correlation ($p=0.05$) between aggregate stability and soil HWSOC and a significant negative correlation ($p=0.05$) between clay dispersibility and soil HWSOC (data not shown). This finding highlights the role of polysaccharide C in soil aggregation and the structural stability of the studied soil (see more detailed discussion in Paper I, section 4.2). OM did not affect fungal hyphae length (Table 4 and Paper I, Table 5). Hence, in this study, the bonding effect of polysaccharide C is more likely the primary driver in the aggregation process rather than the binding effect of fungal hyphae length.

3.1.3. Effects of OM on structural strength

OM amendment over a period of 13-14 years clearly affected soil tilth conditions and soil structural strength. We observed a more friable soil with a less cloddy structure which fragments better than un-manured soil after this period (Table 4 and Paper I, Fig. 3). Moreover, the OM-amended soil indicated a better soil tilth, with ease of tillage (i.e. lower bulk soil tensile strength) and lower resistance to seedling emergence and root elongation (i.e. lower bulk density, less dispersible clay and enhanced stability of wet aggregates).

In general, OM application modified soil responses to compressive and tensile stresses (Paper I, Figs. 3, 4 and 5a and b). Interestingly, there was a significant difference in the reaction of the ORG- and MIN-treated soils to the soil compression test at different initial bulk densities. In un-manured soil (MIN) nearly identical soil deformations (strain) were registered, while OM-amended soil (ORG) behaved differently at different initial bulk densities (Paper I, Fig. 6a). Due to the lower bulk density (i.e. higher porosity) of ORG-treated soil (ORG-REF and ORG-ROT), the higher strains observed (Paper I, Fig. 6a) were expected (McBride and Watson, 1990; Zhang and Hartge, 1995). Accordingly we should also expect a higher strain for compacted soil in the organic soil (ORG-PAC) compared to the un-manured soil (MIN-PAC). However, there was tendency for ORG soils to exhibit less strain at high bulk density than for MIN soils (Paper I, Fig. 6a). This might be ascribed to the development of a better aggregated soil structure as a result of the aggregation ability of the OM. More interestingly, the reaction of the MIN soil to compressive stress significantly differed from the ORG soil (significantly different slopes in Fig. 6a) and it was less affected by differences in the initial bulk density. This suggests a more rigid soil structure for the MIN than for the ORG soil.

Very interestingly, a significant interaction between OM treatment and bulk density was observed for the direct tensile strength of soil samples (Paper I, Fig. 6b). A significantly larger increase in direct tensile strength was registered for the MIN than for the ORG soil with increasing soil bulk density (from REF to PAC). This reveals the crucial importance of OM in soil subjected to compaction, in terms of bestowing ease of tillage and soil fragmentation. This finding was also reflected in the results of the friability (MWD) test where the ORG soil was less affected by compaction than the MIN soil (Table 4 and Paper I, Fig. 3).

3.2. Tillage and traffic effects (Papers I, II & III)

The effect of tillage and traffic were studied in two experiments (Papers, I, II and III). In the LAM experiment (Paper I) the rotovation treatment (ROT) was regarded as an intensive tillage operation and the compaction treatment (PAC) as the intensive traffic. However, the main tillage system in this experiment was a combination of mouldboard ploughing and harrowing to a depth of 5 cm, and the ROT treatment to a depth of 10 cm was applied only in the last two years before sampling (more details in Paper I). In the CENTS experiment (Papers II and III) the effect of three tillage systems including direct drilling (D), harrowing to a depth of 8-10 cm (H) and mouldboard ploughing (MP) to a depth of 20 cm are discussed.

3.2.1. Tillage and traffic effects on chemical and biological soil properties

In the LAM experiment (Paper I), tillage (ROT) and traffic (PAC) did not affect organic matter fractions. The lack of tillage (ROT) effect on OM fractions is not surprising, because, as mentioned above, primary tillage treatment in this experiment (in all plots) was conventional tillage (mouldboard ploughing) in combination with harrowing, and the two years of ROT application probably was not long enough to detect changes in OM fractions (Powlson et al., 2011; Richter et al., 2007). However, tillage and traffic tended to decrease fungal hyphae lengths (Paper I, Table 4). This indicates the negative effect of mechanical energy input on the binding effects of fungal hyphae in the aggregation process and may help explain its detrimental effect on aggregate stability and clay dispersibility (Table 4 and Paper I, Table 5) (further discussed in next subsection).

In the CENTS experiment, 10 years application of different tillage systems clearly affected

SOC, N, K, P and pH levels (Table 4 and Paper II, Table 2). Here, conservation tillage (D and H) resulted in a clear vertical stratification of SOC and N. This vertical stratification (i.e. highest concentration in the top layer) was expected due to the shallow incorporation of OM residues in these two tillage systems. Álvaro-Fuentes et al. (2008), Franzluebbers (2002), Hernanz et al. (2002) and Kay and VandenBygaart (2002) also reported a similar vertical stratification. For MP, the SOC content was evenly distributed at 0-10 and 10-20 cm depth, indicating an effective incorporation of the OM residues in the plough layer during ploughing. N levels followed the levels of SOC in the two soil layers (0-10 and 10-20 cm) and indicated that the major fraction of total N most likely was in the form of organic nitrogen (Table 4 and Paper II, Table 2). Likewise, a vertical stratification of K was registered in all tillage treatments and for P and pH in conservation tillage systems (D and H) (Table 4 and Paper II, Table 2), which again is related to the crop residue incorporation approach for each tillage system. The amount of available K and P at 0-10 cm was significantly lower for MP than for D and H (Table 4 and Paper II, Table 2). A greater concentration of K in the topsoil (0-13 cm) was also reported by Comia et al. (1994) for reduced tillage compared with MP, but not for the P concentration. On the other hand, Jones et al. (2007), Franzluebbers and Hons (1996) and Crozier et al. (1999) reported the highest concentrations of P at the surface for reduced tillage. A higher pH level for MP compared with D and H was also detected in this study (Table 4 and Paper II, Table 2). This is not surprising since the inversion process that normally takes place in the ploughing tillage system moves the lime-rich lower topsoil layer (10-20 cm) to the upper topsoil layer (0-10 cm).

3.2.2. Tillage and traffic effects on soil structure, strength and friability

3.2.2.1. Effects on soil strength and friability

Intensive tillage and traffic clearly affected soil friability, structural strength and tilth condition. In the LAM experiment (Paper I), mechanical energy input (ROT and PAC) reduced the stability of wet aggregates and increased the amount of dispersible clay (Table 4 and Paper I, Table 5), indicating a weaker aggregation process as the result of intensive tillage and traffic. (Watts et al., 1996a; Watts et al., 1996b) also reported a high sensitivity of clay to dispersion as the result of intensive mechanical disruption. The pronounced negative effect of ROT on aggregate stability was probably due to the puddling effect caused by the kinetic energy input of the rotovation process, as this process is apparently more injurious to soil aggregate stability. Compared to the REF soil, the compacted soil (PAC) had a higher bulk density, higher bulk soil tensile strength, higher shear strength components (cohesion and friction) and poorer soil fragmentation (Table 4 and Paper I, Table 5 and Fig. 3). This indicates its higher soil strength and a need for a higher energy input in tillage operations for seed bed preparation and is consistent with the results from Munkholm and Kay (2002) and Munkholm et al. (2002).

In the CENTS experiment, ploughing (MP) resulted in a more friable soil with the best structural quality, especially at 10-20 cm depth (i.e. the smallest MWD and the lowest VESS score, aggregate rupture energy and aggregate tensile strength) compared with D and H (reduced tillage) (Table 4 and Paper II, Fig. 1, 2 and 4). This was related to the higher SOC content (Table 4 and Paper II, Table 2) and lower bulk density (Table 4 and Paper III, calculated from pore characteristics data) and is consistent with the lower penetration resistance (PR) (Table 4 and Paper II, Fig. 5). However, a prominent plough pan layer (20-40 cm depth) was detected by PR data for all tillage treatments (Table 4 and Paper II, Fig. 5). This could be interpreted as the effect of long-term (decades) operation of mouldboard ploughing before the establishment of the experiment in 2002.

Reduced tillage (D and H), on the other hand, produced a less friable soil (i.e. largest MWD) at 10-20 cm depth with a higher wet aggregate stability (WSA) and greater VESS scores and PR (Table 4 and Paper II, Fig. 1, 2, 3 and 5). Schjønning and Rasmussen (1989) and Hamblin (1980) also reported a higher WSA with reduced tillage. The poorer friability (highest MWD) in H at 10-20 cm (Table 4 and Paper II, Fig. 1) than for D and MP was consistent with the higher tensile strength and rupture energy for H (Table 4 and Paper II, Fig. 4). However, rupture energy and aggregate tensile strength did not show similar trends for the two studied depths (Paper II, Fig. 4).

3.2. 2.2. Effects on soil pore characteristics

The effects of tillage and traffic on pore characteristics for the LAM experiment have been studied by Eden et al. (2011) and here only a brief discussion is presented. Compared to ROT and REF, compaction (PAC) reduced macroporosity (>30 μm) and consequently total porosity (Table 5). They also found a more tortuous soil under compaction at -10 kPa and reported a minor impact of ROT on the soil pore system. They concluded that there is a considerable reduction in the volume of pores larger than ~10 μm and in the advection and diffusion ability of soil under compaction (PAC) (for more details, please see Eden et al. (2011)).

In the CENTS experiment, 10 years application of tillage showed little effect on total and air-filled porosity, relative gas diffusivity and air permeability at –10 kPa and on pore organisation at 4-8 and 18-27 cm depth (Table 4 and Paper III, Table 1 and Fig. 1). However, the model-derived parameters including effective pore diameter for gas flow (d_B) and the number of conducting soil pores per cm^2 (n_B) showed a distinct effect of tillage systems at 4-8 cm depth (Paper III, Table 5). After 10 years of using direct drilling (D), d_B was significantly higher and *PO* tended to be positively affected compared with MP. This was consistent with the findings of Kawamoto et al. (2006) and Møldrup (2010), who interpreted the higher values of d_B as indicative of a well-structured soil with a larger pore organisation (*PO*). Furthermore, the similar effect of D on *PO* and d_B at 12-16 cm depth supports the existence of a direct relation between d_B and *PO* (Kawamoto et al., 2006; Møldrup, 2010). At the 12-16 cm depth MP significantly increased total porosity and air-filled porosity at -10 kPa (i.e. pore volume with equivalent diameter >30 µm) compared with reduced tillage (Table 4 and Paper III, Fig. 1ab). From this observation and the retention curve of tillage treatments at 12-16 cm depth (Paper III, Fig. 5), it can be concluded that the higher total and air-filled porosity in MP than in D and H is related to the greater volume of macropores (i.e. pores with equivalent diameter >30 µm).

Table 5. Selected soil properties averaged for both years of investigation for mechanical treatments (adapted from Eden et al. (2011), Table 2)

Mechanical treatments #	Porosity (m^3/m^3)			Relative diffusivity, DS/DO (-) at -10 kPa	Pore organization at -10 kPa, log (PO) (µm^2)
	<30-µm	>30-µm	Total		
REF	0.276	0.189^a	0.465	0.019^a	1.63^a
PAC	0.303	0.116^b	0.417	0.006^b	1.29^b
ROT	0.274	0.191^a	0.465	0.018^a	1.49^a

Where the statistical model showed significant interaction between mechanical treatments, different letters indicate significant difference between estimated means in each column.

3.3. Cover crop effects (Papers II & III)

The effect of cover crop residues on the enrichment of SOC fractions was discussed in the OM effect section. The cover crop itself as a plant with an efficient rooting system and its biological behaviour influenced other soil properties, which are discussed below. However, some of these effects might be ascribed to the combined effects of rooting system, biological behaviour and cover crop residues.

3.3.1. Cover crop effects on chemical and biological soil properties

The cover crop did not affect the levels of SOC, N, P and pH in this study (Table 4 and Paper II, Table 2). Neither did Villamil et al. (2006), Sainju et al. (2006) nor Liebig et al. (2002) detect a cover crop effect on total N. Sainju et al. (2003) studied this aspect in a short-term study (five years) and attributed this lack of effect to the slow changes of recalcitrant and labile pools of N (total N components) with time and suggested the need for a long-term study to detect significant changes in total N. Later, Thomsen and Christensen (2004) showed an increase in total N following the long-term use of cover crops. The total N levels for cover crop treatments showed the same picture as for SOC in two soil layers (0-10 and 10-20 cm) and once again indicated that a major part of total N is most likely in the form of organic nitrogen. Our results indicated the scavenging capacity (Isse et al., 1999; Wagger, 1998) of cover crop (fodder radish in this study) on soil nutrients. Fodder radish increased the concentration of available K in the topsoil (0-10 cm) and led to a lower leaching loss of available K (Table 4 and Paper II, Table 2). This is important in the studied area with a sandy loam soil and a humid climate, where the leaching risk of K is significant.

3.3.2. Cover crop effects on soil structure, strength and friability

3.3.2.1. Effects on soil strength and friability

Five years of application of cover crop showed a generally positive effect on soil strength and friability. Although this effect was not clear from the VESS scores and aggregate stability and strength (Table 4 and Paper II, Fig. 2, 3 and 4), PR data manifested the positive effect of cover crop in the soil profile (Table 4 and Paper II, Fig. 5). This effect was more pronounced in the plough pan region where the use of cover crop significantly decreased PR in the 32-38 cm layer (Table 4 and Paper II, Fig. 5). This is an indication of the potential of fodder radish to alleviate soil compaction and could be attributed to its ability to form biopores and biological loosening (Stirzaker and White, 1995). The drop-shatter test also revealed a positive effect of cover crop on soil friability (Table 4 and Paper II, Fig. 1). This will be discussed later in section 3.4 entitled “Interaction effects of tillage systems and cover crop”.

3.3.2.2. Effects on soil pore characteristics

Five years application of cover crop affected the soil profile differently. At the 4-8 cm depth there was a positive effect of cover crop on air-filled porosity (and not total porosity), air permeability and *PO* (Table 4 and Paper III, Table 1; Fig. 2). However, the cover crop did not affect model-derived parameters (i.e. n_B and d_B) at this depth (Table 4 and Paper III, Table 5; Fig. 2). Nevertheless, the cover crop reduced the number of blocked pores (p=0.062) which is consistent with the higher levels of *PO* and air permeability for this depth (Table 4 and Paper III, Table 1; Fig. 2). The effect of cover crop on the 12-16 cm layer was more pronounced. The *PO* at all investigated matric potentials and air permeability at -3 and -10 kPa matric potentials were significantly affected by the cover crop (Table 4 and Paper III, Table 1; Fig. 2). A positive effect of cover crop on d_B and *PO* at this depth once again supported the existence of a direct relation between these two parameters, as discussed earlier in the effect of tillage systems (Table 4 and Paper III, Tables 1 and 5; Fig. 2). However, this relation was not surprising as it also relates to the mathematical expressions of the two properties. Pore organisation (PO) includes air permeability, k_a, and air-filled porosity, ε_a. Equivalent pore diameter, d_B, also includes k_a and diffusivity. As diffusivity is rather simply related to ε_a, the expressions are clearly related.

The significant ($p<0.10$) reduction of blocked porosity at 12-16 cm depth (Paper III, Table 4) in plots with a cover crop was consistent with the positive effects of the cover crop on PO and d_B at this depth (Table 4 and Paper III, Tables 1 and 5; Fig. 2). This was also consistent with the results reported by Villamil et al. (2006), although their measurement of blocked air porosity was carried out in a different way. The use of cover crop also affected pore characteristics in the transition layer between the Ap and plough pan (18-27 cm). A positive effect of cover crop was registered for PO and air permeability at this depth, indicating an alleviation of the plough pan compaction (Table 4 and Paper III, Table 1; Fig. 2). This is consistent with the alleviation effects of cover crop on penetration resistance reported above (Table 4 and Paper II, Fig. 5). The cover crop did not affect infiltration rate (Paper III, Table 1). This might be related to the complex function of topsoil and subsoil strength and friability as highlighted by Folorunso et al. (1992) when discussing the effects of cover crop on soil infiltration rate. Furthermore, the existence of a plough pan in all tillage treatments (Paper II, Fig. 5) due to the long-term application of ploughing operations before the establishment of the experiment (discussed above) has most likely blurred the effects of recent management strategies including tillage and cover crop.

3.4. Interaction effects of tillage systems and cover crop (II & III)

In the sections on OM effects and tillage effects, the interaction effects of management practices have to some extent been discussed. Since In the CENTS experiment we hypothesised that the cover crop would reduce the need for intensive tillage, in this section the interaction effects between tillage and cover crop are discussed. The interaction effects were only detected in the drop-shatter test (Paper II, Fig. 1) and extracted pore characteristics from CT scanning ($p<0.10$) (Paper III, Table 3).

The positive effect of the cover crop on soil fragmentation behaviour (Paper II, Fig. 1) of the direct-drilled soil (D) supported the hypothesis that using a cover crop in combination with direct drilling would reduce the need for intensive tillage operations. As discussed above, this is attributed to the improved soil physical properties due to biological loosening of the soil profile and the potential biopore formation by the cover crop (fodder radish in this study). However, this was not the case for shallow tillage treatment (H) where the fragmentation behaviour of the soil showed the worst soil friability (highest MWD) of the tillage treatments (Table 4 and Paper II, Fig. 1). Penetration resistance (PR) data indicated a relatively dense layer at 10-20 cm (Table 4 and Paper II, Fig. 5) under the H treatment and this might have hindered the root growth of the cover crop and positive effects of expected biological loosening.

Although traditional core measurements did not reveal interaction effects between tillage and cover crop, X-ray CT data indicated an almost significant interaction ($p<0.01$) for some of the pore characteristics (Paper III, Table 3). As can be seen in this table, the cover crop had negative effects on these pore network characteristics (number of branches, number of junctions and number of endpoints) for D and H and positive effects for MP. This trend is consistent with the 3-D images (obtained from X-ray CT data) for the same treatment combinations (Paper III, Fig. 3), which show a larger number of connected pores (red colours) for MP+CC than for D+CC and H+CC. This is contradicting the results obtained from traditional core samples (Paper III, Table 1; Fig. 2) and in-situ fragmentation tests (Paper II, Fig. 1) in the current study, where we observed positive effects of cover crop on air permeability and PO and a better soil fragmentation (lower MWD, better soil friability) for direct-drilled soil in combination with cover crop (D+CC). Furthermore, a negative correlation between MWD and macroporosity (Paper II, Fig 6) suggests that X-ray CT data should indicate a positive effect of cover crop on direct-drilled soil. These inconsistent findings might be due to different pore size distributions and the size of samples used in these methods. Our X-ray CT data accounted for very large pores (i.e. >430-µm) in the 0-20 cm depth, whereas traditional core data analysed micro- (i.e. <30-µm) and macropores (i.e. >30-µm) at the specific depth intervals of 4-8 cm and 12-16 cm. If we had been able to scan the samples from these depths with a finer resolution, a better correspondence between the core data and X-ray CT data might have been observed.

3.5. Assessment of soil productivity function

The Muencheberg Soil Quality Ratio (M-SQR) method was able to differentiate the yield data for both sites. Relative yield (RY) was significantly lower in Flakkebjerg than in Foulum (respectively, 1.08 and 1.2) (Paper IV, Table 5). The overall soil quality score (M-SQR score) was also significantly different for both sites (respectively, 71.7 and 84.2). Higher M-SQR scores in Foulum than in Flakkebjerg was consistent with higher RY values in Foulum and supported the feasibility of using M-SQR to assess crop yield potential in two different locations with almost similar soil types but different water budgets. This was in agreement with Mueller et al. (2012) who reported the feasibility of using the M-SQR method to rate agricultural soil quality and crop yield potentials over 20 locations.

The average RY of study sites was affected by rotation systems and R2 resulted in a lower RY compared to R3 and R4. There was no difference in RY between R3 and R4 (Paper IV, Table 5). This was consistent with the overall soil quality (M-SQR) scores at Flakkebjerg, where this was lowest for R2 and the same for R3 and R4. The M-SQR score at Foulum and the average M-SQR for both sites were not consistent with the trends of RY in crop rotations.

The RY of both sites (average) and RY on Flakkebjerg were significantly affected by tillage systems. Mouldboard ploughing resulted in significantly higher RYs compared to harrowing (H) and direct drilling (D). This was consistent with the M-SQR scores for Flakkebjerg and the average M-SQR for both sites (Paper IV, Table 5).

The correlation between RY data and overall M-SQR scores provides a better view of the strength and weakness of the M-SQR method in the prediction of crop productivity. We tried to evaluate the feasibility of using this method to differentiate the effects of management practices (i.e. tillage and rotation effect on crop yield) as well. The results indicate that the potential for using this method to predict the crop yield is promising.

3.6. Remarks on indicators used in the study

It is widely accepted that the assessment of soil quality requires a combined assessment of soil physical, chemical and biological indicators and their interaction in the whole soil system (Seybold et al., 1998). In this study we tried to use the most relevant indicators to assess the quality of soils following the implementation of different management systems in the humid climate of Denmark. It is difficult to select a standard set of indicators to evaluate soil quality as it is site and soil-specific and is dependent on the primary function of soil (Karlen and Stott, 1994; Schjønning et al., 2004a). According to previous studies in the study area (Schjønning et al., 2002; Schjønning et al., 2007), we used a number of chemical, biological and physical soil properties (Tables 1-3) as a standard set of soil quality indicators for the sandy loam soil. However, some of these selected soil properties were not common between two experiments (See Tables 1-3). The results of implementing these soil quality indicators show that not all the selected indicators were sensitive to management changes in the short term (five-year cover crop effect) or even in the medium to long term (13-14 year OM application effect). For example, in the LAM experiment, fungal hyphae lengths, microbial biomass C and friability index (k_Y) (Paper I, Table 5) were not sufficiently sensitive indicators to be able to detect the management changes. In the CENTS experiment, total nitrogen (Paper II, Table 2), gas diffusivity and infiltration rate (Paper III, Table 1) were not sensitive enough to detect the management changes. In order to suggest a suitable minimum data set

(MDS) to be used in future studies, principal component analysis (PCA) (Dunteman, 1989) was carried out for the existing variables in our data set. The principal components (PCs) for a data set are defined as the linear combination of variables that account for the maximum variance in the existing data set (Dunteman, 1989). I performed PCA for all variables that had shown statistically significant differences between management systems and selected the PCs with high eigenvalues (eigenvalues ≥1 (Kaiser, 1960)) as the best representatives of variation in the systems (Andrews et al., 2002). Another criterion for the selection of variables for the final MDS was the correlation between variables in each selected PC (Andrews et al., 2002). Results indicated that for the LAM experiment, most variables that showed significant differences in management treatments were suitable for inclusion in a MDS (Table 6). However, since aggregate tensile strength was highly correlated with MWD (r=68.8) and both variables had almost the same loading factor (eigenvector), MWD was retained in the MDS as its measurement is easier and faster. Aggregate organic C was also well correlated with SOC (r=59.3) and may therefore likewise be excluded from the MDS. In the CENTS experiment, MBC, available P and available K, should be excluded from the MDS variable list (Table 7). Moreover, since air permeability and air-filled porosity at -10 kPa and soil porosity >30 µm were highly correlated with bulk density (correlation was 90.0, 62.0 and 44 percent for air-filled porosity, air permeability and soil porosity >30 µm, respectively), they should be excluded from the MDS. The result also suggests the exclusion of total N, since it was highly correlated with SOC (r=93.1). Although these variables were shown to be redundant in a MDS, they were very useful for interpreting other results, as shown in the discussion section. Based on the above discussion, a future MDS for soil quality research would contain: SOC, clay dispersibility, aggregate stability, soil polysaccharide C, MWD, bulk density, VESS, pH, soil porosity>30-µm and aggregate tensile strength. This may not be a final MDS for the area of study as we did not include enough biological and chemical indicators in our study. As Bending et al. (2004) suggested, we need to include more biological indicators than chemicals, because biological indicators are more effective in differentiating the management impacts on soil quality changes. They concluded that the “arbuscular mycorrhizal fungus colonization potential”, “microbial ATP”, “biomass-N”, “chitin content”, “the ratios of ATP: biomass” and “basal respiration: biomass” have the potential to be used as biological indicators in a MDS. Since total N may not be a good representative for the N status in a soil system, I suggest including potentially mineralisable N (Luce et al., 2013; Stanford and Smith, 1972) or labile organic nitrogen (Bending et al., 2004) as a more sensitive chemical representative of the N content of soil in the final MDS.

Table 6. Results of principal components analysis of soil quality indicators having significant differences between the management systems in the LAM experiment.

Principal component	**PC1**	**PC2**	**PC3**	**PC4**
Eigenvalue	2.52	2.28	1.23	1.21
Percent	28.00	25.28	13.65	13.40
Cumulative percent	28.00	53.27	66.92	80.33
Eigenvectors [a]				
Clay dispersibility	**-0.474**	-0.105	**0.378**	-0.131
Soil Polysaccharide C	**0.398**	0.258	0.125	**-0.454**
SOC	0.**453**	-0.169	0.330	0.092
Aggregate stability	0.311	**0.416**	-0.104	0.033
Aggregate OC	**0.439**	0.005	**0.383**	**0.433**
Aggregate polysaccharide C	-0.022	**-0.523**	0.120	**0.430**
Aggregate tensile strength	-0.281	**0.465**	0.222	0.219
MWD	-0.204	**0.454**	0.359	0.326
Bulk density	0.029	0.159	**-0.618**	**0.491**

[a] Boldface factor loadings correspond to the indicators suitable for a MDS according to the eigenvector in each PC.

3.7. Minimum data set for other climates and soil types

All the experiments in this study took place in humid conditions on a sandy loam soil type. The interaction between soil and management systems is very complex and requires an understanding of the processes and functions in the soil exposed to different management systems (Schjønning et al., 2004b). The knowledge obtained here helps achieve a better understanding of the soil system and sustainable management practices that affect the whole soil system. We used a number of soil-type-independent indicators to assess the management impacts. However, under different climate conditions and with different soil types we may need to add a few indicators or remove some of the indicators included in our MDS. For example, in drier conditions we need to focus more on the soil quality indicators related to the "water-holding capacity function" of the soil. Moreover, in arid regions soils are most likely salt-affected and suffering from salinity and/or alkalinity. In these regions you would need to include indicators that are related to these soil problems (e.g. electrical conductivity (EC_e), Na^+, Cl^-, sodium adsorption ratio (SAR)) in the MDS (Yao et al., 2013).

Based on the holistic knowledge derived from this thesis and similar studies, it would be possible to advice farmers and decision-makers on the implementation of suitable management strategies for sustainable agriculture with different soil types and climatic conditions.

Table 7. Results of principal components analysis of soil quality indicators having significant differences between the management systems in the CENTS experiment.

Principal component	PC1	PC2	PC3	PC4	PC5
Eigenvalue	4.48	2.77	1.83	1.55	1.14
Percent	29.85	18.48	12.17	10.34	7.62
Cumulative percent	29.85	48.33	60.49	70.83	78.45
Eigenvectors [a]					
MBC	0.247	0.030	0.210	0.219	-0.018
Aggregate stability	-0.106	0.261	-0.108	**0.419**	0.238
Clay dispersibility	0.027	0.007	**-0.592**	0.150	-0.352
VESS	**0.335**	-0.023	0.259	0.132	**-0.441**
Porosity> 30-µm	0.285	-0.011	-0.178	0.132	**0.442**
Bulk density	**-0.348**	-0.176	0.267	0.337	0.040
Air-filled porosity at -10 kPa	**0.377**	0.215	-0.296	-0.099	0.144
Air permeability	**0.349**	0.067	-0.296	0.094	0.029
Aggregate tensile strength	-0.010	-0.190	-0.105	**0.691**	-0.132
Available P	0.304	-0.129	0.171	-0.204	-0.309
Available K	0.280	-0.289	0.105	0.015	0.291
SOC	0.168	**0.485**	0.285	0.065	0.069
Total N	0.172	**0.418**	0.312	0.203	0.030
pH	**-0.309**	0.330	-0.072	-0.150	0.191
MWD	0.154	**-0.440**	0.117	-0.008	**0.409**

[a] Boldface factor loadings correspond to the indicators suitable for a MDS according to eigenvectors in each PC.

4. Conclusions

Management strategies affected soil system and soil quality differently:

Effects of organic matter amendment:

Organic matter amendments boosted the SOC fractions.

Polysaccharide C was shown to be an important bonding agent in the process of aggregate formation. Its influence on soil aggregation was found to be more important than that of fungal hyphae.

Application of OM modified the soil responses to compressive and tensile stresses. In un-manured soil the reaction to compressive stress was less affected by differences in initial bulk density than in OM-amended soil. This indicates a more rigid soil structure for the un-manured soil.

A soil compaction effect on soil friability was less pronounced in an OM-amended soil than in a mineral soil.

Effects of tillage and traffic:

Intensive pto-harrowing and traffic affected soil tilth condition and resulted in a problematic soil tilth condition.

The conventional tillage system (MP) appeared to produce a better soil quality with the best soil friability (smallest MWD), lowest VESS score and the lowest PR in the topsoil. It also resulted in larger total and air-filled porosity at field-capacity water content.

Reduced tillage (D and H) resulted in greater soil strength and poorer topsoil structure (i.e. larger MWD, VESS score, PR, WSA, aggregate tensile strength and rupture energy).

Effects of cover crop:

The five-year application of cover crop indicated its potential to alleviate soil compaction by reducing PR in the plough pan layer and creating continuous macropores (biopores) to facilitate water and gas transport and root growth in the soil system. Our results also highlighted the potential use of cover crop in combination with direct drilling in overcoming the limitations of a poorer topsoil structure following the utilisation of reduced tillage systems.

Assessment of soil productivity function:

The Muencheberg soil quality rating method was able to differentiate the potential crop productivity of two different locations with the same soil type (sandy loam soil) but different water budgets. Significant correlations were found in most cases between soil quality indices and relative yield. This highlights the influence of soil quality and soil structure in particular on crop yield potential.

5. Future perspectives

What we have done in this study was a "*comparative assessment*" of soil quality in mid- to long-term experiments. Future research is needed to apply another effective way of assessing soil quality, "*dynamic assessment*", to evaluate the effect of management practices over time. This will help to determine the trend and magnitude of changes in soil quality due to the management systems practised.

Soil quality assessment has a site-specific nature. What has been done in this study was at a plot/field scale. As the research output is designed for the use by farmers at a later date, there should be an opportunity to involve relevant farmers in the research process. Consequently, there is a need for tools and policies/institutions to help farmers to understand and interpret management changes on their own farm and to transfer the research output to their specific situation. Moreover, there is a need to identify a minimum data set of indicators for a meaningful soil quality monitoring programme at the regional/national scale to be able to monitor overall soil quality for sustainable development. These indicators should indicate the soil's capacity to deliver ecosystem goods and services.

We reported the clear effects of management systems on SOC and its fractions. The potential contribution of labile organic matter fractions in soil tilth formation and aggregation processes following the application of these management systems was also revealed. More studies are needed addressing the roles played by mineral particles/fractions (clay and ions) in these important processes to reveal more aspects of their contribution separately or in combination with SOC fractions.

As stated in the discussion, there is a need to include other biological and biochemical indicators in the evaluation of management impacts on soil quality. However, as no single biological indicator is suggested to have all the criteria needed (Ritz et al., 2009) in the context of soil quality monitoring, future studies in this area may benefit from including a set of complementary indicators (i.e. biotic and abiotic indicators) as suggested by Pulleman et al. (2012). Consequently, there is a need for further research to develop a complementary set of biotic and abiotic indicators in the research area and also across the other agricultural areas.

During the sampling campaigns and PhD study, the need for a more accurate sampling strategy became obvious to avoid the large disturbance of study plots and assure the representativeness of the samples. Such a sampling strategy may include the use of a mechanical auger with the ability to sample the bulk soil and also cores from different depths. This mechanical auger may be operated by a skilled technician or researcher. This is more important in the core sampling campaigns that require accurate sampling. As suggested in paper III, to get the most out of supplementing core sampling with X-ray computed tomography, there is a need for a higher resolution CT scanning. The output of this higher resolution in combination with the result of the above-mentioned accurate sampling may serve to disclose more interesting results from the intended study.

Although the cover crop affected the soil system in the short study (five years), the lack of clear effects of cover crop on SOC, MBC and interactions with tillage systems highlighted the need for more studies in this area. One suggestion is to include new species of fodder radish with longer roots to serve as a natural chisel in a direct-drilled soil. Another suggestion is to include a mix of several cover crops in the experiment to benefit from different characteristics of each species. This mixture might benefit from including legume, cereal and brassica cover crops. A longer study to evaluate the potential long-term effects of cover crop is also recommended.

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Supporting papers

Paper I

The effects of organic matter application and intensive tillage and traffic on soil structure formation and stability.

Lotfollah Abdollahi, Per Schjønning, Susanne Elmholt and Lars J. Munkholm (2014)

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The effects of organic matter application and intensive tillage and traffic on soil structure formation and stability

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ABSTRACT

Management strategies like organic matter (OM) amendment and mechanical energy inputs are known to influence the soil system. A long-term (13–14-year) field experiment was used to evaluate the effects of these management strategies on soil structural formation, structural stabilization and soil tilth of a sandy loam soil in Denmark. OM was applied as manure and by retention of plant residues (ORG) to be compared with plots dressed only with mineral fertilizer (MIN). The soils were rotovated (ROT), compacted (PAC) or left undisturbed (REF) as split-plot treatments in the main plots with OM management over two years prior to sampling. In two consecutive years, undisturbed soil samples were collected from the 6 to 13 cm soil layer in the field grown with winter wheat to assess soil organic carbon (C) fractions (total organic C, polysaccharide C and microbial biomass C), total organic C and polysaccharide C of 1–2 mm macro-aggregates, bulk density, hyphal length, aggregate stability, clay dispersibility, aggregate tensile strength, direct tensile strength and shear strength. The ease of fragmentation and the torsional shear strength of soil were measured in the field as well. OM application increased all soil organic C fractions. Response patterns of organic C fractions in aggregates were the same patterns as for whole-soil. Polysaccharide C appeared to be an important agent in the aggregation process. The effect of microbial C and fungal hyphae on the aggregation process was not clear. Extensive tillage and traffic produced unfavourable tilth conditions in terms of a greater degree of clay dispersion, lower aggregate stability, higher soil tensile strength and poorer soil fragmentation. OM affected soil reaction to compressive and tensile stresses applied at differing initial bulk densities. The results also indicated the profitability of supplementing the classical laboratory analysis with in situ measurements to better evaluate management effects on soil structure.

1. Introduction

Many studies have highlighted the adverse impacts of intensive tillage and traffic on soil structural stability (e.g. Munkholm and Schjønning, 2004; Watts et al., 1996a,b), soil pore characteristics (e.g. Eden et al., 2011; Schjønning et al., 2007) and consequent influences on soil functions (Carter, 2002). Heavy and powerful machinery used for tillage and transport in modern mechanized agriculture applies large mechanical stresses to the soil. Moreover, the trend in weight and power of agricultural machinery will remain undiminished in the foreseeable future (Kutzbach, 2000). Field traffic generates compressive forces due to the weight of the machinery and generates shear forces from traction. Power take-off (pto)-harrows also transmit kinetic energy to the soil. The energy input adversely affects the structural stability of the soil and also increases dispersion of soil colloids (Munkholm and Schjønning, 2004; Watts and Dexter, 1997; Watts et al., 1996a,b) and decreases the stability of aggregates (Tisdall et al., 1978). Dispersed clay may cement on soil surfaces (on the topsoil or on inner surfaces of aggregates) and hence affect soil friability and aggregation (Schjønning et al., 2012; Shanmuganathan and Oades, 1982; Watts and Dexter, 1998). Watts et al. (1996b) investigated the influence of tillage operations (different intensities) on soil structural stability including mouldboard ploughing and rotary cultivation over a range of soil water contents. They recorded the specific energy for each implement and measured the mechanical dispersion of clay to assess aggregate deformation. The energy input from rotovation was three to four times greater than that from mouldboard ploughing, and at a given soil water content, rotovation resulted in larger amounts of dispersed clay.

Management strategies such as conservation tillage and soil organic matter (OM) management have been suggested to avert

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the detrimental effects of intensive tillage and traffic (da Silva et al., 1997; Govaerts et al., 2009; Karlen et al., 1992; Schjønning et al., 2002). OM is generally assumed to reinforce the soil reaction to compaction (Kay, 1990; Soane, 1990; Soane et al., 1980), to increase the production of stable aggregates (Tisdall et al., 1978) and to decrease its sensitivity to mechanical damage even when severe mechanical disruption occurs. Some studies also indicate a positive effect from management-derived soil OM on the resistance of soil to compaction (Holthusen et al., 2012; Schjønning et al., 2007).

The aim of this study was to quantify the effects of OM application and intensive tillage and traffic on soil structure formation and soil structural stability. We made use of a long-term field experiment that had compared soil dressed only with mineral fertilizers with soil amended with animal slurry and plant residues through a period of 13–14 years. Mechanical impacts using either wheel-by-wheel traffic with a tractor or intensive pto-harrowing of the topsoil were then applied on two or three occasions over a two-year period prior to sampling and measurements. We hypothesized that an increased content of soil organic carbon (SOC) would lessen the impacts of the mechanical inputs. Eden et al. (2011) reported the soil pore characteristics of the same treatments.

2. Materials and methods

2.1. Soil type and field trial

For the purpose of the study we used a long-term field experiment located at Research Centre Foulum, Denmark (56°30′ N, 9°34′ E). Mean annual temperature and precipitation (1961–1990) at the site were 7.3 °C and 626 mm, respectively. The soil is a sandy loam (Typic Hapludult) with ~9% clay. A range of soil properties are given in Table 1. The field experiment was initiated in 1989, 13–14 years prior to sampling. It includes four neighbouring fields in a four-year crop rotation consisting of winter wheat (*Triticum aestivum* L.), oilseed rape (*Brassica napus* L.) alternating with field peas (*Pisum sativum* L.), and two years with spring barley (*Hordeum vulgare* L.). Standard tillage operations including mouldboard ploughing to approx. 0.2 m and two times harrowing with an S-tine harrow with a driving speed of ~9 km h^{-1} to approx. 0.05 m depth were carried out before sowing each crop in the crop rotation. In each field, two different management strategies were applied.: fertilization with slurried pig manure and straw incorporation (treatment ORG), or fertilization with only mineral fertilizers and with all crop residues removed (treatment MIN). Averaged across the four-year crop rotation, the MIN soil was dressed with 124 kg N ha^{-1} $year^{-1}$ in NPK mineral fertilizer. The ORG soil received the same amount of N, half of it through NH_4-N in the pig slurry and the other half in form of calcium ammonium nitrate. In the ORG plots, straw was chopped and left on the soil for incorporation. The amount of straw was not quantified but was typically ~4 and ~5 Mg ha^{-1} for spring barley and winter wheat, respectively, as based on general knowledge of straw production for Danish soil and weather conditions (Schjønning et al., 2009). Details on nutrients and N-dynamics for the treatments can be found elsewhere (Debosz et al., 1999; Thomsen and Sørensen, 2006). The main plots with MIN and ORG treatments were replicated three times in a randomized block design. Two years prior to sampling for the present investigation, subplots with different mechanical treatments were added to each main plot (Fig. 1). The soil was rotovated (treatment ROT), compacted (treatment PAC) or left undisturbed (treatment REF) as split-plot treatments in the main plots (Fig. 1). The mechanical treatments were carried out immediately after each mouldboard ploughing operation over a two-year period prior to sampling as detailed in Table 2. A small tractor (Massey Ferguson 135) with narrow tyres (rear wheels: 12.4/11–32) loaded 1.2 Mg at an inflation pressure of 250 kPa was used to apply wheel-by-wheel traffic (treatment PAC), while a Howard RotoLabour cultivator performed the rotovation treatment (treatment ROT) to a depth of approx. 0.1 m. The rotarycultivator had a working width of 2.3 m, fitted with a total of 104 Rotalabour blades (~2.2 cm working distance) and a rotor diameter of 0.42 m. Rotor gears were selected to give a rotor speed of 235 rpm for a nominal 540 rpm PTO speed. We used a low tractor gear and the same throttle setting for all ROT plots, giving a nominal bite length (the distance between

Table 1
Basic characteristics of the plough layer soil for the fields under investigation. Data is averaged across 2002 and 2003.

Soil parameter	Value
Organic carbon (g 100 g^{-1})	1.6
Clay (<2 μm) (g 100 g^{-1})	9.0
Fine silt (2–20 μm) (g 100 g^{-1})	11.1
Coarse silt (20–63 μm) (g 100 g^{-1})	12.4
Fine sand (63–200 μm) (g 100 g^{-1})	27.9
Coarse sand (200–2000 μm) (g 100 g^{-1})	36.9
pH ($CaCl_2$)	6.2
Particle density (g cm^{-3})	2.61
Bulk density in the reference soil (g cm^{-3})	1.4
Potassium (mg kg^{-1})	85
Magnesium (mg kg^{-1})	36
Phosphorus (mg kg^{-1})	42

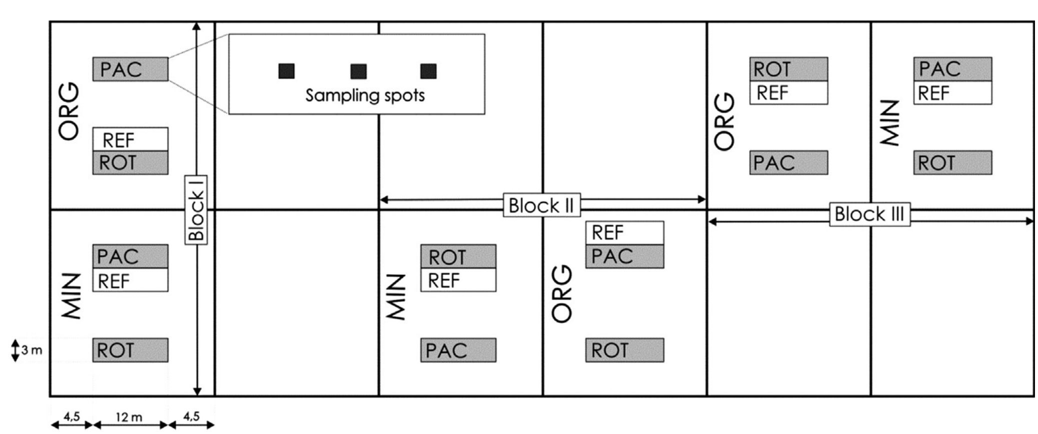

Fig. 1. Outline of the experimental design used in this study. The figure shows the relative position of the main plots with organic treatments MIN and ORG as well as the split-plot treatments REF, ROT and PAC for the field labelled S15 sampled in 2002. Main plots with no labels were used for other organic treatments not included in this study.

Table 2
Survey of crops, mechanical treatments and sampling in the two experimental fields.

Year	Season	Field S14		Field S15	
		Crop growth	Treatment/sampling	Crop growth	Treatment/sampling
2001	Spring Autumn	Spring barley	PAC, ROT[a]	Summer rape	PAC, ROT[a] PAC, ROT[b]
2002	Spring Autumn	Summer rape	PAC, ROT[a] PAC, ROT[b]	Winter wheat	Sampling
2003	Spring Autumn	Winter wheat	Sampling	Spring barley	

Reproduced from Eden et al. (2011).
[a] Mechanical treatments applied immediately following mouldboard ploughing for spring crop.
[b] Mechanical treatments applied immediately following mouldboard ploughing for winter wheat.

Table 3
Overview of samplings and measurements. The numbers are for each split-plot unit (each combination of organic matter treatment, mechanical treatment and field experimental block).

Experi-mental year	Field label	Texture, C fractions, etc.	Bulk density[a]	Annulus shear test	Aggr. stab./ clay disp.	Direct tensile strength	Drop shatter test	Torsional shear box test[b]
		kg soil	Replicate cores or lab tests				Replicate tests	
2002	S15	~3	6	–	3	8	4	6
2003	S14	~3	6	6	3	8	4	6

[a] Data derived from cores investigated by Eden et al. (2011).
[b] Only mechanical treatments REF and PAC.

successive tine entry points) of ~106 mm for a peripheral tine speed of 5.17 m s^{-1}. The ROT treatment did not include wheeled traffic on the test soil. The six combinations of treatments are labelled MIN-REF, MIN-ROT, MIN-PAC, ORG-REF, ORG-ROT and ORG-PAC.

2.2. Soil sampling and field measurements

Sampling and field measurements were carried out in the spring of 2002 (field S15) and 2003 (field S14). In both years, winter wheat was grown in the studied field. Selected soil properties were measured in the field and soil samples collected for laboratory studies. Measurements and samplings were applied to three sampling locations in each experimental plot in order to cover the intra-plot soil variation (Fig. 1). That is, each year we measured at 54 specific sites in the experimental field (2 OM treatments × 3 mechanical treatments × 3 blocks × 3 sampling spots). Minimally disturbed soil cubes (7 cm × 8 cm × 11.5 cm, ~650 cm^3) were sampled from the 6 to 13 cm layer as described by Schjønning et al. (2002). Undisturbed soil cores (6.1 cm diameter, 3.4 cm height, 100 cm^3) were taken from the 6 to 10 cm layer by inserting steel cylinders gently into the soil. In a similar way, we sampled undisturbed soil cores (6 to 11 cm) in unified two-piece cylinders as described by Munkholm et al. (2002). In short, two metal cylinders (4.5 cm diameter, 2.5 cm height) were held together by strong PVC tape, which allowed later measurement of direct tensile strength as described below. Cubes and cores were taken to the laboratory and stored at 2 °C until analyses could take place. Bulk soil was sampled from the ~6 to 15 layer as well.

In the field, a drop-shatter test was performed as described by Schjønning et al. (2002). In short, undisturbed soil cubes were collected from the 6 to 13 cm layer as described above and dropped from 75 cm height into a metal box. Soil fragmentation was quantified as the mean weight diameter (MWD) of the aggregate size distribution from sieves with apertures of 2, 4, 8, 16 and 32 mm. In situ soil shear strength was quantified by rotating a 10-cm diameter torsional shear box as described by Munkholm et al. (2002) following in principle the method of Payne and Fountaine (1952). The shear plane was at a depth of 12 cm, and we applied normal stresses in the range 7.3–32.3 kPa. Soil cohesion and internal friction were taken as the intercept and slope, respectively, from a regression of the shear stress and the normal load. Table 3 gives an overview of the replicate tests performed and sampling units collected each year at each of the 18 experimental plots (2 OM treatments × 3 mechanical treatments × 3 blocks).

2.3. Laboratory analyses

2.3.1. Sample pre-treatment

The bulk soil sampled in the field was air-dried upon arrival at the laboratory by spreading the soil in a dry, ventilated room at approximately 25 °C. The soil was inspected daily during drying and large clods carefully fragmented by hand when reaching a water content of maximum friability. Air-dried aggregates in the size fractions 1–2, 2–4, 4–8 and 8–16 mm were isolated by the procedure described in detail by Elmholt et al. (2008). Disaggregation of large clods only included shear forces in order to facilitate fragmentation along natural planes of weakness.

2.3.2. Chemical and biological soil properties

SOC was measured by a LECO Carbon Analyser following tests for carbonates. In addition, we determined the carbon that could be extracted by hot water (labelled HWSOC) as described by Elmholt et al. (2008). HWSOC can be taken as an estimate of extracellular polysaccharides (e.g. Ball et al., 1996). SOC and HWSOC were measured on bulk soil as well as on samples of 1–2 mm sized aggregates. The fumigation–extraction method (Vance et al., 1987) was used to quantify soil microbial biomass as detailed by Elmholt et al. (2008). The length of soil mycelial hyphae was analyzed by direct microscopy as described by Elmholt et al. (2008). Crushed 1–2 mm aggregates were dispersed in sodium hexametaphosphate for releasing hyphae from the soil structural units, and the length of soil mycelial hyphae was analyzed by direct microscopy as described in detail by Elmholt et al. (2008).

2.3.3. Physical soil properties

The texture of the air-dried soil was determined using a combination of the hydrometer and sieve methods. In order to have a balanced data set for both years, we calculated dry bulk density from the soil cores used by Eden et al. (2011) for studies of soil pore characteristics. An additional estimate for the year 2003 was obtained from the soil cores taken for measuring annulus shear strength (see below).

Wet aggregate stability and clay dispersibility were measured using soil from the minimally disturbed 650 cm^3 soil cubes (6 to 13 cm layer). Core subsamples were taken from the cubes and bulked to yield a total of approximately 45 g per cube. Soil from each subsample was gently fractionated by hand to pass an 8 mm sieve. A sample of approximately 35 g soil was transferred to a 20-cm diameter sieve with 250-μm openings and a water film exactly covering the threads of the sieve when in its upper position in the sieving apparatus (Yoder-type sieving). The soil was allowed to saturate through a 30-s initial capillary water contact, whereafter the soil was exposed to a 2-min vertical sieving process with strokes of 27 mm and at a frequency of 38 cycles per minute. Aggregate stability was calculated as the fraction of soil remaining on the sieve after the sieving period and corrected for mineral particles >250 μm. For clay dispersibility, we used the method suggested by Pojasok and Kay (1990). In short, subsamples of ~3 g were added to cylindrical plastic bottles containing 50 ml distilled water. The bottles were immediately rotated end-over-end (33 rotations min^{-1}, 0.23-m-diameter rotation) for 2 min and immediately thereafter placed in an upright position for 3 h 50 min, allowing particles >2 μm to settle. The suspended clay was dried in a ventilated oven at 80 °C and related to soil similarly calibrated for primary soil particles >250 μm.

Tensile strength of air-dry aggregates of the four size classes 1–2, 2–4, 4–8 and 8–16 mm was measured as described by Dexter and Kroesbergen (1985), which involved crushing the aggregates individually between two parallel plates in an indirect tension test. We tested 15 individual aggregates for each combination of sampling year, aggregate size class, and experimental plot (2 years × 4 size fractions × 18 plots × 15 aggregates = 2160 tests). The aggregate tensile strength (Y) was calculated from the equation (Dexter and Kroesbergen, 1985):

$$Y = 0.576 \times \frac{F}{d^2} \quad (1)$$

where F (N) is the polar force required to fracture the aggregate and d (m) is the mean aggregate diameter. In this study d was estimated from:

$$d = \frac{o_1 + o_2}{2} \quad (2)$$

where o_1 and o_2 are the openings of the upper and lower sieves for the specific size-class.

Soil friability was calculated for each experimental plot based on average test data from aggregate crushing tests. Friability based on tensile strength data, k_Y, was estimated from the equation (Utomo and Dexter, 1981):

$$\log_e(Y) = -k_Y \times \log_e(V) + A_Y \quad (3)$$

where $\log_e$ is the natural logarithm, A_Y is the predicted $\log_e$ strength of 1 m^3 soil, and V (m^3) is the estimated aggregate volume. Another indicator of aggregate strength, Y_4, defined as the strength of a 4-mm ($\log_e(V) = -17.2$ m^3) aggregate was calculated from the linear regressions obtained in Eq. (3).

Direct tensile strength was measured on soil at field-sampled water content using an automatically operated mechanical press as described in detail by Munkholm et al. (2002). In brief, the lower half of the two-piece cylinders was fixed in a specially designed rigid frame. The upper half of the two-piece cylinder and similarly fixed with a cap. Immediately before testing, the tape that held the two-piece cylinder together was pulled off as gently as possible. The cylinders were pulled apart with a longitudinal strain rate of 2 mm min^{-1} and the force was measured by a strain-gauge transducer. Tensile strength was then derived by relating the force to the square area of the sampling cylinder.

Soil shear strength was determined on 100-cm^3 soil cores drained to a matric potential of −300 hPa. We applied the annulus shear method developed by Schjønning (1986). The six soil cores sampled per plot were tested at one of the following normal loads: 10, 40, 70, 100, 130 and 160 kPa. In this way we ensured that the loads were evenly distributed over the three sampling spots and two soil cores within the plot. The inner and outer diameters of the shear annulus carrying the load were 18 and 40 mm, respectively. This means a 10-cm^2 area of the ~30-cm^2 surface of the soil core was loaded and sheared. Displacement of the annulus was recorded when the load had been applied, prior to and after the shear. The shear rate of one annulus revolution per 2 min corresponds to a shear rate of 45.6 mm min^{-1} at the mean shear radius. For each experimental plot, we estimated soil cohesion and internal friction as the interception and slope, respectively, of a regression of maximum shear stress and normal load. The displacement, s, prior to shear may be taken as the result of a uniaxial, semi-confined compression test. We calculated the strain, ε, as the ratio of the deformation and the height of the soil core, H: $\varepsilon = s/H$.

2.4. Statistical analyses

The aggregate tensile strength was log-transformed to yield a normal distribution. The other variables were normally distributed except hyphal lengths that more properly fitted a gamma distribution and hence was analyzed accordingly. We tested the effects of experimental treatments in a mixed model with treatments as fixed effects and block and year as random effects. OM treatment was considered as a main effect with mechanical treatment as a split-plot effect. We used Akaike's information criterion (Akaike, 1973) for comparing alternative models describing the same data set. The MIXED procedure of the statistical software SAS version 9.2 (SAS Institute Inc., 2009) was used.

3. Results

The application of OM (ORG treatment) over a period of 13–14 years increased significantly SOC and HWSOC in both whole soil and 1–2 mm aggregates as compared to mineral fertilization (MIN treatment) (Table 4). Microbial C was not significantly affected by OM application (Table 4) as compared to the MIN treatment. Generally, the mechanical treatments did not affect the C fractions (data not shown). SOC in the aggregates was generally higher than

Table 4
Organic matter treatment effects on soil organic matter fractions including SOC, HWSOC, soil microbial C, aggregate organic C, aggregate HWSOC, and hyphal length. Data is averaged across 2002 and 2003 and across the mechanical treatments, which showed no significant effects. Numbers followed by identical letters are not significantly different ($P < 0.05$ level).

Carbon fraction and hyphal length	Organic matter treatments	
	MIN	ORG
SOC[a] (g kg^{-1})	16.0[b]	17.0[a]
HWSOC[b] (mg g^{-1})	0.169[b]	0.186[a]
Microbial C (mg g^{-1})	0.206[a]	0.224[a]
Aggregate organic C (g kg^{-1})	17.1[b]	18.7[a]
Aggregate HWSOC (mg g^{-1})	0.164[b]	0.178[a]
Fungal hyphae lengths (m g^{-1})	11.3[a]	10.9[a]

[a] SOC, soil organic C.
[b] HWSOC, hot-water extractable C.

Table 5
Treatment effects on physical soil properties. Data is averaged across 2002 and 2003, except bulk density and lab shear data (cohesion and friction) which is for 2003. Values followed by the same letter for a given parameter are not significantly different at the $P < 0.05$ level.

Soil property	Organic matter treatments		Mechanical treatments		
	MIN	ORG	REF	ROT	PAC
Water stable aggregates ($mg\,g^{-1}$ soil)	538^{a}	593^{a}	589^{a}	541^{b}	566^{ab}
Clay dispersion ($mg\,g^{-1}$ soil)	5.27^{a}	4.40^{b}	4.55^{b}	4.90^{a}	5.06^{a}
Calculated tensile strength of aggregate size 4 mm, Y_4 (kPa)	45.8^{a}	47.9^{a}	46.2^{b}	48.9^{a}	45.6^{b}
Friability index, k_Y (–)	0.198^{a}	0.205^{a}	0.204^{a}	0.198^{a}	0.203^{a}
Direct tensile strength (kPa)	1.71^{a}	1.28^{b}	1.21^{b}	1.22^{b}	2.04^{a}
Bulk density ($g\,cm^{-3}$)	1.46^{a}	1.42^{b}	1.40^{b}	1.40^{b}	1.53^{a}
Cohesion (kPa) (lab measurement)	53.3^{a}	49.1^{a}	42.3^{b}	45.0^{b}	66.3^{a}
Friction, $t_g(\varphi)$ (–) (lab measurement)	0.50^{a}	0.50^{a}	0.53^{a}	0.48^{a}	0.49^{a}
Cohesion (kPa) (field measurement)	10.7^{a}	11.5^{a}	9.6^{b}	nd	12.6^{a}
Friction ($t_g(\varphi)$ (–) (field measurement)	0.68^{a}	0.64^{a}	0.54^{b}	nd	0.78^{a}

in whole soil samples, whereas the opposite was the case for HWSOC (Table 4).

There was no effect of OM treatments on hyphal lengths (Table 4). Averaged across years, mechanical energy input tended to decrease the hyphae lengths, and in 2002 this tendency was significant for both mechanical treatments (15 for REF compared to 11.2 and 10.5 $m\,g^{-1}$ for ROT and PAC, respectively).

The 13–14 years of animal slurry and plant residue (ORG) amendments tended to increase aggregate stability ($P \sim 0.12$) and decrease clay dispersion compared to soil under MIN treatment (Table 5). Both PAC and ROT treatments increased significantly the clay dispersion compared to the REF treatment. Also the stability of the macro-aggregates to mechanical breakdown was reduced by the mechanical treatments, but significant only for the ROT treatment.

The friability index, k_Y, was not significantly affected by either organic or mechanical treatments (Table 5). However, rotovation increased Y_4, which is an expression of the level of aggregate strength, compared to the REF and PAC treatments (Table 5 and Fig. 2). OM (ORG treatment) decreased significantly the direct tensile strength of soil cores compared to the MIN-treated soil (Table 5). The PAC treatment caused significantly higher direct tensile strength than the REF and ROT treatments.

Soil bulk density was significantly lower for ORG than for MIN soil, while the PAC treatment considerably increased bulk density compared to the REF and ROT treatments (Table 5). The shear annulus tests indicated that the PAC treatment also gave a more cohesive soil than REF and ROT (Table 5), while soil internal friction was unaffected. There was no significant effect of OM treatments on the shear-annulus estimated cohesion and friction. The estimates of soil cohesion from the torsional shear box applied in the field were much lower than those from the lab shear annulus method. The opposite was the case for soil internal friction (Table 5). Neither were there any significant effects of the OM treatments for the field measurements. However, there were similar effects of mechanical treatments as with the lab method (Table 5).

The OM treatment with no mechanical energy input (ORG-REF) showed the lowest value of MWD, which indicates the highest ease of tillage (Fig. 3). Soil compaction (PAC) increased MWD in the MIN as well as in the ORG treatments, being most pronounced for the MIN soil. This significant interaction indicates that soil OM has alleviated the compaction effect. Rotovation (ROT) increased MWD for the MIN as well as the ORG soil, though significantly only for the latter.

The strain, ε, after loading the soil samples prior to annulus shear increased with normal load (Fig. 4). When averaged across normal loads, the strain of the ORG soil was significantly higher for REF and ROT than for PAC treatments (data and statistics not shown), which is also detectable in Fig. 4. We found a significant

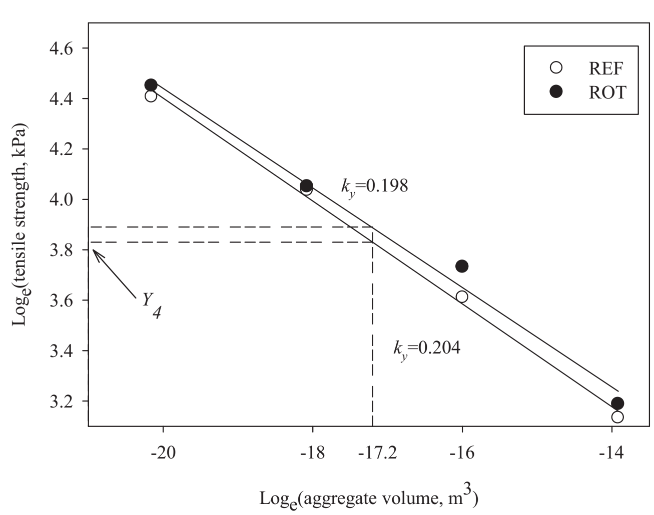

Fig. 2. Log$_e$ aggregate tensile strength as a function of log$_e$ estimated aggregate volume averaged for REF and PAC soils across organic matter treatments. The soil friability index, k_Y, is the slope of the regression lines of each soil. Y_4, is an expression of the level of aggregate strength.

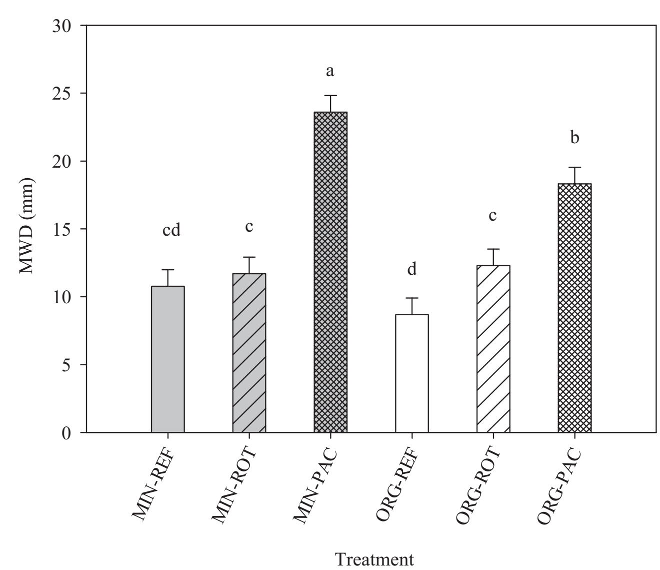

Fig. 3. Effects of different management systems on the Mean Weight Diameter (MWD) determined from the size distribution of aggregates following a drop shatter test. Bars labelled by identical letters are not significantly different at the $P < 0.05$ level.

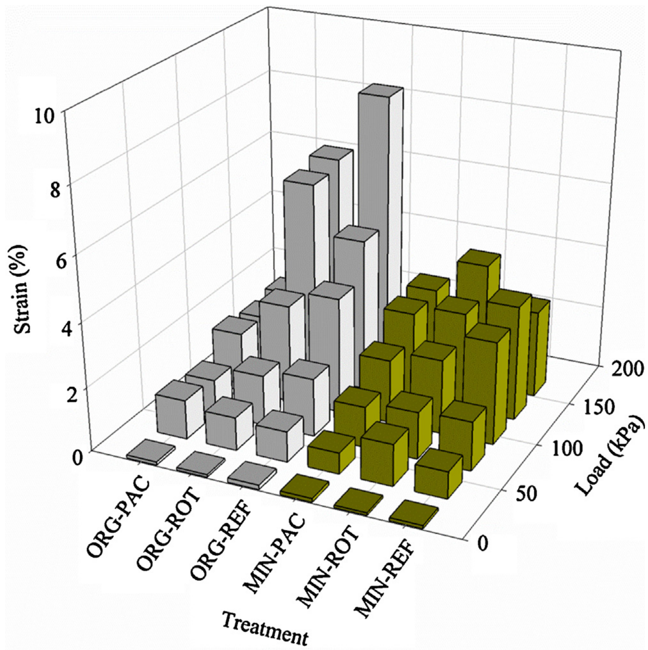

Fig. 4. Strain (%, (soil displacement/soil sample height) × 100) at different normal loads (kPa) applied in the annulus shear test (displacement prior to shear meaning a uniaxial, semi-confined compression test).

interaction between mechanical treatments and OM application. The low-density ORG-REF and ORG-ROT soils had significantly higher ε than ORG-PAC, which differed from that of all MIN treatments (Fig. 6a; statistics not shown; results are further discussed in Section 4).

4. Discussion

4.1. Enrichment with soil organic matter

Over a 13–14 year period, OM application resulted in higher SOC levels in the plough layer (22 cm in this study). SOC levels were 16 g kg^{-1} and 17 g kg^{-1}, for MIN and ORG, respectively (Table 4). This corresponds to a higher C sequestration in ORG of

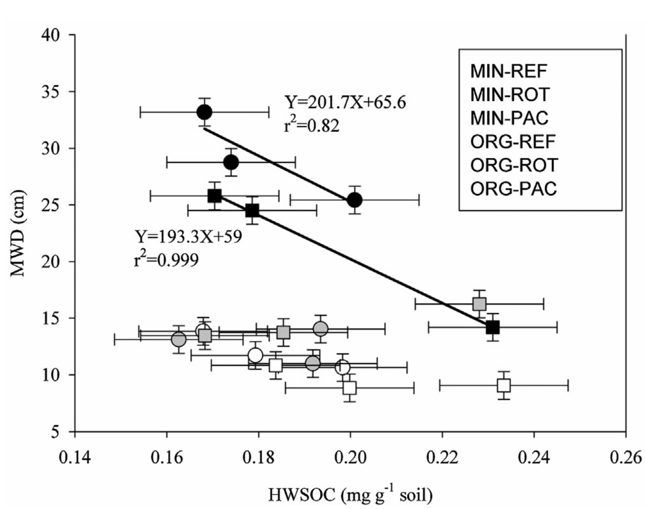

Fig. 5. The relation between field-measured soil friability (MWD in a drop-shatter test) and hot-water extractable carbon (HWSOC) at the level of experimental plot in the field in 2002. Regression lines are provided for compaction treatments in MIN and ORG, respectively. No significant correlation was found for the remaing data. Error bars indicate SE of the mean.

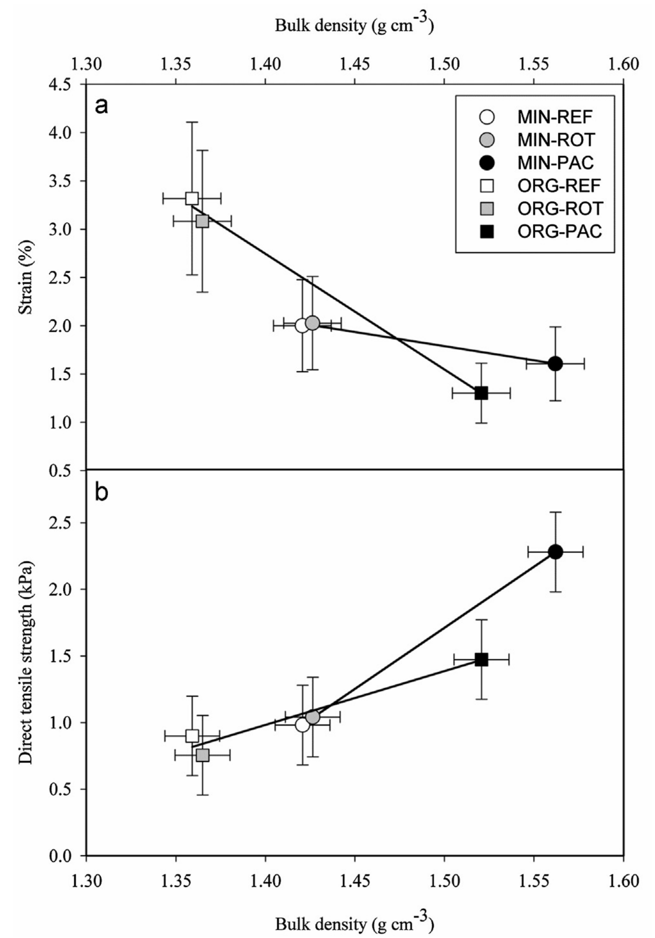

Fig. 6. Correlation between soil strain (a) and direct tensile strength (b) with bulk density for different treatment combinations. Data is from 2003. Error bars indicate SE of the mean at treatment level. For strain, the standard errors are calculated as a mean for different normal loads used in the test.

3.1 Mg ha^{-1} and indicates a storage rate of 220–240 kg C ha^{-1} yr^{-1}. Other researchers (e.g. Schjønning et al., 2007; Six et al., 2002; Zhang and Peng, 2006) have similarly reported SOC enrichment after the application of OM or changing the management practices to include more residue incorporation in the soil plough layer.

Carter (2002) emphasized the potential bias in SOC estimates from the existence of particulate OM (e.g. root parts and litters). Hence, we measured SOC and HWSOC in both whole-soil samples and 1–2 mm aggregates (Table 4). Comparing the C concentration in soil aggregates with bulk SOC showed a higher C concentration for 1–2 mm aggregates. This is consistent with a number of other publications (Carter, 1992; Eynard et al., 2004; Schjønning et al., 2007; Zhang and Peng, 2006). However, the amount of aggregate polysaccharide C in 1–2 mm aggregates was lower (Table 4) than that of the whole soil samples though statistically not comparable). Degens (1997a) also reported 15–43% less HWSOC in aggregates >1 mm than in the bulk soil samples amended with 6.2 or 12.5 mg OM g^{-1} soil.

4.2. Aggregation and tilth-forming processes

In order to achieve an optimal soil structure for the support of vital soil functions, the formation and stabilization of primary particles into aggregates are essential. Soil aggregation is a complex process including flocculation of clay particles at domain level; glueing by bonding agents at micro-aggregate level and enmeshment and cross-linking by binding agents at macro-aggregate level (Tisdall and Oades, 1982). Extracellular polysaccharides excreted from plant roots and microorganisms, hardening of dispersible clay, and fungal hyphae and plant roots have been reported as aggregating agents (Degens, 1997b; Karlen, 2005; Tisdall and Oades, 1982). Polysaccharide C, here quantified as the C soluble in hot water, has a glueing effect on mineral particles (Ball et al., 1996; Degens, 1997b). Several studies have highlighted the correlation of labile SOC fractions to the stability of soil structure (Ball et al., 1996; Chaney and Swift, 1984; Elmholt et al., 2008; Haynes and Beare, 1997; Haynes and Swift, 1990; Haynes et al., 1991). The increase in SOC and HWSOC of aggregates in the ORG-treated soil indicated the bonding effect in the aggregation process (Oades, 1984; Zhang and Peng, 2006). As a result of this bonding effect, we observed a higher proportion of stable aggregates and less dispersed clay in the ORG-treated soil (Table 5) than in MIN-treated soil. Moreover, a significant correlation ($P \sim 0.05$) between aggregate stability and soil HWSOC (data not shown) indicates that polysaccharide C is an important driver of the aggregation. For verification, we plotted and statistically tested the correlation between MWD and HWSOC. The result showed a pronounced effect of HWSOC on MWD and revealed polysaccharide C as the fraction of OM involved in the aggregation process. This trend was especially evident in 2002, where HWSOC decreased MWD (i.e. soil cloddiness) for the compacted treatments for both OM treatments (Fig. 5). Moreover, a negative correlation ($P \sim 0.\,05$) between HWSOC and clay dispersibility (data not shown) supports our conclusion that polysaccharide C was responsible for soil aggregation and the structural stability of the studied soil.

Microbial biomass C increased by 8.7% in the ORG soil relative to the MIN soil, although the trend was not statistically significant ($P = 0.28$, Table 4). Fließbach and Mäder (2000) reported a significant increase of microbial biomass C in an organically cultivated system (the manured soil) compared to an un-manured and conventionally cultivated system, after 18 years of management. In several studies microbial biomass has been used as an index of management-induced change in soil biological properties (Powlson and Jenkinson, 1981; Powlson et al., 1987). The authors recommended microbial biomass to be a more useful indicator of aggregate stability than SOC because of its labile nature and because it is easier than SOC to measure over a short period of time. In this study, however, microbial C was less sensitive than SOC and HWSOC.

The binding effect of fungal hyphae in aggregation was not clear in this study, as fungal hyphae length was not affected by the OM application. The aggregation process was therefore more likely due to the bonding effects of polysaccharide C than the binding effects of fungal hyphae. Schjønning et al. (2002) also reported a more evident role of polysaccharide C than fungal colony forming units in a study of the long-term effects of two organic and conventional systems on a range of soil characteristics. However, the negative effect of mechanical inputs on fungal hyphae lengths may help explain the detrimental effects of mechanical treatments on aggregate stability and clay dispersibility (Table 5). Jansa et al. (2003) and Kabir et al. (1998) also reported negative effects of tillage systems on arbuscular mycorrhizal fungi.

Based on work by Hassink (1997), Dexter et al. (2008) proposed that if the ratio, n, between clay content and SOC content of a soil is above 10, the clay is not 'saturated' with SOC, and this would be expected to influence soil physical properties. In contrast, SOC in 'saturated' soils ($n < 10$) would play a minor role in soil structural dynamics. Later de Jonge et al. (2009) and (Schjønning et al., 2012, 2009) confirmed this hypothesis for a range of soils. For the current soil, the n value was 5.6 ((clay content = 9)/(SOC = 1.6) = 5.6)). Therefore, we should not expect pronounced effects of SOC on the soil physical properties according to Dexter et al. (2008). However, we found direct effects of SOC on almost all physical properties of the studied soil. This implies that OM inputs may positively affect soil structural properties even at low n values. Our results thus indicate that the concept of Dexter et al. (2008) – although useful – may need to be supplemented by expressions of the 'quality' of SOC (in this study expressed through the HWSOC).

4.3. Structural strength and mechanical behaviour

Compared to un-manured soil, OM amendment over a period of 13–14 years resulted in a better soil tilth and a more friable soil with a less cloddy structure, better soil fragmentation (Fig. 3), lower bulk soil tensile strength (ease of tillage), lower bulk density, enhanced stability of wet aggregates and less dispersible clay (lower resistance to seedling emergence and root penetration).

On the other hand, intensive tillage and traffic resulted in problematic tilth conditions. Reduced water stability of aggregates, especially in the rotovation treatment, and higher clay dispersibility in both mechanical treatments revealed a weaker aggregation process due to the input of mechanical energy. The high sensitivity of clay to dispersion following intensive mechanical disruption was reported also by Watts et al. (1996a,b) for laboratory as well as field situations. Lower aggregate stability due to mechanical disruption in this study is interpreted as a puddling effect of the kinetic energy applied in the rotovation process; apparently this kind of energy is more injurious to soil aggregate stability.

The compacted soil (PAC) had higher bulk soil tensile strength, higher shear strength components, higher bulk density and poorer fragmentation (Table 5 and Fig. 3) compared to the REF soil. This is consistent with the studies by Munkholm and Kay (2002) and Munkholm et al. (2002).

In general, OM application modified soil reaction to compaction (Figs. 2–4 and 5a and b). A statistical model including the continuous variable bulk density and the interaction between bulk density and soil OM treatment appeared to explain better the measured soil deformation in the semi-confined compression test (strain in shear annulus test before shear). Using this model, the significant interaction between OM and mechanical treatments turned insignificant, and the Akaike criterion (Akaike, 1973) indicated the model including bulk density as the better of the two (analyses not shown). The significant effect of bulk density in soil compactibility is not surprising. More importantly, however, is the significant difference in the way the MIN and the ORG soils reacted to soil compression when they have different initial bulk densities (Fig. 6a). The ORG-REF and ORG-ROT soils had lower bulk densities and consequently higher soil porosity than the MIN-REF and MIN-ROT soils, and here we observed higher strains for the ORG soils. Zhang and Hartge (1995) and McBride and Watson (1990) also reported an increase in the compressibility of soils receiving organic amendments due to a higher initial porosity. According to this observation we should also expect the ORG-PAC soil to exhibit a higher strain compared to MIN-PAC. But we observed a tendency for ORG to show less strain at high bulk density than MIN (Fig. 6a). A lower sensitivity for ORG soils at high bulk density levels might be ascribed to the aggregation ability of the OM, i.e. the ORG soil has developed a better aggregated soil structure. Interestingly, the MIN soil reaction to compressive stress was less affected by differences in the initial bulk density than the ORG soil (significantly different slopes in Fig. 6a). This indicates a more rigid soil structure for the MIN soil. Apparently, the effect on resistance to compaction of a more highly aggregated ORG soil appeared only when the aggregates/particles are in close contact. Noticeably, the ROT treatment did not affect strain in our study. This was not surprising as ROT did not significantly affect bulk density or shear strength.

The discussion above addresses soil reaction to compressive stresses. Very interestingly, we also observed a significant interaction between bulk density and OM treatment for soil tensile strength as estimated by the direct tensile strength test (Fig. 6b). Also here the statistical model including bulk density as a continuous variable levelled out the class variable effects (main effects of OM and mechanical treatment) and explained the data better, as evaluated by the Akaike criterion (analyses not shown). For the tensile strength, however, only the interaction of OM treatment and bulk density – and not bulk density itself – had a significant effect. The results in Fig. 6b thus indicate that the tensile strength of the MIN soil increases significantly more with an increase in soil bulk density than is the case for the soil amended with OM. A high tensile strength of a soil implies the need for high energy inputs in tillage. Our results thus indicate that SOC may not be crucial for fragmentation in tillage at low densities, while it may prove essential for ease of tillage when soil is compacted. The observation correlates well with the field tests of soil fragmentation (Fig. 3).

4.4. Consistency between measurements

In the laboratory measurements, it is possible to control the test conditions better than in the field. However, the latter are useful for information on soil behaviour in the field and may serve as checkpoints of measured values in the laboratory. The results obtained in the laboratory were consistent with field measurements, but also added to our understanding of scale effects.

Laboratory measurements of soil shear strength (Fig. 7) were consistent with the soil fragmentation from the drop shatter test (MWD) (Fig. 3), i.e. the compacted soil (PAC) produced larger aggregates (lower friability), indicating a higher cohesive force in the soil structure and a need for higher energy input for tillage and seedbed preparation. However, calculated cohesion in the laboratory using the annulus shear test was four times higher than in field measurements (Table 5 and Fig. 7). This difference is probably due to the way the two methods interact with the soil. In the field torsional shear test, the soil tends to break along natural planes of weakness, where inter-aggregate forces prevail. In the laboratory the loaded annulus shears the soil in a fixed horizontal plane, where stronger intra-aggregate forces prevail. Lebert and Horn (1991) suggested that inter- and intra-aggregate shear properties might be evaluated by including tests at low as well as high normal loads. They found the inter-aggregate cohesion to be lower than the intra-aggregate (or bulk soil) cohesion, while the soil internal friction, in turn, was higher between aggregates (small loads) than for the bulk soil. We concur in this interpretation but note that also the method applied will influence the results.

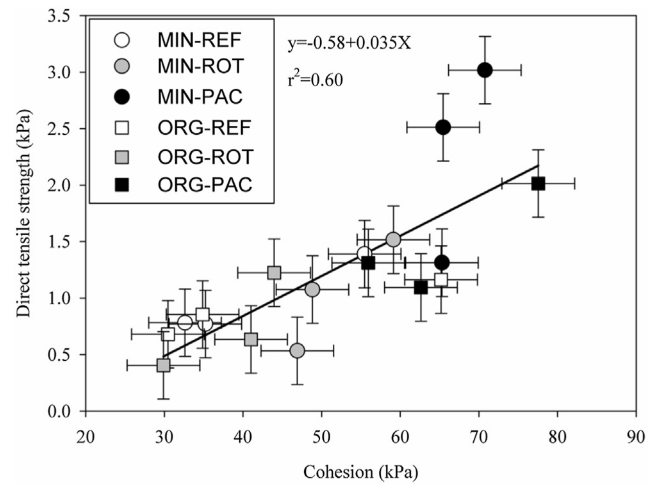

Fig. 8. Correlation between direct tensile strength and estimated cohesion from the annulus shear test for different combinations of treatments in 2003.

The aggregate tensile strength and the associated soil friability results (Table 5) were not in agreement with the drop shatter test results (Fig. 3). In the field (the drop shatter test), our results showed that OM addition ameliorated the negative impact of compaction, while this was not reflected in lab aggregate tensile strength data. We attribute this to the different water contents of the samples used in the two measurement methods (Munkholm and Kay, 2002) and also the different inter and intra-aggregate forces involved in the tests. The direct tensile strength of bulk soil samples (moist samples) agreed well with MWD results, i.e. the OM treatment (ORG) decreased and compaction (PAC) increased the tensile strength of soil samples. As the direct tensile strength data derives from a larger area/volume of soil (reflecting the drop shatter test conditions better than aggregates), the observations may also relate to scale.

The cohesion estimated from the annulus shear test correlated well with direct tensile strength (Fig. 8). This is partly explained by the difference in mechanical treatments, with PAC increasing soil cohesion as well as direct tensile strength. Within the REF and ROT treatments, however, we observed a correlation (Fig. 8). This result is interesting as it somehow contradicts the interpretation that the estimates of cohesion derived from the annulus shear test are only related to intra-aggregate forces (Fig. 7).

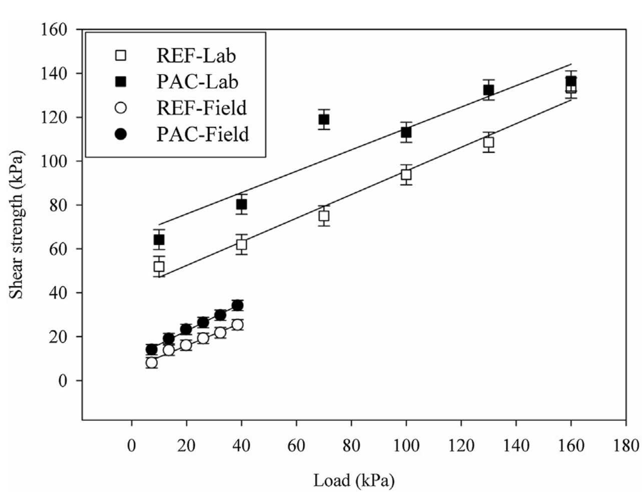

Fig. 7. Shear strength of mechanical treatments (REF and PAC) averaged across organic matter treatments as measured in the field and the laboratory for different normal loads applied in the tests. All data derives from 2003.

5. Conclusions

Management strategies clearly affected soil tilth condition. Application of OM and residue management boosted the amount of SOC in several fractions. Our results suggest that polysaccharide C is as an important bonding agent in the aggregation process, and that it is of larger importance than the binding effects of fungal hyphae.

Intensive tillage and traffic resulted in a poorer soil tilth condition. OM application changed the soil response to compressive as well as tensile stresses. The soil dressed with mineral fertilizer had nearly identical compactibility with an increase in bulk density, while the soil amended with OM behaved differently at different initial densities. The friability of the organic soil was less affected by soil compaction than the soil dressed only with mineral fertilizers. Our results indicate that soil OM may help soils cope better with the detrimental effects of traffic and tillage.

Our results also confirmed the importance and advantages of combining in situ and classical laboratory measurements for a more comprehensive evaluation of management effects on soil structure formation and stabilization.

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Paper II

Tillage System and Cover Crop Effects on Soil Quality:I. Chemical, Mechanical, and Biological Properties

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Tillage System and Cover Crop Effects on Soil Quality: I. Chemical, Mechanical, and Biological Properties

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Optimal use of management systems including tillage and winter cover crops is recommended to improve soil quality and sustain agricultural production. The effects on soil properties of three tillage systems (as main plot) including direct drilling (D), harrowing to a depth of 8 to 10 cm (H), and moldboard plowing (MP) with and without a cover crop were evaluated in a long-term experiment on a sandy loam soil in Denmark. Chemical, physical, and biological soil properties were measured in the spring of 2012. The field measurements included mean weight diameter (MWD) after the drop-shatter test, penetration resistance, and visual evaluation of soil structure (VESS). In the laboratory, aggregate strength, water-stable aggregates (WSA), and clay dispersibility were measured. The analyzed chemical and biological properties included soil organic C (SOC), total N, microbial biomass C, labile P and K, and pH. Reduced tillage (D and H) resulted in a stratification of the chemical properties within the 0- to 20-cm topsoil layer but a uniform distribution for MP. There was an accumulation of SOC, total N, and labile P and K and reduced pH in the 0- to 10-cm layer. Reduced tillage increased soil strength in terms of greater MWD, VESS, WSA, aggregate tensile strength, and rupture energy. Five years of using a cover crop alleviated plow pan compaction at the 20- to 40-cm depth by reducing penetration resistance. A significant interaction between tillage and cover crop treatments indicated the potential benefit of using a combination of cover crops and direct drilling to produce a better soil friability. The usefulness of the VESS method for soil structural evaluation was supported by the high positive correlation of MWD with VESS scores.

Abbreviations: +CC, plots with cover crop; −CC, plots without cover crop; D, direct drilling; H, harrowing to a depth of 8 to 10 cm; MBC, microbial biomass carbon; MP, moldboard plowing to a depth of 20 cm; MWD, mean weight diameter; PR, penetration resistance; SOC, soil organic carbon; VESS, visual evaluation of soil structure; WSA, water-stable aggregates.

The need for sustainable management strategies to maintain and improve soil quality and enhance agricultural production has been stressed by many studies in the light of an increasing world population and climate change (Komatsuzaki and Ohta, 2007; Lal, 2009). In recent years, the concept of conservation agriculture has been promoted as an integrated management tool to meet the challenges of the future (Verhulst et al., 2010). The conservation agriculture concept includes conservation tillage, diverse crop rotations, residue management, and cover crops as key elements. Many studies have assessed the impact of the different conservation agriculture elements on soil quality individually, but few studies have quantified the effect of conservation tillage combined with cover crops.

Using conservation tillage such as direct drilling is universally accepted as a way of protecting the soil against structural degradation and erosion (Hargrove, 1991; Reeves et al., 2005). It has widely been observed that different tillage sys-

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tems have influenced soil properties. Conservation tillage has been shown to increase aggregate stability, organic matter content, K, biological activity, and soil strength (Comia et al., 1994; Marinari et al., 2006; Schjønning et al., 2011; Munkholm et al., 2008; Munkholm and Hansen, 2012; Sainju et al., 2003). On the other hand, increased bulk density at the 0- to 25-cm depth and increased accumulation of P and acidity near the soil surface has been mentioned as disadvantages of direct drilling (no-till) (Soane et al., 2012). The stratification effects of reduced tillage on soil chemical properties (such as organic matter) in the soil profile have also been reported (Franzluebbers, 2002; Jones et al., 2007; Robbins and Voss, 1991).

The inclusion of winter cover crops in crop rotations dominated by summer crops may provide a range of vital ecosystem services and benefits. Winter cover crops scavenge the soil for nutrients and reduce nutrient losses (Dabney et al., 2001; Ewing et al., 1991; Fageria et al., 2005; Gómez et al., 2009; Hargrove, 1991; Isse et al., 1999; Munkholm and Hansen, 2012; Wagger, 1998). Cover crops have also been shown to improve soil quality and C sequestration (Motta et al., 2007; Mutegi et al., 2013; Thomsen and Christensen, 2004; Weil and Kremen, 2007). The use of cover crops may alleviate problems with soil compaction and thereby reduce the need for intensive tillage. Stirzaker and White (1995) explored the potential use of a winter legume cover crop on the alleviation of soil limitations after the application of a no-till system. They reported a significant ameliorating effect of the cover crop on a compacted sandy loam and the possibility of using a cover crop as an alternative to extensive tillage operations due to the formation of biopores. Positive effects on soil structure have also been reported from using *Brassica* cover crops (Chen and Weil, 2010; Williams and Weil, 2004).

In northern Europe, the adoption of conservation tillage strategies such as no-till and shallow tillage is low and this is partly due to problems with poor topsoil structure (Soane et al., 2012); it has been speculated that increased biological activity may reduce the need for intensive tillage. Our study examined the effect of different tillage treatments including direct drilling (D), harrowing to a depth of 8 to 10 cm (H), and moldboard plowing to a depth of 20 cm (MP) in combination with cover crop use (fodder radish, *Raphanus sativus* L.) on the properties of a sandy loam soil in a long-term field trial. The soil properties included: soil organic C (SOC), N, P, and K status, pH, microbial biomass C (MBC), mean weight diameter (MWD), visual evaluation of soil structure (VESS), penetration resistance (PR), water-stable aggregates (WSA), dispersible clay, aggregate tensile strength, and aggregate rupture energy. We hypothesized that the cover crop would reduce the need for intensive tillage and positively affect the nutrient status of the soil.

MATERIALS AND METHODS

Soil Type and Field Trial

The field experiment was performed on a long-term tillage and rotation trial (initiated in 2002, 10 yr before sampling) at Research Centre Foulum, Denmark (56°30′ N, 9°35′ E). Mean annual temperature and precipitation (1961–1990) at the site were 7.3°C and 626 mm, respectively. The soil is a Typic Hapludalf according to the U.S. soil taxonomy and a Mollic Luvisol according to the FAO system (Krogh and Greve, 1999). In the 0- to 25-cm depth, it has 9% clay (<2 μm), 13% silt (2–20 μm), 75% sand (20–2000 μm), and 3.1% organic matter (the texture was analyzed according to the IUSS classification system) (Munkholm et al., 2008). The experiment was a split plot with three replications and two factors: tillage as the main plot and cover crop as subplots. The tillage systems included in this study were D, H, and MP. A chisel coulter was used in the H and D treatments and a traditional Nordsten seed drill was used in the MP treatment. Each tillage plot consisted of two 3-m-wide tillage bands of 72.2-m length (Munkholm et al., 2008). The main crop was spring barley (*Hordeum vulgare* L.) in every experimental year. Paired subplots (13.7 by 3 m) with (+CC) or without (−CC) a fodder radish cover crop were used for this study, and the CC treatments were placed in the same subplots every year during the period of cover crop application (i.e., 2007–2011). Fodder radish was established in the +CC subplots by the surface broadcasting of seeds, 2 wk before harvesting of the spring barley. The six combinations of treatments are labeled D+CC, D−CC, H+CC, H−CC, MP+CC and MP−CC.

Soil Sampling and Field Measurements

In the spring of 2012, an extensive sampling and in-field measurement program was performed at soil moisture contents near field capacity (0.283 $m^3 m^{-3}$ at −10 kPa). Minimally disturbed soil cubes (~650 cm^3) were sampled from the 0- to 10 and 10- to 20-cm depths (144 samples) as described by Schjønning et al. (2002). The cubes were taken to the laboratory and stored at 2°C until analyses could take place. Using a small auger, bulk soil (a composite sample including 10 points) was sampled from each subplot (a total of 18 samples per depth for 0–10 and 10–20 cm). In another sampling, 72 minimally disturbed bulk soil samples were taken from the 0- to 10- and 10- to 20-cm depths and air dried for the measurement of aggregate tensile strength.

In the field, a drop-shatter test was performed as described by Schjønning et al. (2002). In short, 72 undisturbed soil cubes (72 samples) were collected from the 10- to 20-cm layer as described above and dropped from a 75-cm height into a metal box. Soil fragmentation was quantified as the mean weight diameter (MWD) of the aggregate size distribution from sieves with apertures of 2, 4, 8, 16, and 32 mm.

The VESS method described by Ball et al. (2007) was used for a holistic, semiquantitative evaluation of the topsoil structural quality in the field at near-field-capacity water content. In short, considering the aggregation, root growth, strength, and porosity (Table 1), the topsoil (a block of soil profile dug out with a flat-faced spade from the 0–20-cm depth) is evaluated and graded on a scale from Sq1 to Sq5, where Sq1 is the best (Table 1). Evaluation is based on a score card that was developed for this purpose. The average of two evaluations per subplot (18 plots × 2 points = 36 points) was used for statistical analysis.

Table 1. Description of soil structure and distinguishing features in each of the five categories of quality in the visual examination of soil structure (VESS) method (improved chart, adapted from Guimarães et al., 2011, Fig. 7).

Structure quality	Size and appearance of aggregates	Visible porosity and roots	Description of natural or reduced fragments of ~1.5-cm diam.
Sq1: friable Aggregates readily crumble with fingers	mostly <6 mm after crumbling	highly porous; roots throughout	the action of breaking the block is enough to reveal them; large aggregates are composed of smaller ones, held by roots
Sq2: intact Aggregates easy to break with one hand	mixture of porous, rounded aggregates from 2 mm to 7 cm; no clods present	most aggregates are porous; roots throughout	aggregates when obtained are rounded, very fragile, crumble very easily and are highly porous
Sq3: firm Most aggregates break with one hand	mixture of porous aggregates from 2 mm to 10 cm; <30% are <1 cm; some angular, nonporous aggregates (clods) may be present	macropores and cracks present; both porosity and roots within aggregates	aggregate fragments are fairly easy to obtain; few visible pores and rounded; roots usually grow through aggregates
Sq4: compact Requires considerable effort to break aggregates with one hand	mostly large >10 cm and subangular nonporous; horizontal/platy also possible; <30% are <7 cm	few macropores and cracks; all roots are clustered in macropores and around aggregates	aggregate fragments are easy to obtain when soil is wet; in cube shapes that are very sharp edged and show cracks internally
Sq5: very compact Difficult to break up	mostly large >10 cm, very few <7 cm; angular and nonporous	very low porosity; macropores may be present; may contain anaerobic zones; few roots, if any, and restricted to cracks	aggregate fragments are easy to obtain when soil is wet, although considerable force may be needed; no pores or cracks are usually visible

Soil penetration resistance was measured to a depth of 60 cm using an automated cone penetrometer (a prototype that was made in the workshop at Research Centre Foulum) (Olsen, 1988). The measurements were performed at field-capacity soil water content. Ten measurements were performed in each subplot.

Laboratory Analyses

Sample Pretreatment

The bulk soil sampled in the field was air dried on arrival at the laboratory by spreading it in a dry, ventilated room at approximately 25°C. The soil was inspected daily during drying and large clods carefully fragmented by hand when they reached a water content of maximum friability. Air-dried aggregates in the 8- to 16-mm size fraction were isolated by the procedure described in detail by Elmholt et al. (2008).

Chemical and Biological Soil Properties

Soil organic C was measured by a LECO Carbon Analyzer following tests for carbonates. Potassium was analyzed as described by Kalra and Maynard (1991) and P by the bicarbonate method. Soil pH was determined in 0.01 mol L^{-1} $CaCl_2$ using a glass electrode (25 cm^3 of 0.01 mol L^{-1} $CaCl_2$ solution added to 10 g of soil). Total N was measured according to Hansen (1989). The fumigation–extraction method (Vance et al., 1987) was used to quantify MBC, as detailed by Elmholt et al. (2008). In short, 15 g of undisturbed soil samples were weighed and fumigated with ethanol-free $CHCl_3$ for 18 h. Fumigated and unfumigated soil samples were extracted with 0.5 mol L^{-1} K_2SO_4, centrifuged (500 rpm for 5 min), and the supernatant filtered (0.45 µm). Organic C was measured using a TOC analyzer (TOC-V_{CPH}, Shimadzu) and MBC was calculated as (Joergensen, 1996)

$$\mathrm{MBC} = \frac{C_{\mathrm{fumigated}} - C_{\mathrm{unfumigated}}}{K_{\mathrm{EC}}} \qquad [1]$$

where K_{EC} is the extractable part of MBC (K_{EC} was set to 0.45).

Physical Soil Properties

Core subsamples from the 650-cm^3 soil cubes were used to measure aggregate stability and clay dispersibility using a Yoder-type measurement. For the aggregate stability test, a sample of approximately 35 g off field-moist soil was transferred to a 20-cm-diameter sieve with 250-µm openings and a water film exactly covering the threads of the sieve when in its upper position in the sieving apparatus. The soil was allowed to saturate by a 30-s initial capillary water contact, after which it was exposed to a 2-min vertical sieving process with strokes of 27 mm at a frequency of 38 cycles per minute. Aggregate stability was calculated as the fraction of soil remaining on the sieve after the sieving period and corrected for mineral particles >250 µm. For clay dispersibility, we used the method suggested by Pojasok and Kay (1990). In short, subsamples of ~3 g were added to cylindrical plastic bottles containing 50 mL of distilled water. The bottles were immediately rotated end-over-end (33 rotations min^{-1}, 0.23-m-diameter rotation) for 2 min and immediately thereafter placed in an upright position for 3 h and 50 min, allowing particles >2 µm to settle. The suspended clay was dried in a ventilated oven at 80°C and related to soil corrected for primary soil particles >250 µm.

The tensile strength of air-dry aggregates in the 8- to 16-mm size class was measured following the procedure described by Dexter and Kroesbergen (1985), which involved crushing the aggregates individually between two parallel plates in an indirect tension test. We tested 15 individual aggregates for each plot (270 aggregates in total). The aggregate tensile strength (Y) was calculated as (Dexter and Kroesbergen, 1985)

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

where F (N) is the polar force required to fracture the aggregate and d (m) is the mean aggregate diameter. In this study, d [m] was estimated from

$$d = d_0 \left(\frac{m}{m_x} \right)^{1/3} \quad [3]$$

where d_0 (m) is the mean aggregate diameter (12 for the 8–16-mm size class), m (kg) is the mass of the individual aggregate, and m_x (kg) is the mean mass of the 15 aggregates.

The rupture energy, E, was derived by calculating the area under the stress–strain curve:

$$E \approx \sum F(s_i)\Delta s_i \quad [4]$$

where $F(s_i)$ is the mean force at the ith subinterval and Δs_i is the displacement length of the ith subinterval. The specific rupture energy, E_{sp}, was estimated on a gravimetric basis:

$$E_{sp} = \frac{E}{m} \quad [5]$$

Statistical Analyses

The aggregate tensile strength and rupture energy data were logarithmically transformed to yield a normal distribution. The other data were best fitted by a normal distribution. Averages were calculated for each plot and used in the calculation of mean and standard error. The averages were also used as input in mixed models to test for treatment effects. We tested the effects of experimental treatments in a mixed model, with treatments as fixed effects and block as a random effect. Tillage treatment was considered as a main effect, with cover crop treatment as a split-plot effect. The PROC MIXED procedure of the statistical software SAS version 9.2 (SAS Institute, 2004) was used. An autoregressive, AR(1), covariance structure was used to analyze the difference between depth increments of the same sampling points.

RESULTS

In this study, a number of significant differences were observed for the main effects; however, the only significant interaction effect (tillage × cover crop) was found for MWD (Fig. 1, $p < 0.05$). The effect of tillage treatments on soil friability was significant (Fig. 1). Plowing (MP) gave the smallest MWD (best friability) of the tillage treatments. There was no significant difference between D and H treatments in this experiment. Cover crop did not significantly affect the MWD. The interaction between the cover crop and tillage treatments was significant, i.e., cover crop reduced the MWD for D and tended to increase the MWD for MP and H. Lower VESS scores (better soil quality) for MP than for D and H indicated the significant effect of tillage treatments on the visual soil assessment. Cover crop did not significantly affect VESS scores (Fig. 2).

Ten years of different tillage treatments resulted in significant treatment effects on SOC and total N at the 10- to 20-cm depth and for K, P, and pH at the 0- to 10-cm depth (Table 2). The plowing treatment (MP) had the highest SOC concentration, total N content, and pH compared with H and D at the 10- to 20-cm depth. For K, MP gave lower values than H or D (Table 2). In contrast, D gave higher values for P than H or MP at the 0- to 10-cm depth. There was no significant effect of tillage on MBC at any depth. The effect of cover crop on SOC, total N, P, and pH was not significant. Cover crop significantly increased the K content of the soil at the 0- to 10-cm depth, and there was a similar trend ($p = 0.08$) for the 10- to 20-cm layer. Microbial biomass C was weakly ($p = 0.08$) increased by the cover crop at the 10- to 20-cm depth but not in the 0- to 10-cm layer (Table 2).

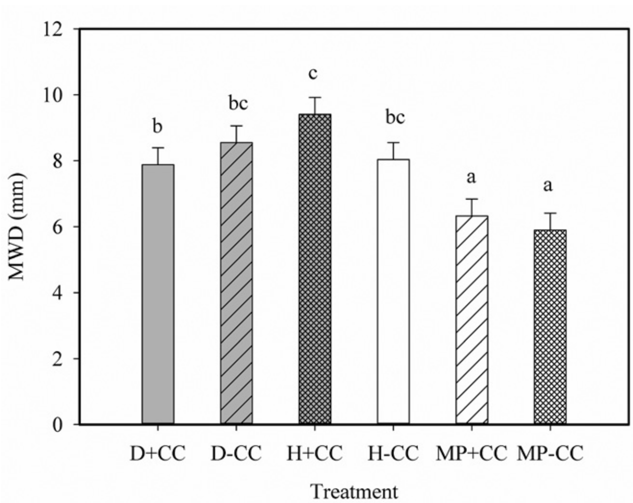

Fig. 1. Effects of different management systems on the mean weight diameter (MWD) determined from the size distribution of aggregates following a drop-shatter test: direct drilling with cover crop (D+CC), direct drilling without cover crop (D–CC), harrowing with cover crop (H+CC), harrowing without cover crop (H–CC), moldboard plowing with cover crop (MP+CC), and moldboard plowing without cover crop (MP–CC). Bars on columns indicate standard error. Bars labeled with identical letters are not significantly different ($p < 0.05$).

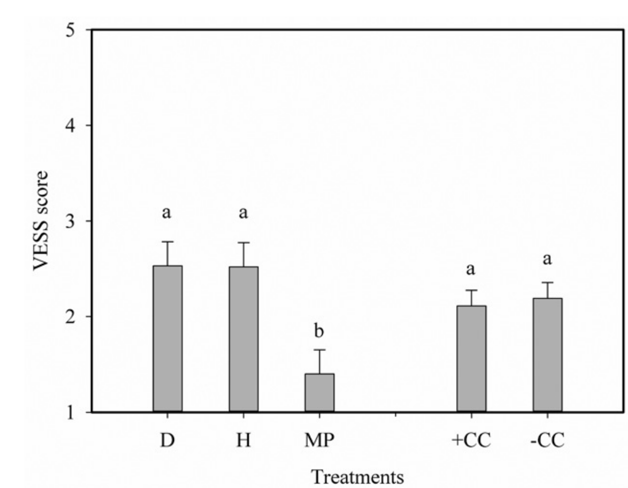

Fig. 2. Effects of different management systems on the visual evaluation of soil structure (VESS): direct drilling (D), harrowing to a depth of 8 to 10 cm (H), moldboard plowing to a depth of 20 cm (MP), plots with cover crop (+CC), and plots without cover crop (–CC). Bars on columns indicate standard error. Bars labeled with identical letters are not significantly different ($p < 0.05$).

The D and H treatments significantly increased the stability of wet >250-µm aggregates (WSA) at the 10- to 20-cm depth compared with MP (Fig. 3). The cover crop did not affect WSA at the 0- to 10-cm depth, but tended to decrease WSA at the 10- to 20-cm depth ($p = 0.057$) (Fig. 3). Clay dispersibility was not affected by the treatments. The autoregressive covariance, AR(1), detected different values of dispersible clay, WSA, and aggregate tensile strength between the 0- to 10- and the 10- to 20-cm depths. Dispersible clay was significantly higher at the 0- to 10-cm depth than the 10- to 20-cm depth. For WSA and aggregate tensile strength, the reverse was true. The tensile strength of dry 8- to 16-mm aggregates was significantly affected by tillage at the 10- to 20-cm depth (H ≥ D ≥ MP) but not by cover crop (Fig. 4). There was no effect of treatments on tensile strength at the 0- to 10-cm depth. The rupture energy of dry aggregates was higher for H than for MP and D in both layers, although the effect was only significant at the 0- to 10-cm depth. The cover crop significantly increased rupture energy in the 0- to 10-cm layer but not in the 10- to 20-cm layer.

Table 2. Treatment effects on soil organic C (SOC), microbial biomass C (MBC), total N, pH, available K, and available P.

Soil attribute	Depth	Tillage treatment†			Cover crop treatment‡	
		D	H	MP	+CC	−CC
	cm					
SOC, g kg^{-1}	0–10	22.0 a§	22.5 a	21.1 a	21.4 a	22.3 a
	10–20	18.9 b	19.0 b	21.2 a	19.4 a	19.9 a
Total N, g kg^{-1}	0–10	1.90 a	1.98 a	1.80 a	1.84 a	1.94 a
	10–20	1.60 b	1.65 b	1.78 a	1.64 a	1.71 a
MBC, g kg^{-1}	0–10	0.351 a	0.586 a	0.336 a	0.434 a	0.415 a
	10–20	0.293 a	0.505 a	0.365 a	0.404 A	0.372 B
Available K, g kg^{-1}	0–10	288 a	299 a	252 b	299 a	260 b
	10–20	178 a	167 a	160 a	174 A	163 B
Available P, g kg^{-1}	0–10	47.2 a	41.3 b	32.8 c	39.9 a	41.0 a
	10–20	33.7 a	29.5 a	34.0 a	31.6 a	33.1 a
pH	0–10	5.80 b	5.83 b	6.13 a	5.87 a	5.97 a
	10–20	6.21 a	6.20 a	6.18 a	6.17 a	6.22 a

† D, direct drilling; H, harrowing to a depth of 8 to 10 cm; MP, moldboard plowing to a depth of 20 cm.
‡ +CC, plots with cover crop; −CC, plots without cover crop.
§ Numbers followed by identical lowercase letters (across the rows for each main effect) are not significantly different at the $p < 0.05$ level; numbers followed by identical uppercase letters are not significantly different at the $p < 0.10$ level.

For both tillage and cover crop treatments, the PR increased gradually and reached critical values ≥1.5 MPa in the plow pan zone at around the 30-cm depth (Fig. 5). There was a significant effect of tillage on PR at the 18- to 23- and 55- to 60-cm depth. At 18 to 23 cm, PR increased in the order MP ,≤ D ≤ H with average values of 0.71, 0.90 and 1.28 MPa, respectively. At lower depths (55–60 cm) the results were the reverse, and H (1.80 MPa) had a significantly lower PR than MP (2.18 MPa) or D (2.14 MPa). The cover crop decreased PR significantly ($p = 0.055$) at the 32- to 38-cm depth (Fig. 5) (1.62 and 1.85 MPa for +CC and −CC, respectively).

DISCUSSION

Effect of Treatments on Chemical Properties

Regardless of cover crop treatment, the effects of 10 yr of different conservation tillage systems on SOC levels were different. A clear vertical stratification of SOC (i.e., the highest concentration in the top layer) was found for the D and H treatments, as expected, and this was related to shallow incorporation of organic matter. This is in agreement with numerous other studies (e.g., Franzluebbers, 2002; Álvaro-Fuentes et al., 2008; Hernanz et al., 2002; Kay and VandenBygaart, 2002). For the MP treatment, the SOC content was similar at the 0- to 10- and 10- to 20-cm depths, indicating an effective mixing of the soil during plowing.

Five-year application of a cover crop did not affect SOC. This corresponds with the results of Mendes et al. (1999), who studied the effect of red clover (*Trifolium pratense* L.) and triticale (×*Triticosecale* spp.) cover crops on soil aggregation in a short-term study (6–7 yr). Steele et al. (2012) also reported no increase in total organic matter and labile organic matter when evaluating the long-term (13-yr) effect of winter annual cereal cover crops on soil physical properties in Maryland. Previous studies in Denmark, however, have shown positive long-term effects of a perennial ryegrass cover crop on SOC (Hansen et al., 2000), and Mutegi et al. (2013) used a model to predict that during a 30-yr

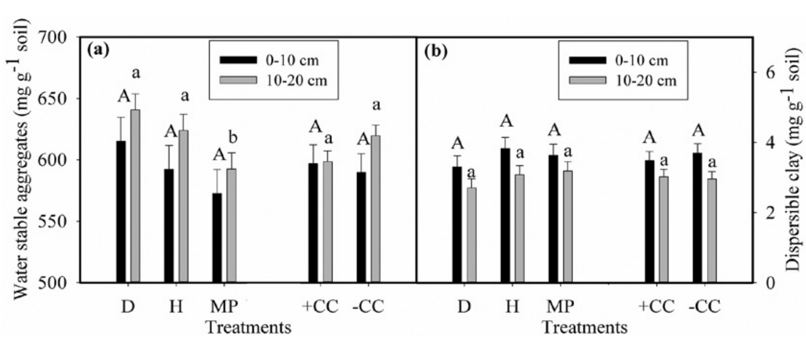

Fig. 3. Effects of different management systems on (a) water-stable aggregates and (b) dispersible clay: direct drilling (D), harrowing to a depth of 8 to 10 cm (H), moldboard plowing to a depth of 20 cm (MP), plots with cover crop (+CC), and plots without cover crop (−CC). Bars on columns indicate standard error. Bars labeled with identical uppercase letters at the 0- to 10-cm depth are not significantly different ($p < 0.05$). Bars labeled with identical lowercase letters at the 10- to 20-cm depth are not significantly different ($p < 0.05$).

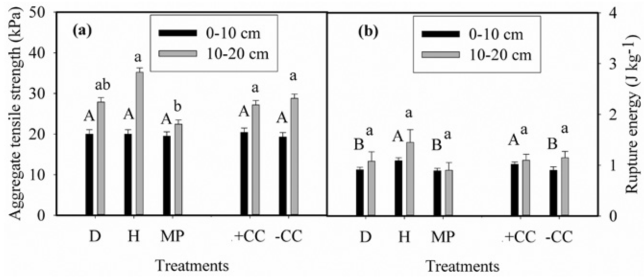

Fig. 4. Effects of different management systems on the (a) aggregate tensile strength and (b) rupture energy of dry aggregates size 8 to 16 mm: direct drilling (D), harrowing to a depth of 8 to 10 cm (H), moldboard plowing to a depth of 20 cm (MP), plots with cover crop (+CC), and plots without cover crop (–CC). Bars labeled with identical uppercase letters at the 0- to 10-cm depth are not significantly different ($p < 0.05$).Bars labeled with identical lowercase letters at the 10- to 20-cm depth are not significantly different ($p < 0.05$).

period with a fodder radish cover crop, C sequestration would be 4.9 Mg C ha^{-1}.

The effect of different treatments on total N was similar to the effect on SOC, indicating that most of the total N is likely to be in organic form. Mendes et al. (1999), Liebig et al. (2002), Sainju et al. (2003), and Villamil et al. (2006) also reported no significant effect of cover crops on total N. Sainju et al. (2003) attributed the lack of a cover crop effect on total N to the slow changes with time of the labile and recalcitrant pools of soil N that constitute total N. However, long-term use of a cover crop may increase total N, as shown by Thomsen and Christensen (2004).

The nonsignificant tendency for the amounts of MBC in H treatments to be higher was surprising and did not follow the trend of SOC and total N (Table 2). The cover crop tended to increase MBC—although insignificantly—despite the lack of effect on SOC and total N (Table 2). The largest increase (8.6%) was found in the 10- to 20-cm layer. An increase in MBC is in agreement with the results of Mendes et al. (1999) and Grünwald et al. (2000). We interpret the weak increase in MBC as an early indication of changes in SOC, as reported by Powlson et al. (1987).

Shallow incorporation of crop residues in the D and H treatments resulted in higher amounts of K and P at the 0- to 10-cm depth compared with MP (Table 2). Our results also showed a vertical stratification for K in all tillage and cover crop treatments and for P and pH in the D and H treatments. Higher concentrations at the top and a clear stratification of P, K, and pH for reduced tillage soils may be ascribed to the absence of or shallow incorporation of plant residues. Comia et al. (1994) also reported a greater concentration of K at the 0- to 13-cm depth for reduced tillage plots compared with plowing. For P, Comia et al. (1994) did not observe a significantly higher concentration at the surface under reduced tillage. This has, however, been shown by Jones et al. (2007), Franzluebbers and Hons (1996), and Crozier et al. (1999). This study also showed significantly lower pH levels at 0 to 10 cm for reduced tillage than for plowing.

Noticeably, the fodder radish cover crop increased the content of available K in the topsoil. This highlights the potential of fodder radish to scavenge soil nutrients (Isse et al., 1999; Wagger, 1998). Lower leaching losses of K would thus be expected. This is of agronomic importance on the studied sandy soil located in a humid climate, where K leaching is of significance. Higher values of pH in the MP treatment are not surprising because plowing via its inversion process normally moves the lime-rich subsoil (10–20 cm) to the topsoil layer.

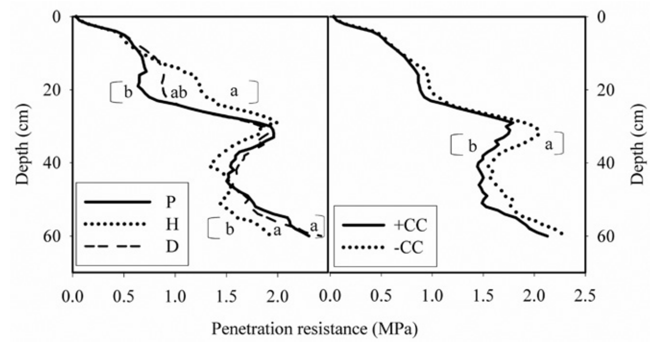

Fig. 5. Penetration resistance (geometric means) determined at water content near field capacity for different tillage systems and cover crop treatments to a depth of 60 cm: direct drilling (D), harrowing to a depth of 8 to 10 cm (H), moldboard plowing to a depth of 20 cm (P), plots with cover crop (+CC), and plots without cover crop (–CC). Brackets show depth intervals significantly affected by the tillage and cover crop treatments. Brackets labeled with different letters show significant differences at the specified depth intervals ($p < 0.05$).

Soil Strength and Friability

The VESS results revealed a significant effect of tillage treatments on soil structural quality (Fig. 2). The best structural quality effect of the tillage treatments (Sq = 1.4) was found for MP, but fair to good structural quality (Sq < 3) was also found for H and D. This indicates that the soil was favorable for agricultural purposes for all tillage treatments (Ball et al., 2007). This is consistent with the results achieved by Munkholm et al. (2013) for a Canadian silt loam soil. Ball et al. (2007), who developed the VESS method partly in the same field, also found a significant effect from tillage systems on Sq values. They also reported the best VESS score for MP (Sq = 1.1); however, their results showed a significantly poorer VESS score for D (Sq = 3.1) than for H (Sq = 2.1). Our results indicate that soil structure had improved under D from 2006 (Ball et al., 2007) to 2012 (this study). Mueller et al. (2009) also reported a positive effect of tillage on soil structural quality in a long-term study in three different countries. The effect of cover crop treatments on soil structural quality was not clear from the VESS scores (Fig. 2).

The PR data supported the VESS data, showing better structural quality in the topsoil (0–20 cm) under MP (Fig. 5). The PR data also showed a prominent plow pan at the 20- to 40-cm depth for all the treatments. This could be related to decades of moldboard plowing before the establishment of the tillage experiment in 2002. The cover crop tended to reduce PR in the soil profile and significantly lowered PR at the 32- to 38-cm depth (plow pan region) across tillage treatments. This implies that Brassicaceae cover crops have the potential to alleviate soil compaction in the subsoil due to biopore formation and the stimulation of natural soil structure formation.

The detailed soil mechanical results for the 10- to 20-cm layer confirmed a significant effect of tillage on soil strength, stability, and fragmentation behavior (MWD) (Fig. 1, 3, and 4). Plowing resulted in a more friable soil (i.e., the smallest MWD and lowest aggregate tensile strength and aggregate rupture energy). This is consistent with the VESS scores and the PR data and can be related to a lower bulk density (calculated for the companion study, Abdollahi et al., 2014) and higher SOC concentration (Fig. 2 and 5; Table 2). A significantly higher wet aggregate stability (WSA) was found for reduced tillage (H and D) than for MP for the 10- to 20-cm layer, with a similar trend in the 0- to 10-cm layer (Fig. 3). Higher aggregate stability with reduced tillage was also found by, e.g., Hamblin (1980) and Schjønning and Rasmussen (1989). For the 0- to 10-cm layer, this could partly be explained by the higher SOC content with reduced tillage. However, that was not the case for the 10- to 20-cm layer, where MP gave the highest SOC content. Higher bulk density (Abdollahi et al., 2014) and aggregate strength with reduced tillage (Fig. 3) probably influenced the results. The aggregate tensile strength and rupture energy results did not show similar trends in all cases. While there was no distinct effect of treatments on the tensile strength of aggregates at the 0- to 10-cm depth, higher rupture energy was recorded for H than for D and MP. At the 10- to 20-cm depth, a significantly higher tensile strength was found for H and also a weak trend ($p = 0.21$) for a higher rupture energy for H (Fig. 4). This observation was consistent with the poorest friability (highest MWD) in the H treatment (Fig. 1).

The MWD correlated negatively with macroporosity (Fig. 6), indicating that soil structural porosity controls the fragmentation behavior and strength of bulk soil. Hallett et al. (1995) also found that preexisting structural pore spaces strongly affected soil fragmentation. Moreover, a significant positive correlation between aggregate stability and MWD (Fig. 7) might indicate that macroporosity also controls the stability of macroaggregates. Lower aggregate stability with the plowing treatment, which appeared to have a higher macroporosity, might be explained in this way. A significant negative correlation between macroporosity and WSA (data not shown) supports this interpretation.

A significant correlation between MWD and VESS scores (Fig. 8) is considered an indication of the suitability of VESS for soil structure evaluation. Munkholm et al. (2013) also found a good agreement between MWD and VESS for a study using soil from a long-term Canadian rotation and tillage experiment on a silt loam. Visible porosity is a key parameter when performing the VESS test (Ball et al., 2007) and thus indirectly confirms the importance of structural porosity for soil structural quality.

Interaction Between Tillage and Cover Crop

This study examined the effect of different tillage systems in combination with the use of a cover crop, hypothesizing that a cover crop would reduce the need for intensive tillage.

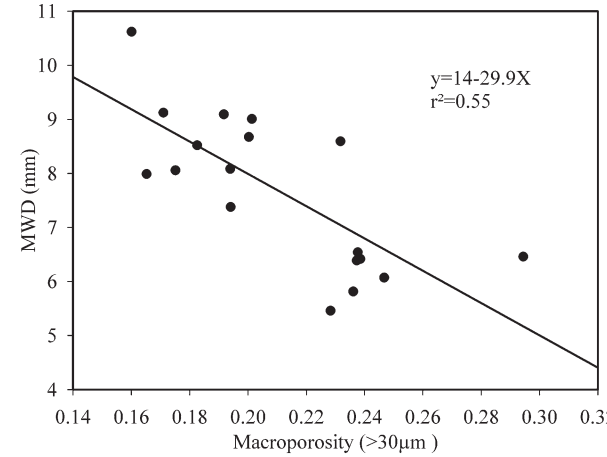

Fig. 6. The correlation between mean weight diameter (MWD) and macroporosity (>30 mm). Macroporosity data were obtained from the companion study on pore characteristics (Abdollahi et al., 2014)

Significant tillage and cover crop effects were found in a number of cases, as discussed above, whereas a significant interaction was found only for the drop-shatter test. The reason for the lack of a significant interaction in most cases is unclear; however, it is well known that it takes time for many soil quality indicators to change (that is, especially the parameters related to the input and turnover of organic matter, as discussed above [Thomsen and Christensen, 2004]). Thus, complex interactions between tillage and cover crop may need longer than 5 yr to manifest significant interactions.

The drop-shatter results (Fig. 1) revealed a positive effect of cover crop on D (i.e., lower MWD/higher friability) and a negative effect on H (although not significant in either case). This means that the D results supports the hypothesis that a cover crop would reduce the need for intensive tillage by improving soil physical properties, whereas the shallow tillage results did not confirm this hypothesis. Chen and Weil (2011) also suggested using fodder radish to alleviate compaction-induced problems in a no-till system of maize (*Zea mays* L.) cropping. The reason for the negative effect of cover crop on friability under

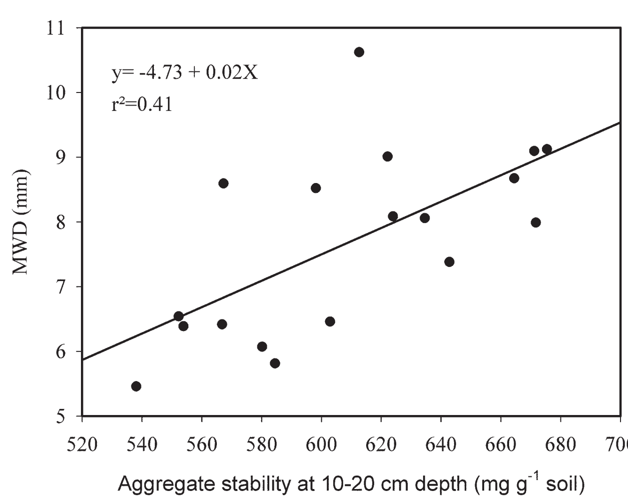

Fig. 7. The correlation between mean weight diameter (MWD) and the stability of wet aggregates (WSA) at the 10- to 20-cm depth.

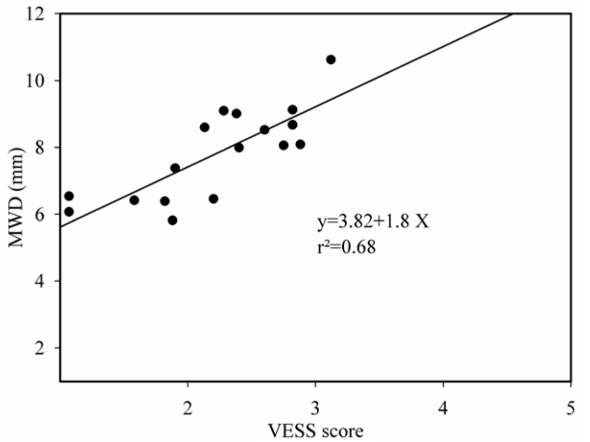

Fig. 8. The correlation between mean weight diameter MWD and visual evaluation of soil structure (VESS).

the H treatment is not well understood in this study. However, a relatively high PR was found for H at the 10- to 20-cm depth (Fig. 5), and this may have hampered cover crop root growth and thus the biological loosening effect.

CONCLUSION

Ten years' application of different tillage treatments influenced soil chemical properties differently. A pronounced vertical stratification was recorded for the reduced tillage treatments compared with a uniform distribution for plowing. The potential of a cover crop (fodder radish) to scavenge the soil for nutrients was manifested in its positive effect on available K. Apart from the positive effect on MBC and K, however, the cover crop did not affect other soil chemical properties. We may need a longer time than 5 yr to be able to detect significant changes in soil chemical properties (Thomsen and Christensen, 2004).

Of the three tillage treatments, plowing (MP) resulted in a better soil quality, producing the smallest MWD (best friability), the lowest VESS score, and the lowest PR within the 0- to 20-cm layer. Generally, reduced tillage (D and H) gave greater soil strength, with a larger MWD, VESS score, WSA, aggregate tensile strength, and rupture energy.

Five-year application of the cover crop treatment reduced PR in the plow pan region, confirming that fodder radish has the potential to alleviate soil compaction. The significant interaction between the cover crop and tillage treatments in the effect on soil fragmentation, i.e., the cover crop had a positive effect on D, indicates that especially D may benefit from a cover crop to yield better soil friability and soil quality.

The negative correlation between MWD and macroporosity shows the pivotal influence that structural pore space has on soil fragmentation. The usefulness of the VESS method for soil structural evaluation was supported by the high positive correlation between MWD and VESS scores.

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Paper III

Tillage System and Cover Crop Effects on Soil Quality: II. Pore Characteristics.

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Tillage System and Cover Crop Effects on Soil Quality: II. Pore Characteristics

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Information about the quantitative effect of conservation tillage combined with a cover crop on soil structure is still limited. This study examined the effect of these management practices on soil pore characteristics of a sandy loam soil in a long-term field trial. The tillage treatments (main plots) included direct drilling (D), harrowing to a depth of 8 to 10 cm (H), and moldboard plowing (MP). The cover crop treatments were subplot with cover crop (+CC) and without cover crop (−CC). Minimally disturbed soil cores were taken from the 4- to 8-, 12- to 16-, and 18- to 27-cm depth intervals in the spring of 2012 before cultivation. Soil water retention and air permeability were measured for matric potentials ranging from −1 to −30 kPa. Gas diffusivity was measured at −10 kPa. Computed tomography (CT) scanning was also used to characterize soil pore characteristics. At the 4- to 8- and 18- to 27-cm depths, pore characteristics did not differ significantly among tillage treatments. At the 12- to 16-cm depth, negative effects of reduced tillage (D and H) were recorded for total porosity and air-filled porosity at −10 kPa (that is, >30-μm pores). Generally, the use of a cover crop increased air-filled porosity at −10 kPa, air permeability, and pore organization and reduced the value of blocked air porosity at all depths for all tillage treatments. Our results show that the cover crop created continuous macropores and in this way improved the conditions for water and gas transport and root growth. The cover crop thus alleviated the effect of tillage pan compaction in all tillage treatments.

Abbreviations: +CC, plots with a cover crop; −CC, plots without a cover crop; CT, computed tomography; D, direct drilling; DA, degree of anisotropy; H, harrowing to a depth of 8 to 10 cm; MP, moldboard plowing to a depth of 20 cm; MWD, mean weight diameter; PO, pore organization.

Sustainable management strategies are needed to avoid soil structural degradation and to maintain or enhance soil quality and agricultural production. Conservation agriculture has been regarded as an important strategy to fulfill the ambition of a sustainable agriculture (Torres et al., 2001; Verhulst et al., 2010; Wall, 2007). Conservation tillage (e.g., Zentner et al., 2002) and cover crops (e.g., Hargrove, 1986; Reeves, 1994) are regarded as two key elements in conservation agriculture. Many studies have assessed the impacts of conservation tillage and cover crops on soil structural properties, but there is lack of information on the combination effect of conservation tillage and cover crop.

The soil pore system is a key soil structural component that controls the air and water exchange in the soil and serves as a habitat for microorganisms. Pore characteristics have been investigated extensively in relation to tillage and traffic (e.g., Ball et al., 1994; Comia et al., 1994; Douglas and Goss, 1987; Douglas et al., 1980; Eden et al., 2011; Schjønning, 1989; Schjønning et al., 2002a). Douglas and Goss (1987) showed that direct drilling will decrease total porosity and the volume

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of macropores compared with plowing. Conversely, Schjønning (1989) showed a higher degree of continuous and less tortuous soil macropores for direct drilling compared with plowing.

Cover crops have been found to influence soil quality (Keisling et al., 1994; Steele et al., 2012). However, the literature contains evidence of both positive and nonexistent effects of winter cover crops on soil structural properties. Keisling et al. (1994), Villamil et al. (2006), and Latif et al. (1992) reported positive effects of winter cover crops on soil physical properties in terms of decreasing bulk density and penetration resistance. In a companion study (Abdollahi and Munkholm, 2014), we also showed that a brassica cover crop may alleviate plow pan compaction across tillage treatments. Other studies have not shown a significant effect of cover crops on soil pore characteristics and related soil properties (bulk density, soil porosity, hydraulic conductivity, and water infiltration rate) (e.g., Carreker et al., 1968; Villamil et al., 2006; Wagger and Denton, 1989). There is a particular lack of quantitative data on the combined effect of conservation tillage and cover crops on the pore characteristics of the soil system.

Recent studies on the application of cover crops in Danish sandy loam soils highlighted the potential use of fodder radish (*Raphanus sativus* L.) for improving soil and air quality (Kristensen and Thorup-Kristensen, 2004; Munkholm and Hansen, 2012; Mutegi et al., 2011). This is related to a significant above- and belowground biomass production. For the soil used in the present study, Munkholm and Hansen (2012) reported an average aboveground biomass production in fodder radish cover crop of 1.8 Mg ha^{-1} dry matter. Mutegi et al. (2011) found a total C input (shoots + roots) to the soil of 1.0 to 1.2 Mg C ha^{-1} from growing a fodder radish cover crop on the soil used in the present study. The objective of our study was to quantify the impact of three tillage treatments including direct drilling (D), harrowing to a depth of 8 to 10 cm (H), and moldboard plowing to a depth of 20 cm (MP) (main plots) with or without a cover crop (fodder radish) treatment (subplots) on soil pore characteristics of a sandy loam soil. We hypothesized that the cover crop will reduce the need for intensive tillage such as moldboard plowing and when combined with reduced tillage, will have a positive impact on the pore system, aiding air and water transport in the soil system.

MATERIALS AND METHODS

Soil Type and Field Trial

The field experiment was performed on a long-term tillage and rotation trial (initiated in 2002, 10 yr before sampling) at Research Center Foulum, Denmark (56°30′ N, 9°35′ E). Mean annual temperature and precipitation (1961–1990) at the site were 7.3°C and 626 mm, respectively. The soil is a Typic Hapludalf according to the USDA classification system and a Mollic Luvisol according to the FAO system (Krogh and Greve, 1999). At the 0- to 25-cm depth, it contains 9% clay (<2 μm), 13% silt (2–20 μm), 75% sand (20–2000 μm), and 3.1% organic matter (texture was analyzed according to the IUSS classification system) (Munkholm et al., 2008).

The experiment was a split plot in three replications with two factors: tillage as the main plot and cover crop as the subplots. The tillage systems included in this study were D, H, and MP. A chisel coulter was used in the H and D treatments and a traditional Nordsten seed drill in the MP treatment. Each tillage plot consisted of two 3-m-wide and 72.2-m-long tillage strips (Munkholm et al., 2008). Paired subplots (13.7 by 3 m) with (+CC) or without (−CC) fodder radish as a cover crop were used for this study, and the CC treatments were placed in the same subplots every year during the period of cover crop application (2007–2011). The main crop was spring barley (*Hordeum vulgare* L.) in every experimental year. Fodder radish was sown every year in spring barley by surface broadcasting of seeds 2 wk before harvest of the barley. The six combinations of treatments are labeled D+CC, D−CC, H+CC, H−CC, MP+CC, and MP−CC.

Soil Sampling and Field Measurements

In the spring of 2012, an extensive sampling and in-field measuring program was performed at a soil moisture content near field capacity (−10 kPa). Undisturbed soil cores (~100 cm^3) were collected from the 4- to 8- and 12- to 16-cm layers, and larger cores (~250 cm^3) were taken from the 18- to 27-cm layer. In total, 324 soil samples were collected for soil pore characteristic measurements in the laboratory. Eighteen topsoil core samples (~1257 cm^3) were taken for X-ray CT scanning. Cores were taken to the laboratory and stored at 2°C until analyses could take place.

The water infiltration rate was measured at two different water tensions in the near-saturated range (approximately −3 and −10 cm) using a tension infiltrometer (UGT, IL-2007) (Ankeny et al., 1991). Measurements were applied at two points per plot and the averages of each plot were used for statistical analysis. The results were then adjusted (interpolated) to a middle point of −4 cm water tension using log–log *x*–*y* axis for plotting infiltration rate (*y* axis) against water tension (*x* axis).

Laboratory Analyses

Pore size distribution was measured by adjusting the core samples to different matric potentials. The soil cores were capillary wetted to saturation and then drained to matric potentials of −1, −3, and −10 kPa using tension tables and drained to −30 and −100 kPa using ceramic plates. The weight of each sample was recorded at each matric potential and after oven drying at 105°C for 24 h. Soil porosity was estimated from the bulk density and particle density. For the latter, we used the value measured by Eden et al. (2011) for the same soil (that is, 2.61 g cm^{-3}). The volumetric water content at each matric potential was calculated from weight loss on oven drying. The air-filled porosity, ε_a, at a specific matric potential was calculated as the difference between the total porosity and the volumetric water content. The air permeability, K_a, was measured on the same cores (above) at matric potentials of −3, −10, and −30 kPa according to the steady-state method described by Iversen (2001).

Gas diffusivity was measured at −10 kPa matric potential by the non-steady-state method (Taylor, 1949) using the one-chamber technique described by Schjønning et al. (2013). In short, the concentration (diffusion) of O_2 in a chamber was recorded every 2 min (for approximately 2 h) following the flushing of the chamber with O_2–free N_2. Fick's second law of diffusion was used to calculate the diffusion coefficient, D_s, which was then converted to gas-independent diffusivity by relating it to the diffusion of O_2 in air, D_o (0.205 $cm^2\ s^{-1}$ at 20°C and atmospheric pressure; Smithsonian Physical Tables). Gas-independent diffusivity or relative diffusivity (D_s/D_o) data were used in the statistical analysis. For CT scanning, 18 topsoil samples were scanned using a medical CT scanner (Aarhus University Hospital) at 120 keV with a voxel size of 0.43 by 0.43 by 0.60 mm, as done previously by, e.g., Garbout et al. (2013). A volume of interest (VOI = 6760 cm^3) was cropped in the CT scan image.

Scanned gray-scale data of the VOI were segmented using the global thresholding method (Otsu's algorithm) to separate solid and pore phases. The Otsu thresholding algorithm was provided in the ImageJ software (version 1.45K) (Rasband, 2009). The detectable pore space (>0.43-mm pores) was separated into two categories: the pores connected to air and the unconnected or isolated pores. The pores were analyzed using the BoneJ plugins (Doube et al., 2010). We measured (i) the degree of anisotropy (DA), (ii) the pore total volume, and (iii) the total surface area. The DA is a calculated geometric characteristic (Odgaard, 1997), as preferential alignment along a particular axis can have a significant impact on transport processes. The DA can take values from 0 to 1, with 1 indicating a high degree of anisotropy, as would be found for a group of aligned long structures. The interconnectedness of the pore volume was characterized by network properties. First, we applied a thinning algorithm to iteratively reduce the diameter of the pores until only a skeleton remained (Lee et al. [1994], available as a plug-in, 3D skeletonize, in ImageJ). This process was performed symmetrically to keep the skeleton lines in a medial position and preserve the connectedness of the pore volume. Second, we used the ImageJ plugin Analyze Skeleton to characterize these networks. In this way, we recorded the number of networks, number of junctions, number of branches, number of endpoints, and the mean branch length for each network.

Estimation of Soil Pore Characteristics from Water Retention, Air Permeability, and Gas Diffusivity Measurements

To study soil morphological characteristics and obtain more information about soil pore characteristics, we used the following calculations and models.

An empirical index of pore continuity or pore organization (PO, μm^2) was calculated for the measurements at −3, −10, and −30 kPa matric potential (Groenevelt et al., 1984):

$$PO=\frac{K_a}{\varepsilon_a} \quad [1]$$

High values express a high capability of a given air-filled pore volume to conduct air, that is, high continuity.

The simple exponential model of Ball et al. (1988) was used to relate air permeability, K_a, to the air-filled porosity of the soil, ε_a:

$$K_a = M\varepsilon_a^N \quad [2]$$

which can be written as

$$\log(K_a)=\log(M)+N\log(\varepsilon_a) \quad [3]$$

where M and N are model constants reflecting soil characteristics.

Ball et al. (1988) regarded a soil with air permeability as low as 1 μm^2 (K_a = 1 μm^2) as a soil with no capacity of air permeability. Thus, we considered the intercept of Eq. [3] on the abscissa [$\log(K_a) = 0$] as an estimate of blocked air-filled porosity, ε_b, which does not take part in the transport of air by convection:

$$\varepsilon_b = 10^{-\log M/N} \quad [4]$$

The tube model of Ball (1981) was used to calculate two important pore characteristics including equivalent pore diameter (d_B, μm) and the number of air-filled pores in a soil transect (n_B). Equivalent pore diameter is considered to be a parameter indicating pores actively conducting air through the soil sample. The equations for d_B and n_B as described by Schjønning et al. (2002b) are

$$d_B = 2\left(\frac{8K_a}{D_s/D_o}\right)^{1/2} \quad [5]$$

and

$$n_B = \frac{\varepsilon_a^{1/2}\left(D_s/D_o\right)^{3/2}}{8\pi K_a} \quad [6]$$

Statistical Analyses

The air permeability, infiltration rate, and CT scanning-derived data were logarithmically transformed to yield a normal distribution. The other data were best fitted by a normal distribution. Averages were calculated for each plot and used in the calculation of mean and standard error. The averages were also used as input in mixed models to test for treatment effects. We tested the effects of experimental treatments in a MIXED model, with treatments as fixed effects and block as a random effect. Tillage treatment was considered as a main effect, with cover crop treatment as a split-plot effect. The PROC MIXED procedure of the statistical software SAS version 9.2 (SAS Institute, 2004) was used. An autoregressive, AR(1), covariance structure was used to analyze the difference between depth increments of the same sampling points.

RESULTS

In this study, a number of significant differences were observed for the main effects. However, no significant interaction effect (tillage × cover crop) was found for many soil properties, although soil structure (as measured by X-ray CT scanning) did show significant interaction effects ($p < 0.1$).

Porosity

The result for the 4- to 8-cm depth showed no significant difference in total porosity among tillage treatments (Fig. 1). The effect of tillage on total porosity was significant in the 12- to 16-cm layer (MP > D = H) and was almost significant ($p = 0.066$) in the transition layer between topsoil and plow pan, that is, 18 to 27 cm (MP ≥ D = H). No significant difference between cover crop treatments (main effect) was observed for total soil porosity for the three studied depths (Fig. 2).

Plowing (MP) caused a significant increase in macroporosity (>30 μm) at 12 to 16 cm as well as on microporosity (<30-μm pores) at 18 to 27 cm compared with H and D (Fig. 1; Table 1). There was no significant effect of cover crop on micro- and macroporosity (Fig. 2; Table 1). For +CC at 4 to 8 cm, however, macroporosity was almost significantly higher ($p = 0.056$) (Fig. 2).

The analyses of the large macropores (>430 μm) derived from X-ray CT images showed no effect of tillage and cover crop treatments on any extracted data; however, MP showed a potential of having greater number of branches, junctions, and endpoints, larger pore volume and pore surface, and lower DA (Table 2). An almost significant interactive effect between tillage and cover crop treatments was detected for the number of branches ($p = 0.071$), the number of junctions ($p = 0.069$), and the number of endpoints ($p = 0.058$) (Table 3). According to Table 3, D+CC had the lowest and P+CC had the largest values of all above-mentioned properties. Figure 3 shows the three-dimensional images of pore characteristics for the treatment combinations.

Air Permeability and Gas Diffusivity (Soil Conductivity)

The air permeability of the studied soil was not significantly affected by the tillage treatments at all investigated depths and for all tested matric potentials (Fig. 1; Table 1). The cover crop significantly increased air permeability at 12 to 16 cm for all investigated matric potentials (Fig. 2 and 4; Table 1). At 4 to 8 cm, the cover crop tended to increase air permeability ($p < 0.10$) at −3, −10, and −30 kPa matric potentials. At 18 to 27 cm, the increase in air permeability due to the cover crop effect was larger at −10 kPa ($p < 0.10$) than at the other investigated matric potentials. Significant increases in air permeability due to cover crop effects were observed at −10 kPa matric potential for the 12- to 16-cm depth and at −3 kPa matric potential for the 12- to 16- and 18- to 27-cm depths (Fig. 2 and 4; Table 1).

Relative gas diffusivity, which was only measured at −10 kPa, exceeded the critical limit of 0.02 (Grable and Siemer, 1968) in all tillage and cover crop treatments. There was no effect of tillage and cover crop treatments on gas diffusivity. Likewise, there was no significant effect of tillage and cover crop treatments on the infiltration rate at −4 cm. However, a weak trend ($p = 0.169$) of a greater infiltration rate for MP than for H and D was found (Table 1).

Estimated Pore Characteristics

The tillage treatments did not affect the pore organization index (PO) at the studied matric potentials (Fig. 1; Table 1). The

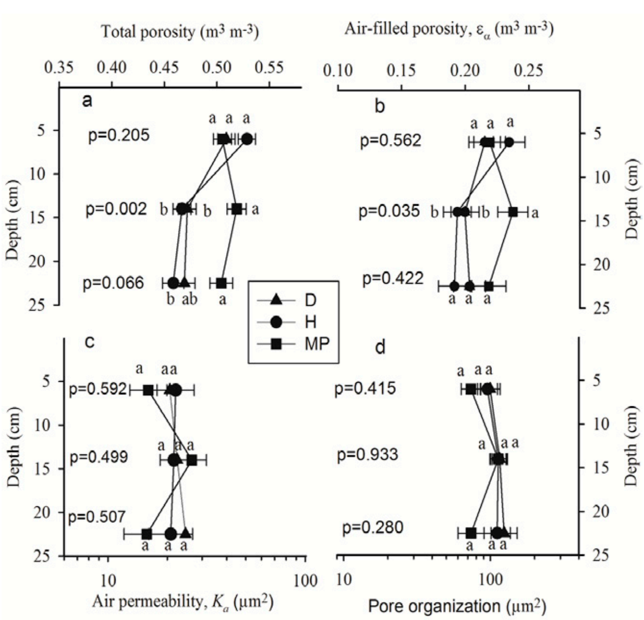

Fig. 1. The effect of different tillage treatments on (a) total porosity, (b) air-filled porosity, (c) air permeability, and (d) pore organization: direct drilling (D), harrowing to a depth of 8 to 10 cm (H), and moldboard plowing to a depth of 20 cm (MP). Values for (b), (c), and (d) measured at −10 kPa matric potential; *x* axes in (c) and (d) are on a logarithmic scale. Bars indicate ± standard error.

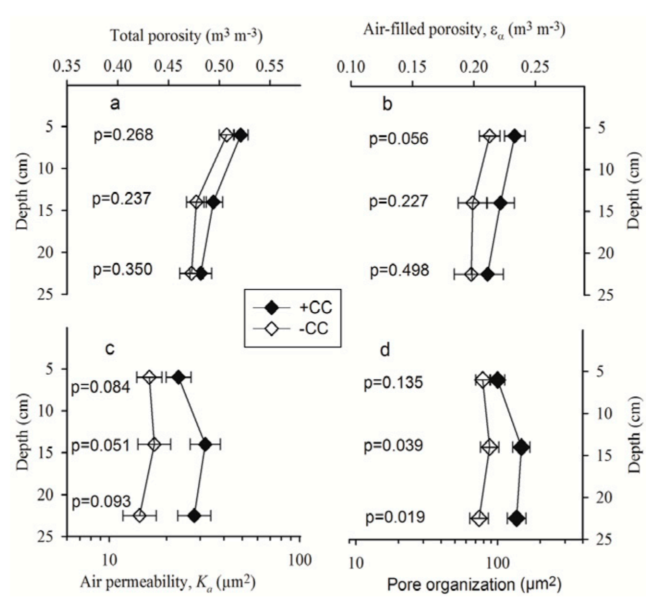

Fig. 2. The effect of cover crop treatments on (a) total porosity, (b) air-filled porosity (c) air permeability, and (d) pore organization: plots with cover crop (+CC), plots without cover crop (−CC). Values for Values for (b), (c), and (d) measured at −10 kPa matric potential; *x* axes in (c) and (d) are on a logarithmic scale. Bars indicate ± standard error.

Table 1. Treatment effect on microporosity (<30 μm), pore organization, and air permeability of soil at different matric potentials (−3 and −30 kPa), relative gas diffusivity, and infiltration rate.

Soil attribute	Depth	Tillage treatment†			Cover crop treatment‡	
		D	H	MP	+CC	−CC
	cm					
<30-μm§ pore volume, $m^3\ m^{-3}$	4–8	0.294 a¶	0.294 a	0.286 a	0.288 a	0.295 a
	12–16	0.272 a	0.273 a	0.281 a	0.273 a	0.278 a
	18–27	0.266 b	0.267 b	0.286 a	0.271 a	0.275 a
Pore organization at −3 kPa, μm^2	4–8	100 a	100 a	67 a	107 a	72 a
	12–16	111 a	123 a	112 a	159 a	83 b
	18–27	104 a	98 a	54 a	121 a`	56 b
Pore organization at −30 kPa, μm^2	4–8	98 a	111 a	77 a	105 a	84 a
	12–16	98 a	99 a	103 a	123 a	81 b
	18–27	nd#	nd	nd	nd	nd
Gas diffusivity at −10 kPa	4–8	0.030 a	0.033 a	0.029 a	0.033 a	0.029 a
	12–16	0.031 a	0.026 a	0.034 a	0.035 a	0.026 a
Infiltration rate at −4 cm, cm d^{-1}	soil surface	156 a	122 a	260 a	170 a	171 a
Air permeability at −3 kPa, μm^2	4–8	11.0 a	11.2 a	7.5 a	12.6 A	7.5 B
	12–16	11.8 a	12.9 a	14.1 a	20.0 a	8.3 b
	18–27	12.3 a	10.7 a	6.3 a	14.6 a	5.8 b
Air permeability at −30 kPa, μm^2	4–8	26.9 a	33.1 a	21.4 a	30.9 A	22.9 B
	12–16	24.6 a	24.6 a	30.2 a	33.9 a	20.4 a
	18–27	nd	nd	nd	nd	nd

† D, direct drilling; H, harrowing to a depth of 8–10 cm; MP, moldboard plowing to a depth of 20 cm.

‡ +CC, plots with cover crop; −CC, plots without cover crop.

§ Soil pore size fraction (<30 mm) was derived from water retention measurements, assuming the approximate relation $d = -3000/y_m$, where d is pore diameter (in μm) and y_m is the matric potential (in cm) (Carter and Ball, 1993).

¶ Numbers followed by identical lowercase letters (across the rows for each main effect) are not significantly different at the $p < 0.05$ level; numbers followed by identical uppercase letters are not significantly different at the $p < 0.10$ level.

nd, not defined.

effect of cover crop on PO was pronounced at all investigated depths and matric potentials, except at 4 to 8 cm where at −3 kPa it was only a trend ($p = 0.061$) (Table 1; Fig. 2).

The model describing the relationship between air permeability and air-filled porosity, Eq. [3], fitted our data well and indicated a strong linear log–log relationship between K_a and ε_a (Fig. 2). Table 4 presents the fitted parameters (log M = intercept and N = slope) and blocked soil porosities, ε_b, for the cover crop treatments. Larger air permeabilities and smaller blocked soil porosities were observed in plots with a cover crop (+CC) than plots without a cover crop (−CC) at both depths (Table 4; Fig. 4). The slope of the regression lines, N, which is considered to be a continuity index (Ball et al., 1988; Dörner and Horn, 2006) tended to be larger for −CC than for +CC, although they were not significantly different at the 4- to 8-cm depth and were almost significantly different ($p = 0.059$) at the 12- to 16-cm depth (Fig. 4; Table 4).

Direct drilling and harrowing tended to increase the estimated effective pore diameter, d_B (Eq. [5]) compared with MP at the 4- to 8-cm depth ($p = 0.058$). This was the case also for the cover crop treatment (+CC) at both depths ($p = 0.13$ and 0.059 for the 4–8- and 12–16-cm depths, respectively) (Table 5).

Plowing and H appeared to have a higher number of air-filled pores, n_B (Eq. [6]) at the 4- to 8-cm depth than D. At the 12- to 16-cm depth, plowing also tended to increase n_B, although it was not significantly different from D and H ($p = 0.145$) (Table 2). The cover crop did not significantly affect n_B at either depth (Table 5).

DISCUSSION

Tillage Effects

There was no significant effect of tillage treatments on total and air-filled porosity, air permeability, pore volumes with equiva-

Table 2. Soil structural properties at the 0- to 20-cm depth assessed from X-ray computed tomography scanning (for connected pores). All values are geometric means.

Soil attribute†	Tillage treatment‡			Cover crop treatment§	
	D	H	MP	+CC	-CC
PV, cm^3	123 a¶	114 a	200 a	136 a	145 a
PS, cm^2	1548 a	1428 a	2421 a	1692 a	1808 a
Networks, no.	200 a	209 a	159 a	164 a	216 a
Branches, no.	3845 a	4410 a	6978 a	4964 a	4855 a
Junctions, no.	1748 a	2030 a	3320 a	2314 a	2238 a
End points, no.	1379 a	1507 a	2006 a	1576 a	1644 a
Branch length, mm	4.77 a	4.43 a	4.86 a	4.87 a	4.50 a
DA	0.45 a	0.45 a	0.37 a	0.43 a	0.42 a

† PV, pore volume; PS, pore surface; DA, degree of anisotropy.

‡ D, direct drilling; H, harrowing to a depth of 8–10 cm; MP, moldboard plowing to a depth of 20 cm.

§ +CC, plots with cover crop; −CC, plots without cover crop.

¶ Numbers followed by identical letters are not significantly different ($p < 0.05$) (across the rows for each main effect).

Table 3. Detected significant interactions between cover crop (CC) and tillage (Till) treatments. All values are geometric means.

Attribute	*P* value CC × Till	Treatment combination†					
		D+CC	D−CC	H+CC	H−CC	MP+CC	MP−CC
Branches, no.	0.0705	2713 b‡	5449 a	3762 B	5170 a	11981 a	4063 a
Junctions, no.	0.0688	1249 b	2447 a	1733 B	2376 a	5720 a	1928 a
End points, no.	0.0575	997 b	1906 a	1318 a	1723 a	2978 a	1352 a

† D+CC, direct drilling with cover crop; D−CC, direct drilling without cover crop; H+CC, harrowing with cover crop; H−CC, harrowing without cover crop; MP+CC, moldboard plowing with cover crop; MP−CC, moldboard plowing without cover crop.

‡ Numbers followed by identical lowercase letters are not significantly different at the $p = 0.05$ level across the rows for each main effect; numbers followed by identical uppercase letters are not significantly different at the $p < 0.10$ level.

lent diameters <30 and >30 μm, relative gas diffusivity at −10 kPa, or pore organization at the 4- to 8-cm sampling depth (Table 1; Fig. 1). This was inconsistent with findings from a number of other studies (that is, Ball and Robertson, 1994; Comia et al., 1994; Folorunso et al., 1992; Schjønning and Rasmussen, 2000). In our study, however, a chisel coulter was used, which loosened and mixed the soil to some extent at the 0- to 8-cm depth. The model-derived parameters showed a distinct effect of tillage treatments on the number of conducting soil pores per square centimeter (n_B) and effective pore diameter for gas flow (d_B) at the 4- to 8-cm depth (Table 5). Ten years of using direct drilling significantly increased d_B compared with MP. As reported by Kawamoto et al. (2006) and Møldrup et al. (2010), higher d_B values may be interpreted as a more well-structured soil in terms of pore continuity or pore organization. Our findings at the 4- to 8-cm depth showed a positive (although not significant) effect of D on PO compared with MP (Fig. 1d). At the 12- to 16-cm depth, a similar effect of tillage was found for d_B and PO (Table 5; Fig. 1d). Our findings therefore support the existence of a direct relation between d_B and PO.

At the 12- to 16-cm depth, direct drilling and harrowing significantly reduced the total porosity and air-filled porosity at −10 kPa (the volume of pores with equivalent diameters >30 μm) compared with plowing (Fig. 1). This is consistent with previous observations from the experiment (Munkholm et al., 2008) and with other studies (Comia et al., 1994; Douglas et al., 1980; Francis et al., 1987). However, tillage treatments did not affect PO at the 12- to 16-cm depth. This was not consistent with the observations of Dowdell et al. (1979), Francis et al. (1988), and Schjønning (1989). Francis et al. (1988) attributed the more rapid leaching through direct-drilled than moldboard-plowed soil to the larger connectivity and size of pores with direct drilling. Schjønning (1989) also reported higher values of PO in direct-drilled than in plowed soil at a moisture content around field capacity (−10 kPa matric potential).

From the observations on total and air-filled porosity at −10 kPa (i.e., equivalent pore volume >30 μm) (Fig. 1a and 1b) and the retention curve for the 12- to 16-cm depth (Fig. 5), we inferred that the higher total porosity in MP than in D and H can be explained by the greater volume of large pores in MP soils. That is, at the 12- to 16-cm depth, MP produced larger total and air-filled porosity (equivalent pore volume >30 μm) and a higher water content (Fig. 5) at matric potentials greater than −10 kPa (that is, −3 and −1 kPa and the saturation point). Consequently, compared with H and D soils, the MP soil retained more water in larger (>30 and >300 μm) pores. Figure 5 shows no difference among tillage treatments in the equivalent pore diameter <30 μm, that is, water content at ≤ −10 kPa matric potential (field capacity). This is consistent with the observations in Table

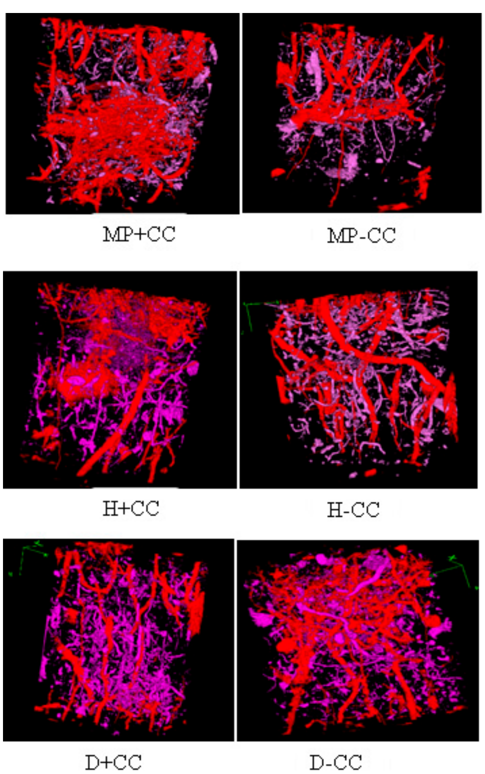

Fig. 3. X-ray computed tomography scanned images of soil pores for the combinations of tillage and cover crop treatments: direct drilling with cover crop (D+CC), direct drilling without cover crop (D−CC), harrowing with cover crop (H+CC), harrowing without cover crop (H−CC), moldboard plowing with cover crop (MP+CC), moldboard plowing without cover crop (MP−CC). Connected pores are in red and unconnected pores in purple.

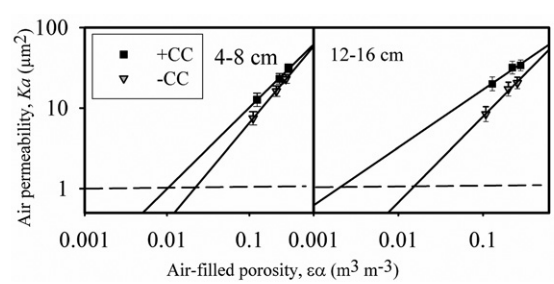

Fig. 4. Air permeability (geometric means) as related to air-filled porosity (arithmetic means) at different matric potentials (−3, −10 and −30 kPa for the 4–8- and 12–16-cm depths) in a log–log plot for cover crop treatments: plots with cover crop (+CC), plots without cover crop (−CC). Lines indicate least squares linear regression. Horizontal dashed line indicates critical level of air permeability (<1 μm²; Ball et al., 1988). Bars indicate ± 1 standard error.

1, which show no difference among tillage treatments for equivalent pore diameter <30 μm at the 12- to 16-cm depth.

The weak and insignificant tendency for greater pore organization with D and H than with MP at the 18- to 27-cm depth suggests that 10 yr of reduced tillage has had a slight, positive influence on soil structure in the plow pan region. More time is probably needed for the soil to recover. Schjønning (1989) reported a similar and significant effect after 18 yr of reduced tillage. The 18- to 27-cm cores were taken at the transition between the Ap horizon and the upper subsoil layers. That is, the MP 18- to 27-cm cores included both an annually plowed part and an unplowed upper subsoil part, whereas the D and H treatment cores included only untilled layers. This may explain the tendency toward higher total porosity at the 18- to 27-cm depth for MP than for H and D (p = 0.066) (Fig. 1a).

Table 4. The predicted results using models expressed by Eq. [2] and [3].

Depth	Treatment†	Model predictions: $\log(K_a) = \log(M) + N \log(\varepsilon_a)$			
		$\log(M)$	N	R^2	ε_b = blocked pores‡
cm					% (v/v)
4–8	+CC	2.00 a (0.052)§	0.97 a (0.094)	1.00	1.18 B (0.378)
	−CC	2.03 a (0.052)	1.20 a (0.094)	1.00	2.18 A (0.378)
12–16	+CC	1.94 a (0.049)	0.71 B (0.095)	0.97	0.34 b (0.269)
	−CC	1.96 a (0.049)	1.05 A (0.102)	0.99	1.48 a (0.281)

† +CC, plots with cover crop; −CC, plots without cover crop.

‡ Means for blocked pore space are not exactly the same as the results derived from the application of Eq. [3] on the values for log(M) and N in this table. This is due to the statistical procedure and calculations used for estimating weighted means.

§ Numbers followed by identical lowercase letters (across the partial columns) are not significantly different at the $p < 0.05$ level; numbers followed by identical uppercase letters are not significantly different at the $p < 0.10$ level. Standard errors are shown in parentheses.

Cover Crop Effects

Unlike the tillage treatments, the cover crop affected the air-filled porosity ($p = 0.056$) and air permeability at all investigated matric potentials ($p < 0.1$) and PO at −3 kPa ($p < 0.05$) at 4 to 8 cm (Table 1; Fig. 2). These results are consistent with the results of Steele et al. (2012). They observed a pattern of increased air permeability and decreased bulk density in the surface soil layer (0–7 cm) following the planting of a cover crop. In our study, however, the cover crop did not affect the total porosity, n_B, and d_B at this depth (Table 5; Fig. 2). Wagger and Denton (1989) were likewise unable to measure an effect of cover crop on total porosity. Nevertheless, a strong tendency at this depth for fewer blocked pores ($p = 0.062$) in plots growing a cover crop is consistent with a higher level of air permeability and pore organization (Tables 1 and 4; Fig. 2).

At the 12- to 16-cm depth, the cover crop affected PO at all investigated matric potentials and air permeability at −3 and −10 kPa matric potentials (Table 1; Fig. 2). The positive effect of a cover crop on d_B and PO at this depth once again is evidence of a close relation between these two model-derived parameters. Lower blocked porosity values at 12 to 16 cm (Table 4) were also consistent with PO and d_B at this depth (Tables 4 and 5). A significant reduction of occluded (blocked) porosity in plots with a cover crop compared with plots without was also found by Villamil et al. (2006), although they measured it in a different way. Lower values of N (Table 4), which was suggested as a pore continuity index (Ball et al., 1988; Dörner and Horn, 2006), at 4 to 8 (not significant) and 12 to 16 cm (p = 0.059) in their cover crop treatments were not consistent with the higher values of PO for cover crop treatments in our study (Table 1; Fig. 2).

Air permeability and PO at the 18- to 27-cm depth were also affected by the cover crop (Table 1; Fig. 2). This indicated a positive effect of cover crop on pore characteristics at the transition between the Ap horizon and the plow pan layer, that is, an alleviation of the plow pan compaction. In Abdollahi and Munkholm (2014), we also reported a positive effect of cover crop on penetration resistance.

We found no effect of cover crop on infiltration rate (Table 1), which was consistent with the finding of Folorunso et al. (1992) in the Central Valley of California, where they used oat (*Avena sativa* L.)–vetch (*Vicia* sp.) and vetch cover crops. They concluded that the final infiltration rate is related to a complex function of topsoil and subsoil strength and permeability. In this study, the existing plow pan in all tillage treatments (reported by Abdollahi and Munkholm, 2014)—caused by previous long-term plowing operations—has most likely blurred the effects of recent differences in soil management as related to tillage and cover crop.

Interaction Effects Between Tillage and Cover Crop

There was no interaction between tillage and cover crop on the pore characteristics obtained from traditional core measurements. On the other hand, the X-ray CT data showed almost significant interactions ($p < 0.10$) for the number of branches (p = 0.071), number of junctions (p = 0.069), and number of

Table 5. Estimates of effective pore diameter, d_B, and number of soil pores, n_B, derived from the tube model of Ball (1981) at a matric potential of −10 kPa for the 4- to 8- and 12- to 16-cm depths (using Eq. [5] and [6]).

Soil attribute	Depth	Tillage treatment†			Cover crop treatment‡	
		D	H	MP	+CC	−CC
	cm					
d_B, μm	4–8	162 A§	152 AB	137 B	156 a	144 a
	12–16	162 a	169 a	159 a	180 A	149 B
n_B, cm^{-2}	4–8	406 b	539 a	568 a	498 a	511 a
	12–16	399 a	345 a	517 a	390 a	450 a

† D, direct drilling; H, harrowing to a depth of 8–10 cm; MP, moldboard plowing to a depth of 20 cm.

‡ +CC, plots with cover crop; −CC, plots without cover crop.

§ Numbers followed by identical lowercase letters are not significantly different at the $p < 0.05$ level (across the rows for each main effect); numbers followed by identical uppercase letters are not significantly different at the $p < 0.10$ level.

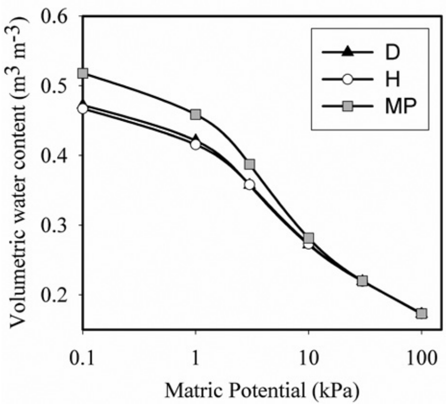

Fig. 5. Retention curve of soils under different tillage treatments at the 12- to 16-cm depth: direct drilling (D), harrowing to a depth of 8 to 10 cm (H), and moldboard plowing to a depth of 20 cm (MP).

endpoints (0.058) (Table 3). As shown in Table 3, the use of a cover crop decreased the values of these pore network properties for D and H but showed the opposite trend for MP. This is also reflected in the three-dimensional images for the treatment combinations shown in Fig. 3. As can be seen in this figure, MP+CC had a larger number of connected pores (red colors) than D+CC and H+CC.

This was not consistent with the results obtained from the traditional soil core measurements (current study) and the in situ drop-shatter field measurements in the companion study (Abdollahi and Munkholm, 2014). Core data showed larger values for air permeability and pore organization in cover crop treatments (Table 1; Fig. 2). Moreover, a decreasing (positive) effect of cover crop on the mean weight diameter (MWD) of direct-drilled soil and a negative correlation between macroporosity and MWD was reported in Abdollahi and Munkholm (2014). Accordingly, we expected a positive effect of cover crop on direct-drilled soil in X-ray CT scan data. The reason for finding the opposite might be the differences between the pore size distribution and the sample sizes used with these methods. Our CT scan accounted for macropores (>430 μm) in the entire 0- to 20-cm layer, that is, only very large pores. In comparison, the core data account for micro- (<30 μm) and macro- (>30 μm) pores at specific 4- to 8- and 12- to 16-cm depths. We might have obtained a better correspondence between the X-ray CT scan and the core data if we had been able to scan with much finer resolution and also directly compare results from the same depth intervals. For future studies, we recommend supplementing with high-resolution scanning (<30 μm) of the cores taken for water retention, air permeability, etc., in the laboratory.

CONCLUSION

We hypothesized that the use of a cover crop would reduce the need for intensive tillage and would have a positive impact on the pore system to facilitate air and water transport in the soil system. Our results showed that the cover crop had created continuous macropores, improving the conditions for water and gas transport and main crop root growth. The cover crop had thus alleviated the effect of tillage pan compaction in all the tillage treatments.

Although the core sample results did not show any interaction between tillage and cover crop treatments on pore characteristics, a negative effect of cover crop on D and H was detected from the X-ray CT scan data, which was inconsistent with our findings for traditional core and in situ infiltration rate measurements. This highlights the need for scanning with a fine resolution and using consistent depth increments or intervals and sample sizes for plausible comparisons.

Ten years of tillage treatments had little effect on the pore characteristics at the 4- to 8- and 18- to 27-cm depths. At the 12- to 16-cm depth, negative effects of the reduced tillage treatments (D and H) were found for total porosity and air-filled porosity at −10 kPa (that is, >30-μm pores). Higher total porosity under MP than D and H at the 12- to 16-cm depth was found to be related to the greater volume of large pores (>30 μm).

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Paper IV

Overall assessment of soil quality on humid sandy loams: Effects of climate, rotation and tillage

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Overall assessment of soil quality on humid sandy loams: Effects of climate, rotation and tillage

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Abstract

Conservation tillage and diversified crop rotations have been suggested as appropriate alternative management systems to sustain soil quality. The purpose of this study was to quantify the “productivity function” of soil and soil structural changes following the application of three crop rotations (R2-R4): R2, a winter-dominated crop rotation with straw incorporated; R3, a mix of winter and spring crops with straw removed; R4, the same mix of crops as in R3 but with straw incorporated and three tillage systems: mouldboard ploughing to a depth of 20 cm (MP); harrowing to a depth of 8–10 cm (H) and direct drilling (D) at two experimental sites with sandy loam soil and different water budgets in Denmark. The Muencheberg soil quality rating (M-SQR) method and simpler soil quality indices (i.e. visual evaluation of soil structure (VESS), overall visual structure (OVS) and overall soil structure (OSS)) were employed to differentiate the effects of these alternative managements on mainly soil structural quality. A Pearson correlation was also employed to find the correlation between the soil quality indices and relative crop yield (RY). Relevant soil properties for calculating the soil quality indices were measured or obtained from previous publications. Crop rotation affected the soil structure and RY. The winter-dominated crop rotation (R2) resulted in the poorest soil structural quality and produced the lowest RY compared to the mixed rotations (R3 and R4). Tillage systems clearly influenced the soil quality and RY. The MP resulted in the best soil structural quality and consequently the highest RY compared with reduced tillage. Significant correlations were found in most cases between soil quality indices (including M-SQR) and RY. This highlights the influence of soil quality - and soil structure in particular - on crop yield potential.

Keywords: crop yield potential, rotation, tillage, Muencheberg soil quality rating, soil structure

1. Introduction

Soil performance plays a crucial role for the survival and development of civilisations by providing food, fibre and essential goods for an ever-increasing world population (Hillel, 2009). The production of food and fibre is based on the soil "productivity function" and is considered one of the main soil functions (Blum, 1993; EC, 2006). Recent studies show that food production is not keeping pace with the increasing demand for food (Cassman et al., 2003; Richter et al., 2007) and suggested a sustainable employment of soil system (Jones et al., 2009; Lal, 2008, 2009) to avoid soil degradation (Lal, 2008, 2009; Oldeman, 1998). Conservation agriculture (Torres et al., 2001) including conservation tillage and diversified crop rotations (Zentner et al., 2002) has been suggested as appropriate alternative management systems to achieve sustainable agriculture (Hatfield and Karlen, 1994). These newly introduced tillage and cropping systems must be economically viable and adapted to the soil and climatic conditions of the arable area and also ensure the quality and quantity of grain yield production (Campbell et al., 1995; Zentner et al., 2002). Development of alternative management strategies has necessitated an assessment of the direct and indirect effects of these management systems. Hence, the concept of "soil quality" was used to evaluate the impacts of different soil management strategies (Doran, 2002; Karlen et al., 1992; Karlen et al., 1997). There is no direct way of measuring soil quality. However, measuring and monitoring the changes in soil quality indicators following the application of a specific management strategy would be a useful approach to infer the current quality status of a soil (Sharma et al., 2008). Indexing soil quality has been proposed as an efficient tool in combining soil information to be used in decision-making activities at different scales and consequently at different accuracies (Andrews et al., 2002a; Karlen et al., 2001). Soil quality test kits (Liebig et al., 1996), visual assessment of soil (VSA) (Shepherd, 2000; Shepherd et al., 2000; Shepherd and Janssen, 2000), visual assessment of soil structure (VESS) (Ball et al., 2007) and linear and non-linear scoring of soil quality indicators to produce additive and weighted additive indices of soil quality (Andrews et al., 2002a) are some of the indexing methods used. Among available assessment approaches of agricultural soil quality we considered a method that focuses more directly on the quantification of land productivity potential. The Muencheberg Soil Quality Rating (M-SQR) (Mueller et al., 2007) has been developed for the quantification of cropland and grassland. This method is based on the ratings of indicators relevant for the productivity function of soil and has been reported to yield reliable, transferable and universally acceptable results (Mueller et al., 2012; Richter et al., 2009). It works with two types of indicators, i.e. "basic indicators" and "hazard indicators". The former relates mainly to the soil substrate (texture) and structural properties of soil that both are relevant to soil productivity function (plant growth). The latter relates to factors that severely restrict plant growth. The two visual methods (VSA and VESS) that are utilised to evaluate crucial soil structural properties (i.e. porosity, root frequency and aggregate size and shape) could both be used in the rating of the Muencheberg overall soil quality score. By including these overall assessment tools (VSA or VESS) this method is benefiting from their strength in the soil quality assessment and also supplements this with other aspects of climate conditions and inherent soil properties.

The purpose of this study was to quantify (rate) the "productivity function" of soil following the application of crop rotations and tillage systems using the M-SQR method at two experimental sites in Denmark. Another purpose was to quantify the effects of crop rotations and tillage systems on the relative yield (RY) and some soil quality indices. Lastly the purpose was to explore the relationship between RY and soil quality indices.

2. Material and Methods

2.1. Rating the overall soil quality

The M-SQR uses both inherent and management-induced soil quality indicators and climate data including thermal and moisture regimes of soil (Fig. 1). Using the scoring tables, two types of indicators ("basic soil indicators" and "soil hazard indicators") are scored, weighted and summarised to yield a final score in the range of 0 to 100 (Mueller et al., 2007). Basic soil indicators include soil substrate, A-horizon depth, topsoil structure, subsoil compaction, rooting depth, profile available water, wetness and ponding and slope and relief, which are quantified in situ (Fig. 1). Each indicator is scored on a scale ranging from 2 (best condition) to 0 (worst condition) with increments of 0.5. Soil hazard indicators are critical soil parameters (mostly determined by climate factors) that may limit soil functions and total soil quality. They are considered as multipliers for the basic soil score. The score for the most severe hazard indicator (0.01-3.0) is used as a multiplier for the basic soil indicator score to yield the overall soil quality rating index (M-SQR score), ranging from 0 to 100 (Fig. 1). Classes of M-SQR rating are: <20 = very poor, 20-40 = poor, 40-60 = moderate, 60-80 = good and 80-100 = very good (More details on the rating system and scoring tables can be found in the manual (Mueller et al., 2007)).

2.2. Study sites and their basic indicators

The study sites were located at research centres Foulum (56°30′ N, 9°35′ E) and

Flakkebjerg (55°19′ N, 11°23′ E), on sandy loam soil in Denmark. Both soils are based on ground morainic deposits from the last glaciation. The soil at Foulum is classified as a Mollic Luvisol and the soil at Flakkebjerg as a Glossic Phaeozem according to the WRB (FAO) system (Krogh and Greve, 1999). The clay (<2 µm), silt (2-20 µm), fine sand (20-200 µm) and coarse sand (200-2000 µm) contents of the soil (0-25 cm) were 92, 126, 444 and 307 g kg^{-1} and 147, 137, 426 and 270 g kg^{-1}, for Foulum and Flakkebjerg, respectively. At both sites, an experiment on rotation and tillage had been running since 2002. The experimental design was a split plot in four replications with two factors: rotation as main plot and tillage as subplot (Hansen et al., 2010). Of the four crop rotation systems, rotations 2 (R2), 3 (R3) and 4 (R4) were used for this study (Table 1). In crop rotation R3 straw was removed and in R2 and R4 straw was left in the field (cut and retained after harvest). R2 included winter crops whereas R3 and R4 consisted of a mixture of winter and spring crops. Except for the years 2010 and 2012 when minor changes took place in R2 due to weather conditions (i.e. spring barley was sown at Foulum instead of winter wheat in 2010 and winter wheat was grown at Foulum instead of winter rape in 2012), the crop rotations were implemented as planned (Table 1). Fodder radish (*Raphanus sativus*) was also used (undersown 14 days before each expected harvest) as a cover crop in R3 and R4 (Table 1). The tillage systems were direct drilling (D), harrowing to a depth of 8-10 cm (H) and ploughing to a depth of 20 cm (MP). Before the establishment of the experiment the fields had been ploughed for decades.

2.3. Measuring and scoring basic soil indicators

To score basic soil indicators there is a need to measure soil properties in the field. Soil texture was determined using a combination of sieving and the hydrometer method. Organic matter was measured by the dry combustion method. Bulk density and rooting depth data were available from previous studies (Abdollahi et al. 2014; Munkholm et al., 2008). A-horizon depth had been measured at the beginning of the experimental setup in 2002. Topsoil structure was evaluated using the visual evaluation of soil structure (VESS) method (Ball et al., 2007; Guimarães et al., 2011) and scored according to Table 2. This visual evaluation took place in October 2013 at soil moisture content near field capacity. The average of two evaluations per subplot (36 plots × 2 points = 72 points) was used for statistical analysis. To evaluate subsoil compaction a data set including soil penetration resistance (PR) that had been measured in R2 plots in 2006 was used. We assumed minor changes in subsoil penetration resistance until 2012 as the plots were not heavily trafficked. This assumption was based on the minor differences in penetration resistance data that were found at Foulum between 2006 (i.e. Munkholm et al. (2008), Fig. 1) and 2012 (i.e. Abdollahi and Munkholm (2014), Fig.5).

Penetration resistance was measured to a depth of 60 cm using an automated cone penetrometer (Olsen, 1988) at soil moisture content near field capacity. Ten measurements were performed in each subplot. An average of PR data for 25-55 cm depths (Mueller et al., 2013) was used for the evaluation of subsoil compaction and PR values were converted into M-SQR ratings according to Table 3.

Profile available water (PAW, basic indicator 6) was calculated from the available retention data for the experimental plots (samples were taken in 2008) and available water content between pF 2.0 and pF 4.2 was calculated by subtraction. The water content at pF 4.2 was estimated using the pedotransfer function of Hansen (1976):

$$IW = 0.365 \times clay + 0.729 \times SOM + 0.630$$

with clay and soil organic matter (SOM) in g $100g^{-1}$, where IW was defined as the gravimetric soil water content (GWC) at pF 4.2 (1500 kPa). In order to convert to volumetric water content (VWC, m^3 m^{-3}), IW was multiplied by bulk density. To calculate the PAW, VWC was multiplied by root depth in each plot. For rating of PAW the M-SQR manual (Mueller et al. (2007), Table 3.2.6.-1) was used. Root depth at both sites was between 110-150 cm (Munkholm et al., 2008) and according to Table 3.2.5.-1 in the manual the score of 1.5 was assigned for the rooting depth indicator. The depth of A-horizon was >25 cm in all plots. This basic indicator was scored according to Table 3.2.2.-1 in the manual. The other basic indicators were wetness and ponding in addition to slope and relief that were the same for both sites and received the same scores for both sites.

2.4. Scoring soil hazard indicators and computing overall soil quality index

For rating soil hazard indicators climate data are required. Monthly climate data for both locations for the main vegetation period of four months (May-August) were used to calculate drought risk score and multiplication factor of hazard risk. This data was taken from an existing data set available in Denmark and drought risk score and multiplier value were calculated according to tables 3.3.7.-1 and 3.3.7.-2 of the field manual, respectively. The only hazard detected in the area (and only at Flakkebjerg) was drought risk. To compute the overall soil quality index (M-SQR score) the score of each basic soil indicator was multiplied by its weighting factor (values in the parentheses behind each indicator, Fig. 1). The weighted sum of basic soil indicators is called the "basic soil score". This score is multiplied by the hazard multiplier derived from the most critical hazard soil indicator (in this case drought risk) to yield the overall soil quality index (M-SQR score), which may range from 0 (lowest) to 100 (highest).

2.5. Crop yield data

Crop yield was harvested using a plot combine and data were converted to dry matter yield. For winter wheat, winter barley and spring barley the dry matter content was determined by near-infrared spectroscopy (Infratec^{MT} 1241 Grain Analyzer, Foss A/S; Büchmann et al. (2001)), while oat and winter rape was dried to 80 °C. To convert the yield data of different crops to a comparable value, relative yield (proportion of measured yield/regional average yield for a specific crop) (Andrews et al., 2002b) was calculated for all the crops in the rotations. To avoid the possible unexpected effects of natural phenomena on the crop yield in each individual year, the available crop yield data for four consecutive years (2009-2012) were averaged and used in the analysis.

2.6. Calculating more soil quality indices

Mueller et al. (2013) computed a complex index of soil structure (i.e. Overall Visual Structure (OVS)) to be used for the analysis of visual soil structure in the context of crop yield and overall soil quality score. They averaged the scores of three basic indicators (Fig. 1) including topsoil structure, subsoil compaction and rooting depth to yield a score between 0 (lowest) to 2 (highest). We calculated this and proposed the computation of another complex index that included topsoil structure and subsoil compaction scores and the score of "A-horizon depth". We added the score for the A-horizon depth because, in our experiment, this score was highly dependent on the organic matter content of soil. In most plots at the Flakkebjerg site, for example, the OC content was less than 2 g 100 g^{-1} and received a score that was 0.5 point lower than plots containing more than 2 g OC 100 g^{-1} soil (see Table 2.2.2.-1 of the field manual). Organic carbon plays an important role for soil productivity function by affecting chemical, physical and biological soil properties (Karlen et al., 1994; Kimetu et al., 2008; Oades, 1984). Furthermore, rooting depth scores for both locations were identical and had no effect on the calculated OVS score. We termed this index "overall soil structure" score (OSS) and tried to relate this to soil productivity function (relative yield).

2.7. Statistics

All statistical analyses were carried out using SAS version 9.2 (SAS Institute Inc., 2009). For different variables, averages were calculated for each plot and used in the calculation of mean and standard error. The averages were also used as input in mixed models to test for treatment effects. We tested the effects of experimental treatments in a MIXED model with treatments as fixed effects and block and location as random effects. Rotation treatment was considered as a main effect with tillage treatment as a split-plot effect. To test the correlation between yield data and M-SQR scores and other complex indices, a Pearson correlation test was carried out at plot level.

3. Results

3.1. Treatment effects on soil structural scores and relative crop yield

3.1.1. Rotation effects

Rotation had no significant effect on soil structure when evaluated by visual evaluation of soil structure (VESS) (Table 5). However, the overall visual structure (OVS) and the overall soil structure score (OSS) revealed a significant effect of rotation on soil structure. The OSS indicated these effects only for the Flakkebjerg site. The average relative yields of the study sites were affected by rotation and R2 resulted in a lower relative crop yield compared to R3 and R4. For R3 and R4 the RY did not differ.

3.1.2. Tillage effects

Tillage systems affected significantly all soil structure representatives (VESS, OVS and OSS, Table 5). Mouldboard ploughing (MP) produced the best topsoil quality (Lowest VESS score) and showed a higher score of OVS and OSS (better condition for plant growth) compared to harrowing to a depth of 8-10 cm (H) and direct drilling (D) (Table 5). Of the tillage systems, D resulted in the poorest soil quality (highest VESS score) for both the studied locations. Harrowing (H) showed an intermediate topsoil quality score (VESS) for both locations. No significant differences were found between D and H for OVS and OSS at both locations. The average relative yields at both sites and RY at Flakkebjerg were significantly affected by tillage (Table 5). The RY for mouldboard-ploughed soil was higher compared to H and D treatments. No significant difference was found between H and D.

3.2. Correlation between relative crop yield (RY) and M-SQR score

The M-SQR scores were calculated as the overall soil quality index for each plot in the studied locations (average of plots shown in Table 5). According to Table 5, the average M-SQR scores for the Foulum site were larger than at Flakkebjerg for different rotation and tillage systems. This was also reflected in the differences between crop yields at both sites, where the RY at Foulum was larger than at Flakkebjerg (Table 5). The correlation test between the M-SQR score and relative crop yield indicated a significant correlation (R^2=0.27) between all measured yield data and calculated M-SQR scores (Fig. 2), which was mainly due to the differences between the two locations. Although this information might be of interest, it would be of greater interest to find a correlation between M-SQR score and crop yield for each individual location. Generally, the overall M-SQR score f or Foulum did not reveal a significant correlation with crop yield data (p=0.62). At Flakkebjerg, the overall soil quality score correlated significantly with RY (R^2=0.24) (data not shown). This correlation differed for the three rotation systems (Fig. 3) where the M-SQR score correlated better with crop yield for R2 (R^2=0.52) than for R3 and R4 (R^2=0.32 and 0.32, respectively). At Foulum a significant correlation between M-SQR score and RY was found for R2 (R^2=0.37) (Fig. 4). At Flakkebjerg, the overall soil quality score significantly correlated with RY (R^2=0.55) for the D tillage system (Fig. 5).

3.3. Correlation between relative crop yield and soil quality indices

The OVS was well correlated with RY for almost all crop rotations at each study site (Table 6). This was more pronounced for R2 and R3 at both study sites and for R4 only at Flakkebjerg. The OVS was also well correlated with RY for the reduced tillage systems (H and D). However, the correlation of OVS with RY in H was more pronounced at Flakkebjerg than at Foulum (R= 0.74 and R= 0.38, respectively). The OSS index showed an almost similar correlation with RY as with OVS (Table 6). However, OSS did not correlate well with RY in R3 and R4 and tillage systems at Foulum.

The VESS score was only significantly correlated with RY for R2 at Flakkebjerg (Table 6). In addition, nearly significant correlations were found for R2 at Foulum and R4 at Flakkebjerg. There was no significant correlation between SOC and RY. Surprisingly, there were two significant or almost significant negative correlations between SOC and RY, i.e. for R3 at Foulum (R= -0.74) and for R2 at Flakkebjerg (R= -0.48).

4. Discussion

4.1. Effect of rotation on soil structure and yield

Although there was no effect of crop rotations on visual soil structure score (VESS), the other representatives of soil structure (i.e. OVS and OSS) indicated the influence of crop rotations on soil structure (Table 5). Generally R2 resulted in the poorest soil structure compared to R3 and R4. This was reflected in the lower RY value in R2 of 1.00 compared with 1.19 and 1.22 for R3 and R4, respectively. Hence, the poorer soil structure in R2 than in R3 and R4 and also the use of a winter-dominated crop rotation in R2 compared with a mix of winter and spring crops in R3 and R4 (Table 1) might have been responsible for the significantly lower RY in R2. A significant reduction in total crop yield for crop rotations that included winter crops was also reported by Tsuji et al. (2006) in a direct drilling tillage system in Japan. The diverse crop rotations (i.e. a mix of spring and winter crops) of R3 and

R4 and the better soil structure might be regarded as drivers of significantly higher RY at both Flakkebjerg and Foulum compared to R2. Munkholm et al. (2013) also reported a profound, positive effect of a diverse crop rotation (i.e. corn, corn, oats (*Avena fatua* L.) and spring barley (*Hordeum vulgare* L.)) on the crop yield and soil structure of a silt loam in a 30-year crop rotation in Canada.

4.2. Effect of tillage on soil structure and yield

The visual assessment of soil structure and other representatives of soil structure included in M-SQR method (i.e. OVS and OSS) clearly revealed the influence of tillage systems on soil structure (Table 5). At both sites, MP resulted in a better soil structure (i.e. the lowest VESS score and the largest OVS and OSS scores) compared with reduced tillage systems (H and D) even though D at Foulum was not significantly different from MP for OVS and OSS. However, the soil structure under reduced tillage was still favourable for agricultural use and the visual structural quality was fair to good (i.e. VESS scores were <3.0, according to Ball et al. (2007)). Nevertheless, D showed a poorer soil structure than H (sq= 2.3 and 2.0 for D and H, respectively). This was consistent with the previous studies conducted at the experimental sites (Abdollahi and Munkholm, 2014; Ball et al., 2007) although Abdollahi and Munkholm (2014) reported the same VESS score for D and H. Soane et al. (2012) in a literature review of problems and opportunities for crop production in Europe have related the low adoption of conservation tillage practices (no-tillage and reduced tillage) in northern European countries to the problems of poorer topsoil structure following these tillage systems.

The better soil quality for MP was generally reflected in the RY averages across sites. MP (RY= 1.18) resulted in a higher RY compared to H (RY= 1.12) and D (RY= 1.12) (Table 5). No effect of tillage system on RY was found at Foulum. Although previous studies in the experimental area (Deike et al., 2008; Munkholm and Hansen, 2012; Schjønning et al., 2010) reported consistent results of tillage effect on crop yield, tillage systems have been shown to produce conflicting and inconsistent effects on crop yield. Dam et al. (2005) did not find a significant tillage effect on corn yield over 11 years of application of different tillage systems in a sandy loam soil in Canada. Díaz-Zorita et al. (2004) however, reported a negative effect of conventional tillage on crop yield and suggested direct drilling as an advantageous tillage system in terms of economic returns. Wang et al. (2007) also recommended no-tillage as the better tillage system due to its ability produce equivalent or higher crop yields compared to conventional tillage. The studies above, however, were conducted under climate conditions that differed from those in Denmark.

4.3. Assessment of soil productivity function

The Muencheberg Soil Quality Ratio (M-SQR) method was able to differentiate the yield data for both sites. Higher M-SQR scores for Foulum (84.2) than for Flakkebjerg (71.7) were consistent with higher RY values in Foulum and supported the feasibility of using M-SQR to assess the crop yield potential in two different locations with almost similar soil types but different water budgets. This was in agreement with Mueller et al. (2012) who reported the feasibility of using the M-SQR method to rate agricultural soil quality and crop yield potentials over 20 locations.

The M-SQR method also appears to have the promising potential of being able to discriminate the management effects (especially tillage systems effects) on RY at individual locations. The higher M-SQR score for MP than for H and D was consistent with the higher RY of MP compared with H and D. The discriminating power of this method for crop rotation effects on RY was only detected for the Flakkebjerg site where a significantly lower M-SQR score (M-SQR score=71.0) for R2 was consistent with its significantly lower RY (Table 5).

The correlation between RY data and overall M-SQR scores provided a better view of the strength and weakness of the M-SQR method in the prediction of crop productivity following the application of different management systems. It successfully discriminated the effects of all the crop rotations at Flakkebjerg (Fig. 3) and R2 at Foulum (Fig. 4). It was also useful in significant discriminating of the direct drilling tillage effect on the RY for the Flakkebjerg site (Fig. 5). The results indicate that there is a promising potential for using this method to predict crop yield.

4.4. The feasibility of using soil quality indices to discriminate management systems

The overall visual structure (OVS) (Mueller et al., 2013) is a complex index of soil structure which takes into account topsoil structure and subsoil compaction scores as well as the rooting depth score. Since the rooting depth score was the same for all plots studied we proposed using another complex index by combining the scores of A-horizon depth with the topsoil structure and subsoil compaction scores. According to the field manual for the M-SQR method, the score for A-horizon depth depends on the SOC content of soil (more detail in section 2.6 above). We assumed that since the OSS score includes the effect of SOC on crop yield, it may show a better correlation with crop yield and thus be more discriminative for management effects compared to OVS. However, OVS was more discriminative for management effects (rotation and tillage in this study) than OSS and even the M-SQR score (Table 6). This was surprising due to the well-known role of SOC in crop production

(Loveland and Webb, 2003). However, in our study SOC did not show any significant correlation with RY at either of the sites (Table 6). The SOC contents of the studied plots varied between 1.03-1.61 g $100g^{-1}$ (all plots had OC<2 g $100g^{-1}$) and 1.40-2.38 g $100g^{-1}$ (1/3 of plots had OC>2 g $100g^{-1}$) at Flakkebjerg and Foulum, respectively. The better yield performance at Foulum than at Flakkebjerg was to some extent related to the higher SOC at Foulum. This was also reflected in the better plant establishment at Foulum during the growing seasons.

The VESS score was in most cases not able to differentiate between management systems. However, for R2 at Flakkebjerg the VESS correlated significantly with RY and close to significant correlations were also found for R2 at Foulum and R4 at Flakkebjerg (Table 6). Significant correlations between VESS and crop yield have also been reported by Munkholm et al. (2013), Mueller et al. (2013) and Mueller et al. (2009). The former reported a significant correlation (R^2= 0.35) between the VESS and the corn yield in a Canadian silt loam soil.

From above it is concluded that although OVS only used topsoil structure and subsoil compaction scores (the rooting depth was equal for all plots) was still more powerful than the other indices at differentiating the management systems in terms of RY. This also suggests the importance of soil structure in the productivity function of soil.

5. Conclusions

- Crop rotation affected the soil structure and crop yield. The R2 which was a winter crop rotation resulted in the poorest soil structural quality and produced the least relative yield compared to R3 and R4.
- Tillage systems clearly influenced the soil quality and relative yield. The MP resulted in the best soil structural quality and consequently the highest relative yield compared with reduced tillage.
- Significant correlations were found in most cases between soil quality indices and relative yield. This highlights the influence of soil quality and soil structure in particular on crop yield potential.

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Fig. 1. Scheme of the M-SQR. Adapted from Mueller et al. (2007, Fig. 2.-1))

Fig. 2. Correlation between M-SQR scores and RY for all data set at plot level.

Fig. 3. Correlation between M-SQR scores and RY for crop rotations at Flakkebjerg

Fig. 4. Correlation between M-SQR scores and RY for crop rotations at Foulum.

Fig. 5. Correlation between M-SQR scores and RY for each individual tillage system at Flakkebjerg.

Table 1. Crop rotations and straw management in study period

Table 2. Conversion of visual structure assessment (VSA) and VESS scores into M-SQR scores. Adapted from (Mueller et al., 2013)

Table 3. Conversion of PR data (MPa) into M-SQR scores.

Table 4. Mean temperature (C°), precipitation (mm) and evaporation (mm) values in main vegetation period of 4 months for the period 2008-2012 used to calculate drought risk score and multiplication factor of hazard risk.

Table 5. Mean relative crop yield (RY), visual evaluation of soil structure (VESS) scores, M-SQR scores, overall visual structure (OVS) score and overall soil structure (OSS) score in different rotation and tillage systems. Numbers followed by identical letters (across the rows for each main effect) are not significantly different at the $P<0.05$ level. For the location effect (last column) numbers followed by identical letters (across the column for each attribute) are not significantly different at the $P<0.05$ level.

Table 6. Pearson correlation between OSS, OVS, VESS scores and SOC with RY in different crop rotations and tillage systems at each location. Bold numbers showed significant correlation.

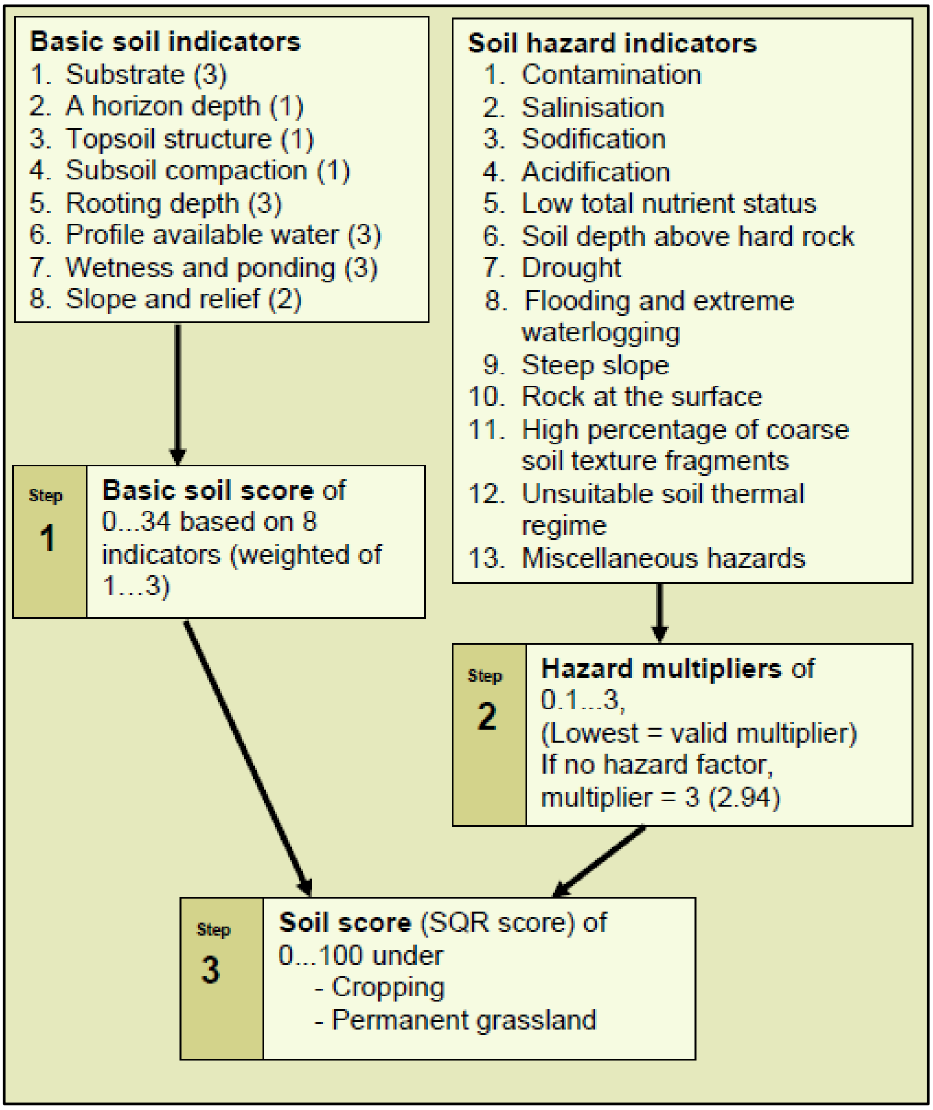

Fig. 1. Scheme of the M-SQR. Adapted from Mueller et al. (2007, Fig. 2.-1))

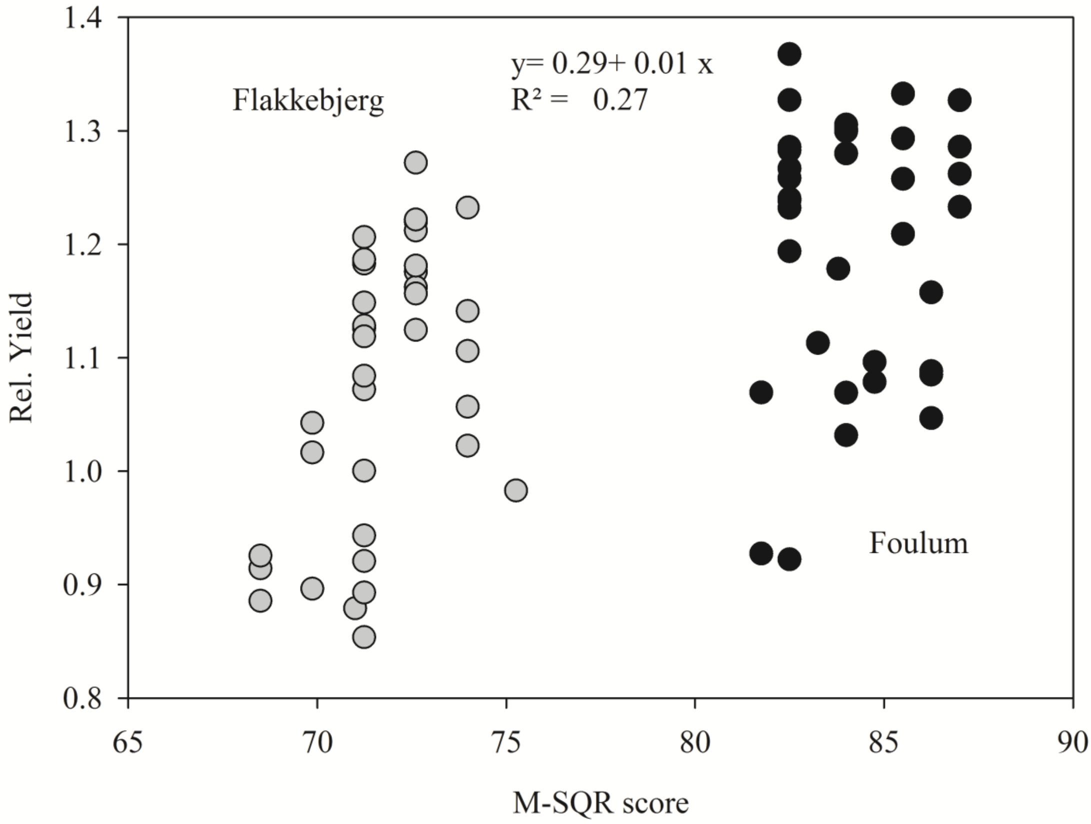

Fig. 2. Correlation between M-SQR scores and RY for all data set at plot level.

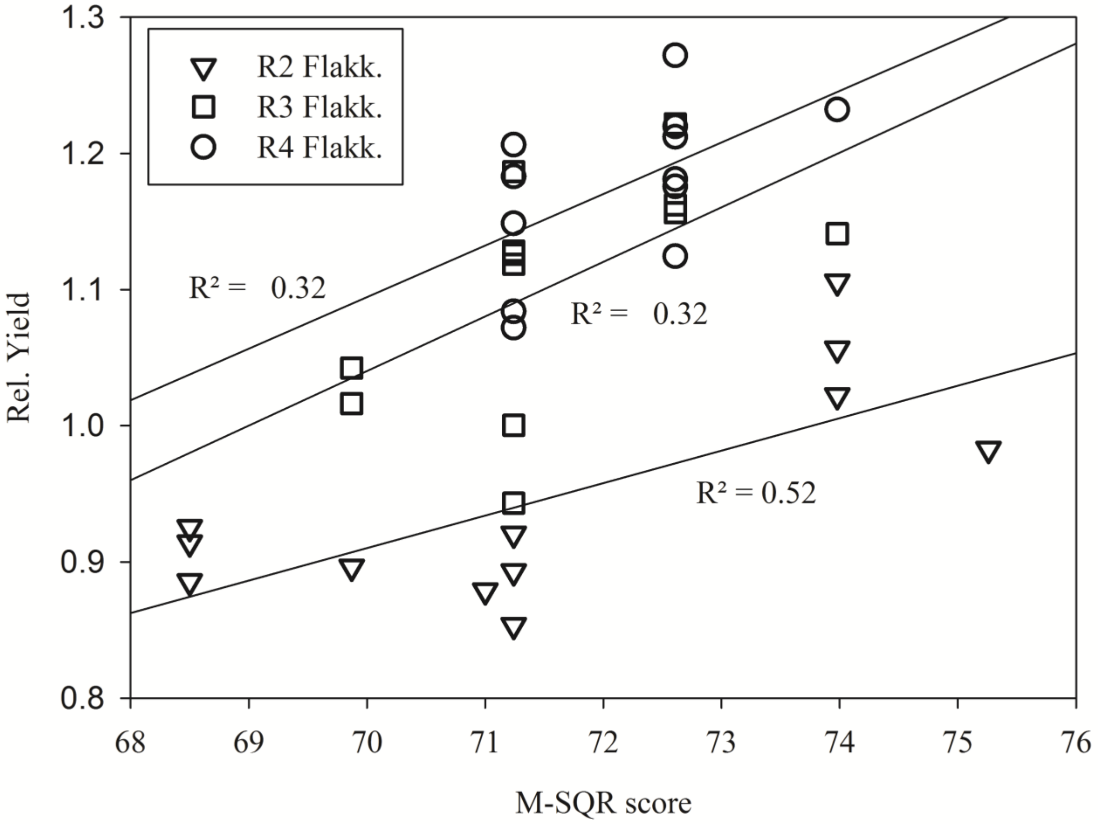

Fig. 3. Correlation between M-SQR scores and RY for crop rotations at Flakkebjerg

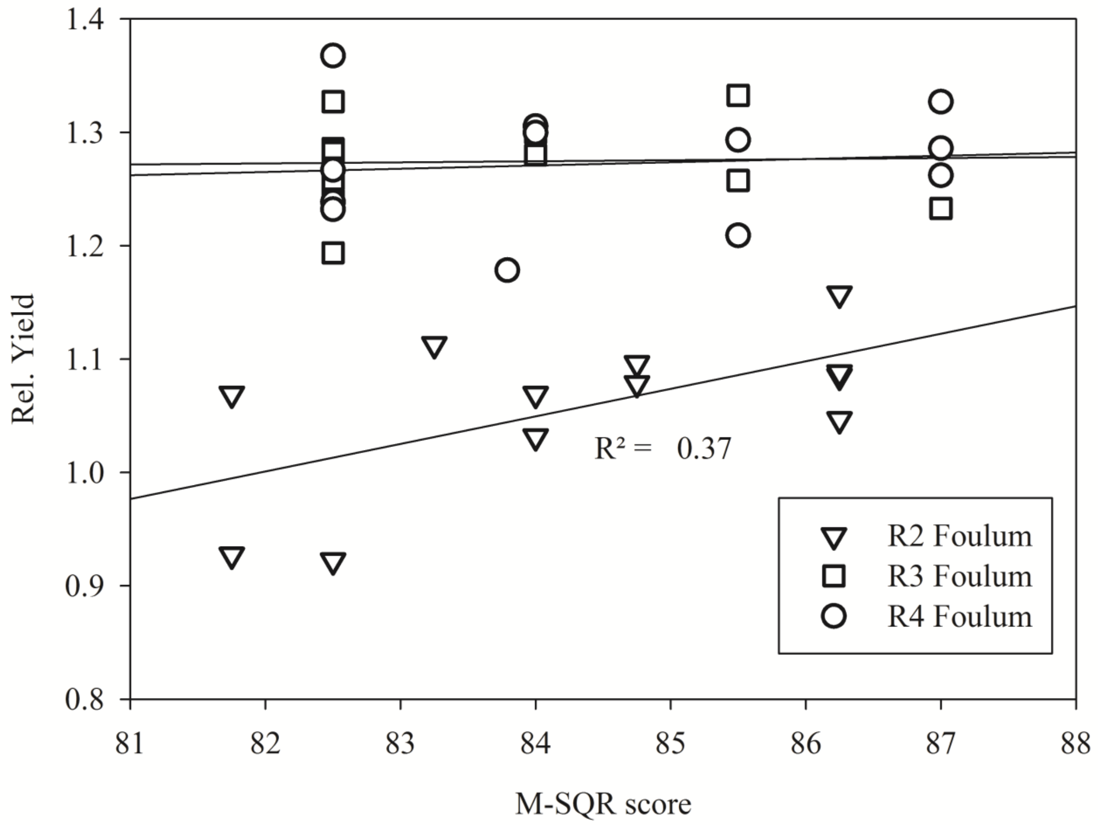

Fig. 4. Correlation between M-SQR scores and RY for crop rotations at Foulum.

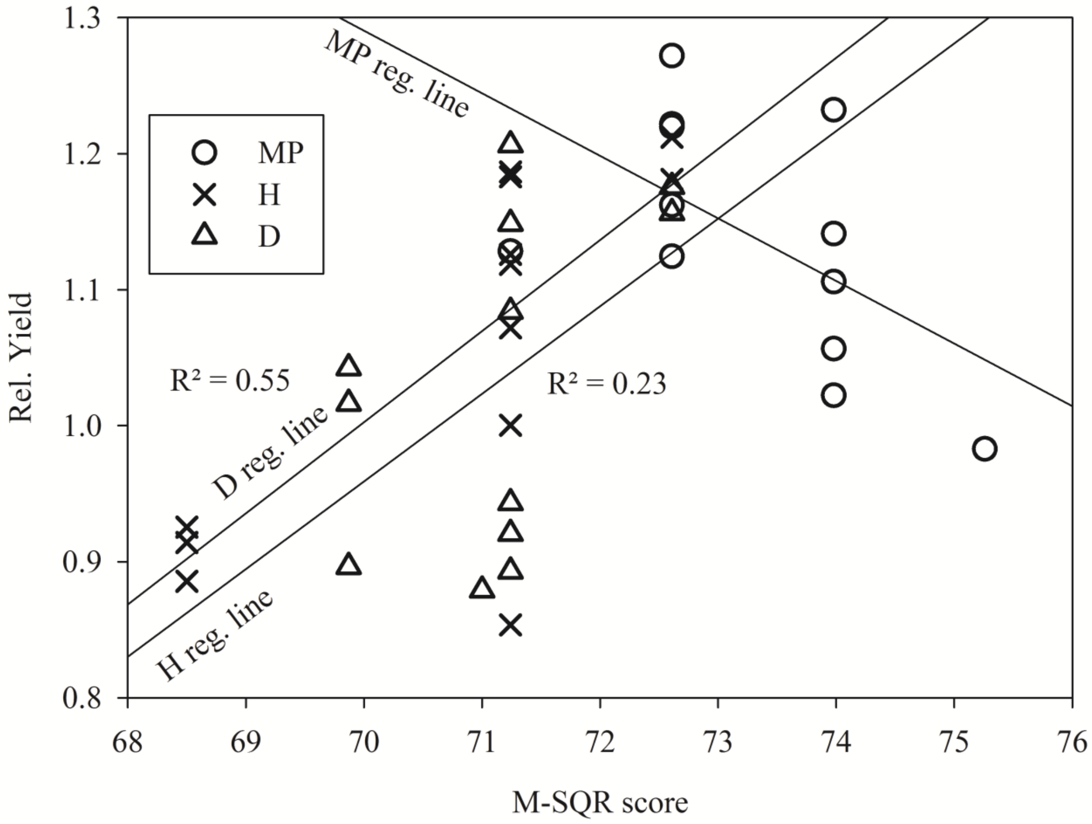

Fig. 5. Correlation between M-SQR scores and RY for each individual tillage system at Flakkebjerg.

Table 1. Crop rotations and straw management in study period

Year	R2	R3	R4
2009	Winter (W). wheat	Oat	Oat
2010	W. wheat/S. barley*	W. wheat/CC#	W. wheat/CC#
2011	W. barley†	Spring (S) barley/CC#	S. barley/CC#
2012	W. rape/wheat**	Oat	Oat
Straw	Left	Removed	Left

* Spring barley was sown at Foulum where winter wheat was injured by frost.

† Spring barley was sown in direct drilling plots at Flakkebjerg where winter barley was injured by frost.

Fodder radish (Raphanus sativus) was under sown as cover crop 14 days before expected harvest.

** Winter wheat at Foulum (sown instead of winter rape to avoid too late sowing of winter rape in a wet autumn)

Table 2. Conversion of visual structure assessment (VSA) and VESS scores into M-SQR scores. Adapted from (Mueller et al., 2013)

VSA structure and/or porosity score (Shepherd, 2000)	VESS score (Ball et al., 2007)	SQR basic score (Mueller et al., 2007)
2 (Good)	1 (Friable)	2 (Optimum)
1.5	2 (Intact)	1.5
1 (Moderate)	3 (Firm)	1
0.5	4 (Compact)	0.5
0 (Poor)	5 (Very compact)	0 (Very poor, massive)

Table 3. Conversion of PR data (MPa) into SQR scores.

Penetration resistance	SQR basic score	Remarks
< 1.5	2	According to Boone et al. (1994) and
1.5 - 2.0	1.5	According to Munkholm et al. (2008)
2.0 - 2.5	1	
2.5 – 3.0	0.5	
> 3.0	0	According to Boone et al. (1994) this is an

Table 4. Mean temperature (C°), precipitation (mm) and evaporation (mm) values in main vegetation period of 4 months for the period 2008-2012 used to calculate drought risk score and multiplication factor of hazard risk.

Experiment location	Mean temperature	Precipitation	Evaporation
Foulum	8.3	550.5	542.5
Flakkebjerg	9.0	461.7	573.1

Table 5. Mean relative crop yield (RY), visual evaluation of soil structure (VESS) scores, M-SQR scores, overall visual structure (OVS) score and overall soil structure (OSS) score in different rotation and tillage systems. Numbers followed by identical letters (across the rows for each main effect) are not significantly different at the P<0.05 level. For the location effect (last column) numbers followed by identical letters (across the column for each attribute) are not significantly different at the P<0.05 level.

Attribute	**Site**	**Location effect**	**Crop rotations**			**Tillage systems**		
			R2	**R3**	**R4**	**MP**	**H**	**D**
Rel. Yield (RY)	Foulum	1.20[a]	1.05[b]	1.27[a]	1.27[a]	1.22[a]	1.18[a]	1.20[a]
	Flakkebjerg	1.08[b]	0.95[b]	1.10[a]	1.18[a]	1.14[a]	1.06[b]	1.03[b]
	both sites	-	1.00[b]	1.19[a]	1.22[a]	1.18[a]	1.12[b]	1.12[b]
VESS score	Foulum	1.75[a]	1.74[a]	1.78[a]	1.73[a]	1.14[c]	1.84[b]	2.27[a]
	Flakkebjerg	2.04[b]	1.99[a]	2.09[a]	2.03[a]	1.58[c]	2.14[b]	2.37[a]
	both sites	-	1.87[a]	1.94[a]	1.89[a]	1.36[c]	2.00[b]	2.32[a]
M-SQR score	Foulum	84.2[a]	84.3[a]	83.8[a]	84.5[a]	85.2[a]	83.3[b]	84.1[ab]
	Flakkebjerg	71.7[b]	71.0[b]	71.6[ab]	72.2[a]	73.1[a]	70.8[b]	70.9[b]
	both sites	-	77.7[a]	77.7[a]	78.3[a]	79.1[a]	77.0[b]	77.5[b]
Overall visual structure (OVS) score	Foulum	1.52[a]	1.44[b]	1.56[a]	1.54[ab]	1.63[a]	1.42[b]	1.50[ab]
	Flakkebjerg	1.54[a]	1.47[b]	1.54[ab]	1.61[a]	1.72[a]	1.44[b]	1.46[b]
	both sites	-	1.46[b]	1.55[a]	1.58[a]	1.67[a]	1.43[b]	1.48[b]
Overall Soil Structure (OSS) score	Foulum	1.53[a]	1.54[a]	1.47[a]	1.57[a]	1.65[a]	1.42[b]	1.51[ab]
	Flakkebjerg	1.38[b]	1.31[b]	1.38[ab]	1.44[a]	1.55[a]	1.28[b]	1.29[b]
	both sites	-	1.42[a]	1.42[a]	1.41[a]	1.60[a]	1.35[b]	1.40[b]

Table 6. Pearson correlation between OSS, OVS, VESS scores, SOC and M-SQR scores with RY in different crop rotations and tillage systems at each location. Bold numbers shows significant correlations.

Site, treatment	Attribute				
	OVS	OSS	VESS	SOC	M-SQR score
Foulum, R2	**0.62**	**0.61**	-0.48	-0.35	**0.61**
Foulum, R3	**0.68**	0.04	-0.17	**-0.74**	0.04
Foulum, R4	0.26	-0.05	0.10	-0.22	0.10
Flakkebjerg, R2	**0.79**	**0.79**	**-0.76**	-0.48	**0.72**
Flakkebjerg, R3	**0.57**	**0.57**	-0.25	0.41	**0.57**
Flakkebjerg, R4	**0.57**	**0.57**	-0.50	-0.04	**0.57**
Foulum, MP	0.26	-0.24	0.12	-0.10	-0.19
Foulum, H	0.38	-0.01	0.32	0.05	-0.01
Foulum, D	**0.77**	0.21	-0.39	-0.11	0.21
Flakkebjerg, MP	-0.20	-0.20	0.27	0.03	**-0.56**
Flakkebjerg, H	**0.74**	**0.74**	0.19	-0.18	**0.74**
Flakkebjerg, D	**0.61**	**0.61**	-0.15	0.27	0.48