PREDICTING SOIL WORKABILITY AND FRAGMENTATION IN TILLAGE

Peter Bilson Obour

PhD Thesis, Science and Technology, 2019

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Preface

This thesis is submitted in partial fulfilment of the requirements for the Doctor of Philosophy (PhD) degree at the Faculty of Science and Technology, Aarhus University. The thesis presents a synthesis of research carried out at the Department of Agroecology between September 2015 and January 2019. The study was part of the "Future Cropping" project financed by Innovation Fund Denmark.

I am thankful to the Almighty God for the gift of life. The completion of this work will not have been possible without the constant guidance and support of my supervisors: Lars J. Munkholm, Mathieu Lamandé, Gareth Edwards and Claus G. Sørensen. I appreciate all your help throughout the thesis. I am grateful to Prof. Thomas Keller from Agroscope Research Institute, Zürich for hosting me during my stay abroad and for the valuable inputs and interesting ideas you contributed to the research.

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January 2019, Foulum, Denmark

Summary

One of the primary aims of tillage operation is to fragment soil to provide a suitable seedbed for crop establishment. Although crops vary in terms of their specific requirements for fragment size distribution in a seedbed, it is generally known that for small grain cereals, a seedbed should neither constitute of soil fragments that are too large (clods) nor too fine. The soil workability defines the ability of a well-drained soil to produce a desirable seedbed during tillage without causing irreversible damage to the soil structure. Because soil water content has a strong influence on soil workability and fragmentation, it is important that tillage operations are performed within a range of water contents appropriate for tillage ($\Delta\theta_{RANGE}$), which is bounded by the wet tillage limit (θ_{WTL}) and the dry tillage limit (θ_{DTL}). The optimum water content is where tillage produces maximum number of small fragments and minimum number of clods. Quantitative information on how soil physical properties and management affect the water contents for tillage is useful for predicting soil workability during tillage.

The objectives of the work presented in this thesis as part of the Future Cropping project were to: (i) review existing approaches for predicting soil workability and fragmentation, (ii) quantify effect of soil organic carbon (SOC) and clay contents on soil workability and fragmentation, (iii) quantify effect of compaction and sowing date on seedbed physical properties and soil workability, and (iv) propose a new approach for estimating the water contents for tillage.
To achieve objective (i), a critical review of literature on the existing approaches for determining soil workability and fragmentation was made. For objective (ii), intact soil cores and bulk soil were sampled from soils with a range of SOC from two long-term experiments in Highfield, UK and Askov, Denmark; and a soil with a naturally occurring clay gradient in an arable field in Lerbjerg, Denmark. Objective (iii) was addressed by sampling soil from a compaction and sowing date experiment in Ås, Norway. Soil workability was assessed in the laboratory from the quantitative measurements of fragment size distribution, tensile strength properties as a function of fragment size and matric potential, and the estimated water contents for tillage. Finally, to achieve objective (iv), a new approach for estimating the θ_{WTL} and θ_{DTL} was proposed, which was then compared with the "water retention" and "consistency approaches" for estimating the water contents for tillage.

During the past few decades, various approaches have been proposed for estimating the water contents for tillage. The approaches have their respective strengths and weaknesses. Two of the state-of-art approaches for estimating the water contents for tillage are the water retention

approach (WRA), which uses fitted parameters of the van Genuchten 1980 equation and the consistency approach (CA), which combines soil plastic limit and tensile strength. In general, there is a limited quantitative information on the water contents for tillage, particularly the dry tillage limit.

In the air-dry state, tensile strength (Y) decreased with increasing SOC whereas specific rupture energy (E_{sp}) increased with increasing SOC, which can be ascribed to the role of SOC in improving soil structural porosity and soil elasticity. In the wet state, aggregates of a soil with large SOC content were relatively stronger than a soil with a small SOC content. Findings indicate that SOC widens $\Delta\theta_{RANGE}$ by reducing soil strength, as soil becomes drier implying that soil clods are easily fragmented by tillage operations. Conversely, SOC increases soil strength as a soil becomes wet implying that soil would not slump under its own weight or due to external stresses inflicted by field traffic. Tensile strength and E_{sp} increased with increasing clay content and with decreasing water content which can be attributed to increased effective stresses as a soil is drained of water. Increase in clay content decreased $\Delta\theta_{RANGE}$.

Compaction and early sowing when soil was wet adversely affected seedbed physical properties such as macroporosity, soil strength and fragment size distribution. Compaction and early sowing date reduced $\Delta\theta_{RANGE}$ compared to the control and the timely sowing date, respectively, although not statistically significant.

The new approach (NA) proposed for estimating the water contents for tillage provided estimates of the wet tillage limit, the optimum water content for tillage and the dry tillage limit. Even though NA accounts for the soil structure, the use of a fixed value of air-filled porosity of 0.10 m³ m⁻³ to estimate the wet tillage limit and a fixed strength value of 50 kPa to estimate the dry tillage limit makes NA somewhat arbitrary which may need to be refined in future. More studies are needed to test whether it is useful to use a fix value for all soils.

Findings of the study will be relevant in practice in many respects: The positive effect of SOC on soil tensile strength and $\Delta\theta_{RANGE}$ implies that management practices that increase SOC content can increase the number of workable days. A soil with a clay gradient exhibits variable $\Delta\theta_{RANGE}$. Therefore, uniform tillage operation on a texturally variable field might not be the best management option unless operations are properly scheduled. Field traffic and tillage in less-than-ideal soil conditions because soil is either too wet or too dry not only affect seedbed physical properties for the current grown crop, but also can potentially reduce soil workability for

subsequent tillage operations. Present and future farmers need to prioritize the implications of compaction and sowing dates on soil physical conditions even more than in the past.

In summary, the quantitative information on the effect of SOC and clay contents on $\Delta\theta_{\text{RANGE}}$, the effect of sowing date and compaction on seedbed physical properties, and the new approach proposed for estimating the water contents for tillage, which are the main outcomes of this PhD work will provide a possibility for reducing tillage-induced soil structural damage and high energy requirement for tillage operations. Knowledge of predicting the water contents for tillage can also be used for developing a decision support system for scheduling tillage operations in modern agriculture.

Sammendrag (Danish summary)

Et af de primære formål med jordbearbejdning er at smuldre jorden med henblik på at danne et passende såbed. Det idéelle såbed afhænger af plantearten, men generelt set bør der ikke være en for stor andel af hverken for store (knolde) eller små aggregater. Jordens "workability" eller bearbejdbarhed er defineret som evnen for en veldrænet jord til at lave et passende såbed ved jordbearbejdning uden at lave skade på jordens struktur. Jordens vandindhold har en stor indflydelse på jordens bearbejdbarhed og derfor er det vigtigt at jordbearbejdning sker indenfor et interval i vandindhold for jordbearbejdning ($\Delta\theta_{RANGE}$). Det er afgrænset af henholdsvis den våde (θ_{WTL}) and den tørre (θ_{DTL}) grænseværdi for jordbearbejdning. Det optimale vandindhold for jordbearbejdning er hvor jordbearbejdning producerer den maksimale mængde mindre aggregater og den minimale mængde knolde. Viden om hvordan jordens fysiske egenskaber og dyrkningen påvirker intervallet i vandindhold for jordbearbejdning er vigtig for at kunne forudsige jordens bearbejdbarhed for en given jord på et givet tidspunkt.

Formålet med denne PhD afhandling, som er lavet som en del af Future Cropping projektet var at: (i) gennemgå og analysere eksisterende metoder til bestemmelse af jordens bearbejdbarhed og smuldreevne (ii) kvantificere effekten af jordens indhold af organisk stof og ler på jordens bearbejdbarhed og smuldreevne (iii) kvantificere effekten af pakning og sådato (vandindhold ved jordbearbejdning) på såbedskvalitet og bearbejdbarhed og (iv) foreslå en ny metode til at beregne intervallet i vandindhold for jordbearbejdning. I forhold til (i) blev der lavet en kritisk gennemgang og analyse af eksisterende metoder til bestemmelse af jordens bearbejdbarhed og smuldreevne. I forhold til (ii) blev der udtaget jordprøver i to langvarige markforsøg (Askov, Danmark og Highfield, Rothamsted, England) med dyrkningsbetinget variation i jordens indhold af organisk stof og på en dyrket mark (Lerbjerg, Danmark) med en stor variation i lerindholdet. I forhold til (iii) blev der udtaget jord i norsk markforsøg ved Ås med forskel i pakningsgrad af pløjelaget og sådato (dvs. forskel i vandindhold ved såning). Jordens bearbejdbarhed blev bestemt i laboratoriet ud fra målinger af aggregatstørrelsesfordelingen og trækstyrken på aggregater af forskellig størrelse og ved forskelligt vandindhold. På basis af disse resultater og vandretentionsdata blev intervallet i vandindhold for jordbearbejdning beregnet. Afslutningvis blev en ny metode til beregning af den våde (θ_{WTL}) og tørre (θ_{DTL}) grænseværdi for jordbearbejdning foreslået (formål iv).

Forskellige metoder til at bestemme tør og våd grænseværdi for jordbearbejdning er blevet foreslået og anvendt indenfor de seneste årtier. Alle metoderne har deres fordele og ulemper. En af de mest udbredte metoder til bestemmelse af vandindhold for jordbearbejdning er

"vandretentions" metoden (VRA), som er baseret på modellering af jordens vandretention med van Genuchten 1980 modellen. En anden anvendt metode, konsistens-metoden (CA), bygger på bestemmelse af vandindholdet ved plasticitetsgrænsen (våd grænseværdi) og vandindholdet ved en jordstyrke, der er 2 gange højere end vandindholdet ved det optimale vandindhold for jordbearbejdning. Generelt set er der begrænset kvantitativ viden om passende vandindhold for jordbearbejdning – særligt i forhold til den tørre grænseværdi.

I lufttør tilstand aftager aggregaternes trækstyrke (Y) med stigende indhold af organisk stof, hvorimod den specifikke brydningsenergi (E_{sp}) øges med stigende organisk stof indhold. Dette kan forklares med organisk stof indholdets betydning i forhold jordens indhold af strukturelle porer og jordens elasticitet. Projektet viser, at intervallet i vandindhold for jordbearbejdning ($\Delta\theta_{RANGE}$) øges med stigende indhold af organisk stof. Det skyldes først og fremmest at aggregatstyrken stiger mindre med stigende udtørringsgrad for jord med højt end med lavt indhold af organisk stof. I våd tilstand var aggregater med højt organisk stof indhold derimod relativt stærkere end aggregater med lavt organisk stof indhold. Det giver større stabilitet i våd tilstand i forhold til eksterne påvirkninger (jordbearbejdning, kørsel med tunge maskiner etc.). Aggregaternes trækstyrke (Y) og brydningsenergi (E_{sp}) øges med stigende lerindhold og udtørringsgrad. Det kan relateres til stigende effektiv hydrostatisk stress i takt med stigende udtørring. Intervallet i vandindhold for jordbearbejdning aftog med stigende lerindhold.

Pakning og tidlig såning (højt vandindhold ved jordbearbejdning) mindskede såbedets kvalitet i form af mindsket makroporøsitet, øget jordstyrke og mere knoldet jord. Pakning kombineret med tidlig og sen såning mindskede generelt set intervallet i vandindhold for jordbearbejdning i forhold til upakket jord ved rettidig såning.

Den foreslåede nye metode (NA) til bestemmelse af intervallet i vandindhold for jordbearbejdning indeholder nye estimater for våd og tør grænseværdi og vandindholdet ved optimal bearbejdbarhed. NA metoden tager hensyn til jordens struktur – våd grænseværdi angives som vandindholdet ved luftfyldt porevolumen ved 0.10 m^3 m^{-3}, mens tør grænseværdi angives som vandindholdet ved en aggregatstyrke på 50 kPa – men grænseværdierne er fortsat relativt vilkårlige. Der er behov for opfølgende undersøgelser til afklare, om de angivne faste grænseværdier kan anvendes på tværs af jordtyper.

PhD studiet er relevant i forhold til landbrugspraksis på en række felter. Først og fremmest viser studiet, at øget kulstofindhold påvirker jordstyrken i våd og tør tilstand og øger intervallet i vandindhold for jordbearbejdning. Sidstnævnte betyder et stærkt forøget antal af mulige

arbejdsdage til rettidig jordbearbejdning. For det andet vil en mark med varieriende lerindhold have en variation i intervallet i vandindhold for jordbearbejdning og derfor er det en udfordring at finde det rette tidspunkt, hvor hele marken har en passende bearbejdbarhed. Det kræver god planlægning. Her kan viden fra projektet være af stor værdi i opbygning af beslutningsstøttesystemer for rettidig jordbearbejdning. For det tredje viser projektet, at kørsel og jordbearbejdning, når jorden er for tør eller for våd ikke kun påvirker jordens struktur indenfor den givne dyrkningssæson, men også påvirker betingelser for jordbearbejdning i den efterfølgende dyrkningssæson. Nuværende og fremtidige landmænd bør øge opmærksomheden på strukturproblemer forårsaget af kørsel og jordbearbejdning under særligt våde forhold. .

Sammenfattende vil de vigtigste resultater fra PhD projektet (1. kvantitative viden om betydning af organisk stof og lerindhold samt jordbearbejdning og kørsel i marken på jordens bearbejdbarhed, 2. den nye metode til bestemmelse af intervallet i vandindhold for jordbearbejdning) øge vores vidensgrundlag med henblik på at mindske skader på jordens struktur forårsaget af jordbearbejdning og kørsel i marken. Den nye viden vil kunne bruges til at forbedre beslutningsstøttesystemer til brug ved planlægning af jordbearbejdning (tidspunkt og intensitet) i moderne landbrug.

Contents

List of supporting papers

This dissertation is based on four published research papers and one manuscript. Throughout the thesis, the papers will be referred to by their Arabic numbers.

1. Obour, P.B., Lamandé, M., Edwards, G., Sørensen, C.G., Munkholm, L.J., 2017. Predicting soil workability and fragmentation in tillage: a review. *Soil Use Management*. 33, 288-298. doi: 10.1111/sum.12340

2. Obour, P.B., Jensen, J.L, Lamandé, M., Watts, C.W., Munkholm, L.J., 2018. Soil organic matter widens the range of water contents for tillage. *Soil & Tillage Research*, 182, 57–65. doi.org/10.1016/j.still.2018.05.001

3. Obour, P.B., Keller, T., Lamandé, M., Munkholm, L.J., 2019. Pore structure characteristics and soil workability along a clay gradient. *Geoderma*, 337, 1186-1195. doi.org/10.1016/j.geoderma.2018.11.032

4. Obour, P.B., Kolberg, D., Lamandé, M., Børresen, T., Edwards, G., Sørensen, C.G., Munkholm, L.J., 2018. Compaction and sowing date change soil physical properties and crop yield in a loamy temperate soil. *Soil & Tillage Research*, 184, 153–163. doi.org/10.1016/j.still.2018.07.014

5. Obour, P.B., Keller, T., Jensen, J.L., Edwards, G., Lamandé, M., Watts, C.W., Sørensen, C.G., Munkholm, L.J., 2019. Soil water contents for tillage: a comparison of approaches and consequences for the number of workable days. Moderate revision submitted to *Soil & Tillage Research*.

In relation to printing of the thesis, the manuscript "*Soil water contents for tillage: a comparison of approaches and consequences for the number of workable days*" which was submitted to the assessment committee as "*The water contents for tillage: a comparison of approaches and consequences for the number of workable days*" has been replaced by the moderately revised version submitted to *Soil & Tillage Research*. The two versions do not have any substantial deviation.

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List of acronyms/Abbreviations

$\Delta\theta_{\text{RANGE}}$	Range of water contents for tillage
θ_{WTL}	Upper/wet tillage limit
θ_{DTL}	Lower/dry tillage limit
DSS	Decision support system
θ_{proctor}	Water content at maximum Proctor density
SWRC	Soil water retention curve
k_a	Air permeability
MPV	Moisture-pressure-volume
PL	Plastic limit
WRA	Water retention approach
CA	Consistency approach
θ	Gravimetric water content
θ_{INFL}	Water content at inflection point
θs_{AT}	Water content at saturation
Y	Tensile strength
E_{sp}	Specific rupture energy
k_Y	Soil friability index
E	Young's modulus
σ_e	Effective stress
WRB	World Reference Base
PR	Penetration resistance
ε_a	Air-filled porosity
Dp/Do	Relative gas diffusivity
GMD	Geometric mean diameter
NA	New approach
DE	Double-exponential equation

1 Introduction

Tillage is one of the common and essential field preparation practices that has been used for centuries prior to sowing crops. The term "tillage" is derived from the old English word "tillen" meaning, "to toil". This alludes to the use of human and animal power, which used to be the available sources of power. With these power sources, it took a long time and 'much toil' for a farmer to till a moderate-sized land. With the advent of agricultural machinery, large areas could be tilled per person (FAO, 2003; p. 49). The Encyclopedia Britannica defines tillage simply as the manipulation of soil into a desired condition through mechanical means by using tools that are human- or animal-powered or mechanized implements to achieve a desired effect (Stewart, 2018). This work focused only on tillage by using powered machinery or implements.

Conventional tillage may be classified as primary and secondary. Primary tillage involves digging, stirring and inverting the soil usually at a greater depth such as during plowing primarily to fragment the topsoil, incorporate organic materials and to control weeds. Secondary tillage is often carried out after primary tillage at a shallow depth to breakdown large soil fragments, mainly to create a homogenous loose seedbed with an even depth, and a desirable fragment size distribution for seeding (Håkansson *et al.*, 2002; Hallett & Bengough, 2013).

It is recognized that crops vary in terms of their specific requirements for fragment size distribution in a seedbed. Notwithstanding this, it is generally accepted that a seedbed consisting of small fragment size favor soil-seed contact, and improves water supply and adequate aeration to seeds (Dexter, 1988), which in turn enhance germination and crop growth. Russell (1961) noted that soil fragments that create an ideal seedbed as those of size 1–5 mm. According to Håkansson et al. (2002), seedbeds that favor crop growth should consist of more than 50% of the soil fragments that are < 5 mm in size. They found that such fine seedbeds increased the number of plants and yield of small grains by 5% compared to the coarse seedbeds for a silty soil in Sweden. Braunack and Dexter (1989b) found that soil fragment sizes of 0.5–8 mm had high inter-aggregate aeration and were less erodible and compactible.

A seedbed consisting predominantly of coarse or fine fragments is less suitable from the point of view of seeding and crop establishment. This is because large soil fragments may be useful for controlling erosion (Lyles & Woodruff, 1962), but can create unsatisfactorily seedbed conditions due to reduced soil-seed and soil-root contact areas, and increased mechanical impedance to roots and plant shoots. In the same manner, too fine fragments can have poor aeration and are

susceptible to water and wind erosion, and soil crusting (Braunack & Dexter, 1989a; Braunack & Dexter, 1989b). Thus, a seedbed consisting of both fine and coarse soil fragments is required to improve water retention and aeration, soil-seed and soil-root contact areas, and to reduce the erodibility of very fine soil fragments. As a rule of thumb, an ideal seedbed for crop establishment should consist of fragments that are neither too fine nor too coarse because domination of either size can be problematic for crop establishment and growth (**Paper 1**).

Soil workability is an important indicator describing the suitability of a soil for tillage. It has been defined as the ability of a soil to produce friable tilth in tillage without causing smearing and compaction (Rounsevell, 1993). In seedbed preparation, soil workability is the ease with which a well-drained soil can be tilled to produce a desirable seedbed (Dexter, 1988), i.e. a seedbed consisting of fragments that are neither too fine nor too coarse. The ease of tillage implies that soil should be friable, and should be neither too wet nor too dry in order to avoid the risk of compaction in the former case and use of high-energy input for soil fragmentation in the latter (**Paper 3**).

Soil water content at tillage is one of the most important physical properties influencing soil workability. Soil is workable within a range of water content ($\Delta\theta_{RANGE}$) bounded between the upper tillage limit (wet tillage limit, θ_{WTL}) and the lower tillage limit (dry tillage limit, θ_{DTL}) (**Fig. 1**). If soil is too wet, i.e. above θ_{WTL}, tillage may deform the soil at the expense of fragmentation (Watts & Dexter, 1998). Consequently, tillage can damage soil structure and create seedbeds consisting of large soil fragments. Likewise, if soil is too dry (i.e. beyond θ_{DTL}), high energy input is required during tillage. Moreover, tillage can create a seedbed consisting of finer fragments (**Fig. 1**), which are susceptible to crusting and wind and water erosion (Braunack & Dexter, 1989a).

The optimum water content for tillage (θ_{OPT}) is defined as the water content where tillage produces the maximum number of small fragments and the minimum number of large soil fragments (Dexter & Bird, 2001). At θ_{OPT}, soil friability is at its greatest. Maximum soil fragmentation during tillage also occurs at this point (Utomo & Dexter, 1981). Therefore, soil fragmentation will require only a few number of passes of tillage implement during field operations to produce suitable seedbeds for crop establishment (Hoogmoed *et al.*, 2003).

Soil fragmentation is the process of crumbling soil fragments under applied stress (Munkholm., 2002). Friability relates to the concepts of brittle fracture and "weakest link" in a material; it is a

characteristic of a material describing the ease of crushing, crumbling or rubbing apart the particles of which the material is composed (Christensen., 1930).
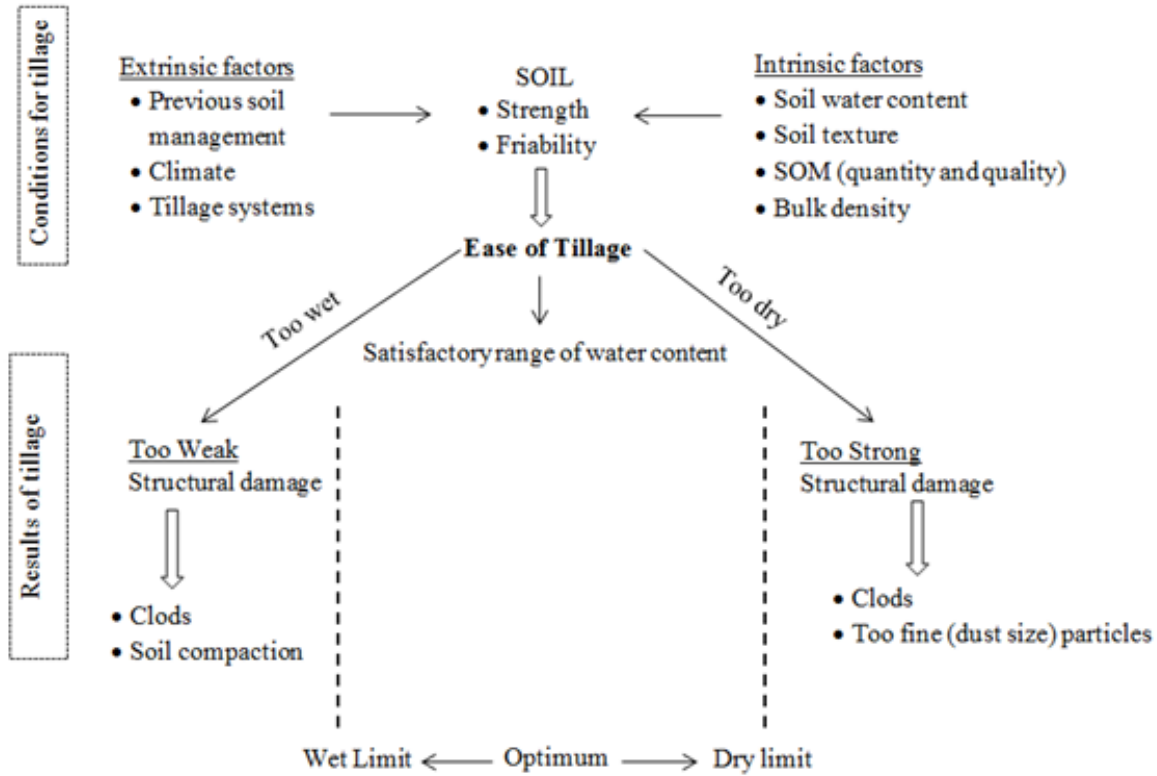
Fig. 1. Schematic presentation of the concept of soil workability and factors affecting it (***Paper 1***).

Utomo and Dexter (1981) gave a broader definition of the concept of soil friability: "the tendency of a mass of unconfined soil to break down under applied stress into a particular size range of smaller fragments". Soil friability is characterized by an ease of fragmentation of undesirably large fragments or clods and a difficulty in fragmentation of minor fragments into undesirable small elements (Munkholm, 2011). Soil friability is an important soil physical property in tillage yielding information on: (i) ability of a soil to reduce energy input required for soil crumbling during tillage, (ii) the ease of producing a seedbed that favors seed-and-root contact, and (iii) ability of soil to support plant growth (Munkholm, 2013). Friability depends on soil water content, soil bulk density, texture, aggregate stability, soil organic carbon (SOC) and soil structure (Utomo & Dexter, 1981; Watts & Dexter, 1998). It may be argued that soil fragmentation, friability and workability are closely inter-connected. This implies that quantitative information on friability

can be used to assess soil workability, management effects on soil structural conditions and soil physical quality.

1.1 Research gaps in soil workability and fragmentation studies

Tillage causes changes to soil structure, which may be beneficial or detrimental depending on a number of factors not least, soil water content during tillage. This indicates that a reliable evaluation of soil workability implies a distinctive definition of the water contents for tillage, robust approaches for estimating tillage limits, and a better understanding of the effects of soil properties on the limits of water contents for tillage.

During the past few decades, several authors have proposed various approaches for estimating soil workability limits as shown in **Table 1** (**Paper 1**). However, except for the scholarly review by Mueller *et al.* (2003), which compared the approaches for estimating θ_{0PT}, the approaches particularly for estimating θ_{WTL} and θ_{DTL} presented in the literature have not yet been critically reviewed to outline their applicability, strengths and drawbacks (**Paper 1**).

Table 1. Soil workability limits reported in the literature.

Soil workability limits			Soils studied	Source
Wet limit	Optimum water content	Dry limit		
water content of 0.24 kg kg⁻¹	–	water content of 0.18 kg kg⁻¹	-	Sitkei (1967)
–	water content at maximum Proctor density ($\theta_{proctor}$)	–	silty clay loam and silt loam (Humid continental climate)	Wagner *et al.* (1992)
water content at plastic limit	0.9 θ_{PL} or θ_{INFL}	water content at which the strength of soil is twice the strength at the optimum water content	clay loam to silty clay loam (Temperate)	Dexter and Bird (2001)
water content at pF 1.9 (−100 hPa) for loam soil and pF 2.1 (−125 hPa) for clay soil	–	water content at pF 3.1 (−1250 hPa) for the loam soil and pF3.5 (−3162 hPa) for the clay soil)	loam and clay soils (Tropical)	Hoogmoed et al. (2003)
–	0.7 of water content at matric potential of −5 kPa	–	soils from different geographical regions	Mueller et al. (2003)
water content of 0.40 kg kg⁻¹	–	water content of 0.33 kg kg⁻¹	clay (Temperate)	Gülser *et al.* (2009)

θ_{PL}: Water content at plastic limit; pF: Logarithm of the absolute value of soil matric potential; θ_{INFL}: Water content at inflection point.

(***Paper 1***)

Soil workability is primarily governed by the mechanical state of soil (Earl, 1997), which in turn is influenced by water content as discussed previously. In addition, soil workability is affected by soil properties such as texture, SOC and bulk density or the state of soil compaction (Ojeniyi & Dexter, 1979). Dexter and Bird (2001) predicted that $\Delta\theta_{\text{RANGE}}$ increases with increasing SOC content, but decreases with increasing clay content and soil bulk density. Until now, only a few studies have quantitatively evaluated these findings. For example, Munkholm. *et al.* (2002a) investigate the effect of SOC on water contents for tillage for a sandy loam soil in Denmark. In general, quantitative information on the effects of soil properties on soil workability is limited. Further, it has been shown that conducting tillage in less-than-ideal soil conditions may mechanically deform soil due to wheel damage or the action of tillage implement (Horn *et al.*, 1994), which in turn can affect soil workability for subsequent tillage operations. However, there is a lack of quantitative information on this effect (**Paper 1)**. Such a quantitative information can be a useful guideline for farmers to improve soil physical conditions for tillage in order to increase the window of soil workability in their fields. Moreover, quantitative information on soil workability and fragmentation can be used to develop a decision support system (DSS) for tillage planning and operations, and for incorporating workability predicting capabilities in comprehensive farm management information systems (Sørensen *et al.*, 2010).

1.2 Project context and objectives

The work presented in the thesis is part of the "Future Cropping" project that aims to improve and optimize the chain of cropping cycle. In line with this aim, the project seeks to bring innovations and new possibilities for precision land use through interdisciplinary and integration of data platform using "big data". Based on these data, decision supporting systems and new technology can then be developed to improve crop production chain in the field — from soil cultivation to harvest — with the ultimate goal of increasing crop quality and yield while minimizing the adverse impacts of production on the environment. The Project Model Landscape, which presents its scope and infrastructure, is shown in **Fig. 2**. The project is divided into nine work packages (WP), which together constitute the "model spirit" of the "Future Cropping project". Each WP has a specific focus. WP1, Data acquisition and processing (data platform); WP2, Impact assessment; WP3, Certification and test; WP4, Intelligent tillage and crop establishment; WP5, Intelligent fertilizer application; WP6, Microbial inoculants; WP7, Crop monitoring and protection; WP8, Intelligent harvest; and WP9, Differentiated N-regulation and drainage filter technologies.
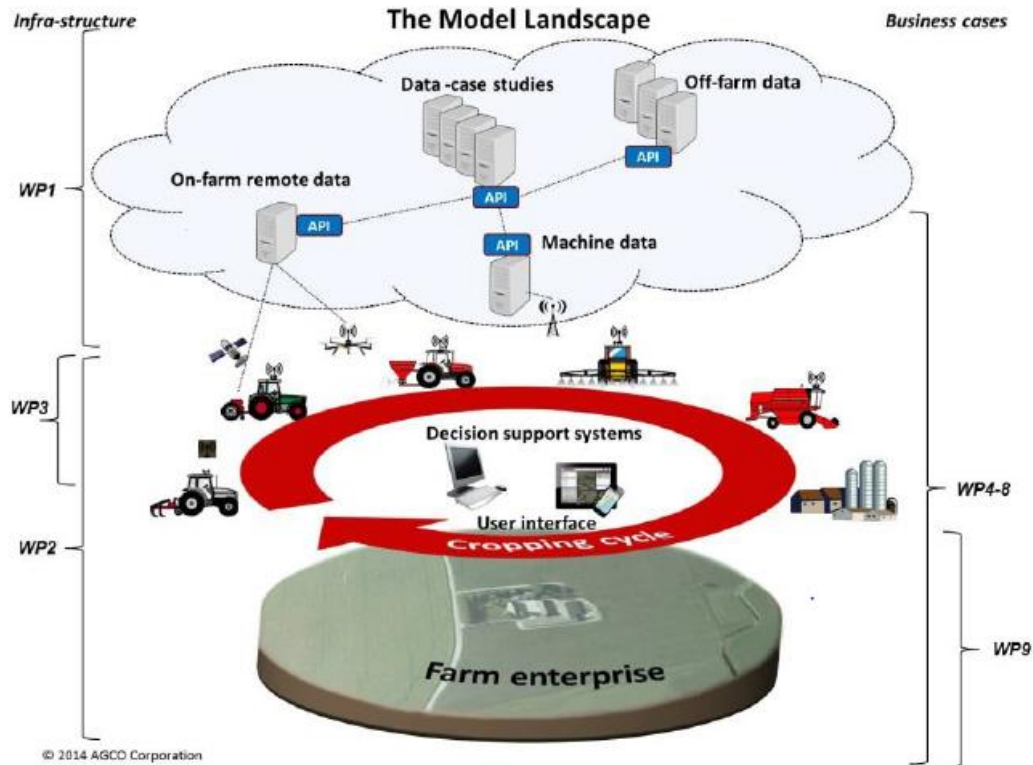
Fig. 2. Project Model Landscape of "Future Cropping" project showing the scope and the infrastructure activities divided between the work packages.

Source: Innovationsfonden (2015).

The presented work contributes to WP4 (Intelligent tillage and crop establishment). WP4 focuses on "integrating site-specific data through DSS to predict when and to what depth the soil is workable and to develop novel tillage and seeding equipment for site-specific field operations based on soil conditions". In line with this aim, previous work within WP4 focused on investigating and developing novel sensing and control technologies for site-specific tillage and seeding operations to improve the conditions of soil for crop establishment (Nielsen, 2018). The overall aim of this thesis is to contribute to the prediction of soil workability and fragmentation in tillage, which is a key prerequisite for developing a decision support system for scheduling and planning tillage operations. Specifically, the objectives were to:

- Review existing approaches for predicting soil workability and fragmentation (**Paper 1**); and to combine existing approaches for assessing soil workability with quantitative approaches for assessing soil friability and fragmentation to:

- Quantify effect of soil organic carbon and clay contents on soil workability and fragmentation (**Papers 2 & 3**).

- Quantify effects of compaction and sowing date on seedbed physical properties and soil workability (**Paper 4**).

- Propose a new approach for estimating the water contents for tillage (**Paper 5**).

1.3 Hypotheses

The main hypotheses in the thesis were:

- Increasing soil organic carbon content increases the range of water contents for soil tillage.

- Increasing clay content decreases the range of water contents for tillage.

- Tillage operations in less-than-ideal soil conditions adversely affect seedbed physical properties and soil workability.

1.4 Thesis outline

The sections in chapter 1 provide an overview of the concepts of tillage and soil workability and fragmentation, outline their interrelationship and factors that influence them, the motivation for the work, research gaps that need be addressed, and concluded with the objectives and hypotheses of the thesis. Chapter 2 presents a synopsis of the approaches existing in the literature for estimating the water contents for tillage. Chapter 3 provides a brief description of the field sites, sampling and finishes off with the measurement techniques used in the study. A synthesis of the outputs from the various studies conducted in the work and the link between these studies as well as between current knowledge, and implications of the results for soil use and management are provided in chapter 4. Chapter 5 presents the new approach proposed from this work for estimating the water contents for tillage. Chapter 6 presents some practical solutions for improving soil workability in arable soils. The main conclusions and perspectives for future studies are presented in Chapters 7 and 8, respectively. Finally, Chapter 9 presents the contributions of the PhD work for advancement of science and practical applications of results in farm management.

2 State-of-the-art approaches for determining water contents for tillage (Paper 1)

This section provides a synoptic review of some of the approaches used for estimating the water contents for tillage (**Fig. 3**). These would be discussed in the following sequence: θ_{WTL} followed by θ_{OPT} and then finish off with θ_{DTL}.
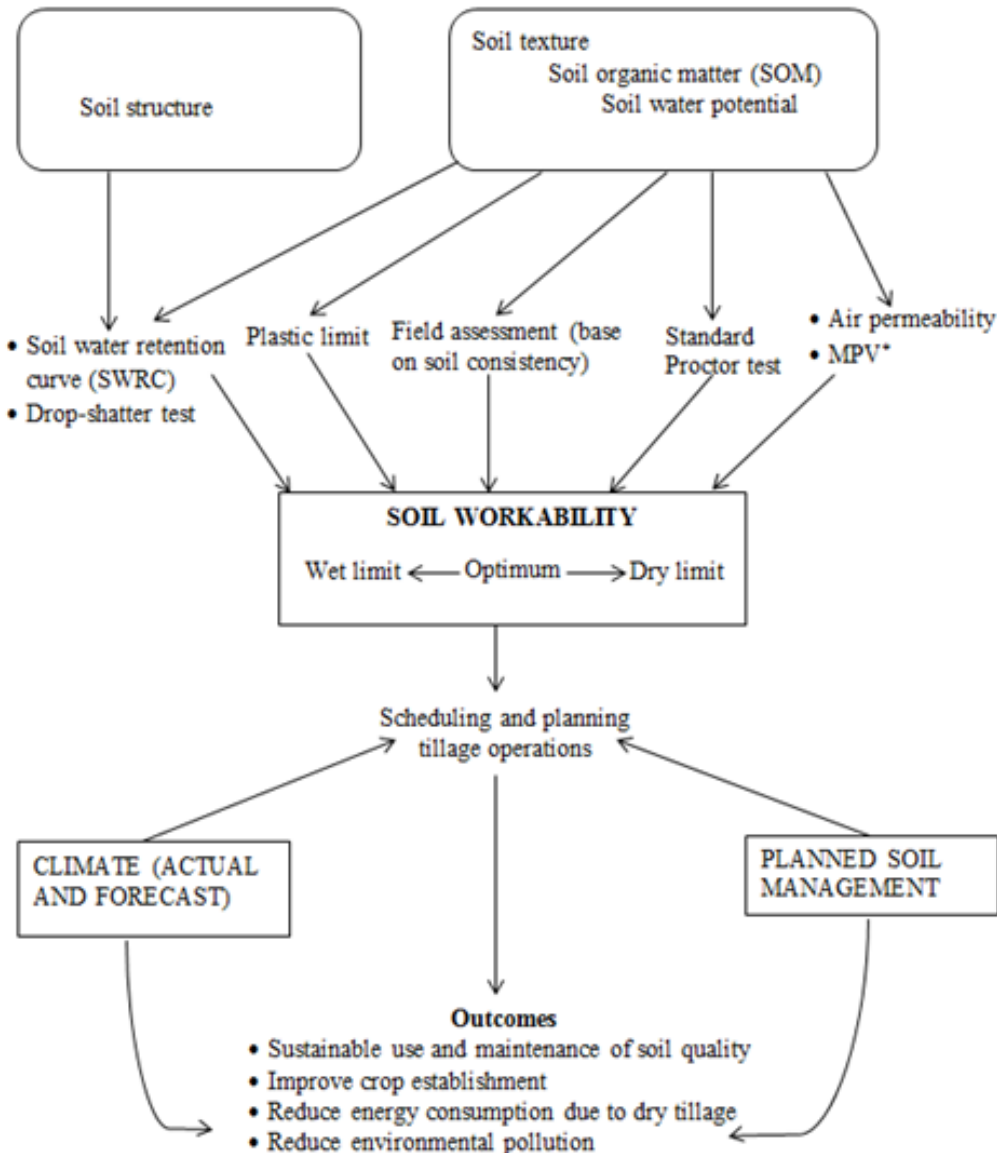
Fig. 3. Approaches for estimating soil workability as part of a Decision Support System *(Paper 1)*.

2.1 Wet tillage limit

The wet tillage limit may be defined as the upper boundary of the water content for tillage. When soil is tilled at water content above θ_{WTL} soil may deform plastically at the expense of fragmentation. Tillage may also produce undesirably large soil fragments, which have less agronomic value in terms of crop establishment (Dexter & Birkas, 2004) as discussed previously in **Section 1**. The θ_{WTL} has been stimated using the plastic limit approach, parameters of the soil water retention curve (SWRC) and based on information on soil air permeability (k_a) and moisture-pressure-volume (MPV).

The plastic limit (PL) is based on Atterberg consistency limits (Atterberg, 1911). The PL of a cohesive soil refers to the gravimetric water content (θ) corresponding to an arbitrary limit between the plastic and semi-solid state of consistency at which a freshly remolded soil changes from plastic to brittle or friable state (McBride, 2007). Dexter and Bird (2001) proposed that $\theta_{WTL}=\theta_{PL}$. The main drawbacks of PL are that it is not applicable to coarse textured soils that are not plastic, water content is determined on a remolded soil (i.e. the soil structure is destroyed), and PL does not take into account pre-existing cracks which play an important role in soil fragmentation (Dexter & Bird, 2001).

Soil water retention curve describes the amount of water retained in a soil at a given matric potential. Dexter and Bird (2001) suggested that θ_{WTL} can be estimated using parameters of the fitted van Genuchten (1980) equation:

$$\theta_{WTL} = \theta_{INFL} + 0.4(\theta_{SAT} - \theta_{INFL}) \qquad [1]$$

where θ_{INFL} is water content at inflection point and θs_{AT} is the water contents at saturation, i.e. at $h=0\ hPa$. Unlike the PL approach, the SWRC approach is determined on undisturbed soils and takes into account soil structure. Despite this strength, SWRC approach does not yield information on soil fragmentation and fragment size distribution produced by tillage.

Hoogmoed et al. (2003) proposed using k_a or the MPV diagram to estimate θ_{WTL}. Soil air permeability is the ability of a soil to conduct air by a convective flow and thus depends on macropores flow. In their study, soil was compacted in the laboratory at different water contents. θ_{WTL} was estimated as the water content where compaction resulted in a remarkable reduction in convective flow of air (for the k_a test) and where the least porosity or isobar of the compression pressure was obtained (for the MPV tests). Compaction of soil implies that results from the tests

may not be directly applicable to non-compacted soils. Air permeability provides an indirect measure of soil fragmentation because it is dependent on air-filled porosity and pore continuity.

2.2 Optimum water content for tillage

Optimum water content for tillage may be defined as the water content where tillage produces a seedbed consisting of neither undesirably larger nor smaller soil fragments. It has been estimated in the laboratory using the PL approach, the SWRC approach and a standard Proctor test, and in the field based on soil consistency state.

Soil water content less than the PL is considered θ_{OPT}. Dexter and Bird (2001) reported that $\theta_{OPT}=$ 0.9 θ_{PL} for most soils. Other authors, for example, Keller *et al.* (2007) found that $\theta_{OPT}=$0.7– 0.9 θ_{PL} for Swedish soils.

Optimum water contents for tillage can also be estimated using the SWRC approach. Dexter and Bird (2001) suggested that θ_{OPT} corresponds to the water content at the inflection point (θ_{INFL}) of SWRC. The θ_{INFL} is the point on a plot of suction of modulus of soil matric potential vs. gravimetric water content, where the curvature of the SWRC is zero (Dexter & Bird, 2001). The authors noted that the inflection point is characterized by "position and slope". The slope provides a qualitative description of soil structure known as the *S*-index (Dexter, 2004). In this work, only the position is considered. Water content at the inflection point can be estimated from fitting water retention data to the van Genuchten (1980) using equation [2]. It is important to emphasize that the SWRC approach does not yield information on why maximum friability occurs at θ_{OPT} or θ_{INFL}.

$$\theta_{INFL} = \theta_{SAT} \left[1 + \frac{1}{1-(1/n)} \right]^{1-(1/n)}$$

[2]

where *n* is a fitted parameter that controls the shape of the curve, *m=1-1/n* (Mualem (1976) restriction).

The standard Proctor test describes the change in bulk density with water content — it describes the optimum water content for maximum soil compaction. The θ_{OPT} corresponds to water content at maximum Proctor density ($\theta_{proctor}$) (Wagner et al., 1992). The reason why θ_{OPT} coincides with $\theta_{proctor}$ may be because at that water content, soil particles are cohesive, but non-plastic which increases the tendency for soil to crumble when stress is applied (Payne, 1988). However, the approach is very laborious due to the manual nature of the compaction test.

The optimum water content for soil workability has also been determined in the field based on soil consistency state. It is similar to the Atterberg (Atterberg, 1911) plastic limit—it involves rolling and pressing soil by the fingers. Soil is workable and maximum fragmentation is expected to occur at a consistency state where soil neither sticks to the palm nor can be rolled into a thin wire without crumbling (Mueller et al., 2003). A major limitation of the approach relates to its practicality. It is very laborious and time consuming to visit many large fields to make the assessment (Edwards *et al.*, 2016).

2.3 Dry tillage limit

The dry tillage limit (θ_{DTL}) may be defined as the lower water content below which a soil has a solid and hard consistency state. Beyond θ_{DTL}, high energy input may be required for soil crumbling. Dexter *et al.* (2005) pointed out that from the perspective of soil structure deterioration, there is no real θ_{DTL} because soil can be tilled in a very dry condition without causing damage to its structure. However, from a seedbed quality standpoint, when soil is too dry, tillage may produce undesirably finer soil fragments, which are susceptible to crusting and wind and water erosion (Braunack & Dexter, 1989a) as stated in **Section 1**. Dry tillage limit is arbitrarily estimated as the water content at which the strength of a soil is twice the strength at θ_{OPT} (i.e. 2τ θ_{OPT} where τ is the soil strength estimated from the effective stress) (Dexter & Bird, 2001).

Dexter et al. (2005) also suggested a simplified approach for estimating θ_{DTL} from the parameters of the water retention data fitted to the van Genuchten (1980) equation:

$$\theta_{DTL} = \theta_{SAT} \left[1 + (\alpha h_{DTL})^n \right]^{1-(1/n)} \tag{3}$$

where h_{DTL} is the matric potential at the dry tillage limit and α is a scaling factor for h. The SWRC approach does not provide information on physical implication of soil strength for soil crumbling.

Other approaches such the drop-shatter test (Hadas & Wolf, 1984) has been used by Hoogmoed et al. (2003) to determine θ_{DTL} for tropical soils in Mexico. The drop-shatter test can be used to assess the friability of a bulk of soil, and it gives information on the fragment size distribution after applying a specific stress (Munkholm, 2013). It is worth mentioning that there is, generally, limited research on θ_{DTL}, particularly in temperate regions. This may be because in colder regions like northwestern Europe, soil workability is most likely to be limited by a wetter conditions rather than drier conditions (Müller *et al.*, 2011).

In order to address the research gaps in soil workability and fragmentation studies there is a need to combine existing approaches for assessing soil workability with semi-quantitative and quantitative approaches for assessing soil friability such as drop-shatter test, tensile strength (Y) and specific rupture energy (E_{sp}). Measurement of Y and E_{sp} at several matric potentials can be useful to determine soil workability based on the water content where a soil has the lowest Y or E_{sp} and the maximum friability. That is to say, a combination of different approaches for estimating soil workability and fragmentation in tillage would be helpful to understand robustness of the approaches for different soils and to capitalize on the strengths of each approach (**Paper 1**).

In sections 3 and 4, the water retention approach (WRA) and the consistency approach (CA) are combined with quantitative approaches for assessing soil friability to quantify: (i) effect of SOC and clay contents on soil workability and fragmentation, and (ii) effect of compaction and sowing date on seedbed physical properties and soil workability.

3 Materials and methods

3.1 Field sites and sampling

Field selection and sampling are important components in any experimental study because they have a huge influence on observed effects and repeatability of results. Therefore, it is important that the choice of a particular field site conforms to the specific aims of the study to successfully achieve the expected outcomes. To quantify effect of SOC and clay contents on soil workability and fragmentation, fields with SOC and clay gradient provided ideal platforms. For the effect of compaction and sowing date on seedbed physical properties and soil workability, a study of a compacted experiment provided an ideal field site. The field sites, soils and sampling procedures used in this work are briefly described below.

3.1.1 Long-term Highfield ley-arable and Askov long-term fertilization experiments (**Papers 2 & 5**)

The Highfield long-term experiment located in Rothamsted Research, UK (51°80′ N, 00°36′ W) was started in 1948 to study different crop rotation strategies (Johnston, 1972). The experimental site was originally grassland, but for ~56 years prior to sampling, each of the plots had an unbroken history under its present management. As a result, soil with similar origin had a SOC gradient in the topsoil for the Bare fallow (BF), Continuous arable rotation (A), Ley-arable (LA) and Grass (G) treatments in the order: G>LA=A>BF. The soil at Highfield is a silt loam classified as Chromic Luvisol according to the World Reference Base (WRB) soil classification system (Watts & Dexter, 1997). The A, LA and G treatments were included in a randomized block design with four field replicates whereas the four BF replicates were not part of the original design and were located at one end of the experimental site.

The long-term fertilization experiment on animal manure and mineral fertilizers is located in Askov Experimental Station, Denmark (55°28′ N, 09°07′ E). The experiment was a randomized block design with three field replicates, and includes the following four nutrient treatments: Unfertilized plots (UNF), and plots that received ½ mineral fertilizer (½NPK), 1 mineral fertilizer (1NPK), and 1½ animal manure (1½AM). The nutrient treatments amounted to ½, 1 and 1½ times the standard rate of a given crop for total nitrogen (N), phosphorus (P), and potassium (K) in AM or NPK fertilizer (Christensen *et al.*, 2017). The different levels of nutrients applied resulted in a SOC gradient among the treatments in the order: 1½AM>1NPK=½NPK>UNF plots. The soil

at the site is a sandy loam. It is classified as an Aric Haplic Luvisol according to the WRB classification system (IUSS Working Group WRB, 2015).

At Askov, sampling took place in September 2014 following harvesting of winter wheat (*Triticum aestivum* L.). At Highfield, sampling was done in March 2015. At both Askov and Highfield, soil cores (6.1 cm inner diameter, 3.4 cm high, 100-cm^3) were taken from 6–10 cm depth and bulk samples at 6–15 cm depth.

3.1.2 Clay gradient in Lerbjerg (**Papers 3 & 5**)

A naturally occurring clay gradient was identified in an arable field near Lerbjerg, Denmark (56°22′ N, 9°59′ E). The field was developed on Weichselian morainic deposits. For many years, the field has been cropped with mainly winter cereals and dressed with pig slurry and mineral fertilizers (Kristiansen et al., 2006). At sampling, the field was established with winter barley (*Hordeum vulgare* L.) with an undersown grass. A reduced-tillage system has been employed for ~15 years (2000–2015). Since 2015, tillage management has been a conventional chisel plowing to ~15 cm depth. To investigate the influence of clay content on soil workability and fragmentation, intact soil cores (6.1 cm inner diameter, 3.4 cm high, 100-cm^3) and bulk soil were sampled at 5–15 cm depth on September 29, 2016 at four locations with clay contents of 0.119, 0.220, 0.289 and 0.446 kg kg^{-1}. The locations will be referred to as L12, L22, L29 and L45 throughout the thesis to indicate the clay contents.

3.1.3 Compaction and sowing date experiment in Ås (**Paper 4**)

To investigate the effect of compaction and sowing date on seedbed physical properties, soil workability and crop yield, the "A02" compaction experiment was identified in Ås, Norway (59°39′47″ N 10°45′49″ E). Soils at the site are characterized as loam over silt loam and silty clay loam. It is classified as Luvic Stagnosol (Siltic) in the WRB classification system (WRB, 2006). The experiment was established in 2014 and the same experimental treatments were repeated in 2015, 2016 and 2017. This work investigates results for soil physical properties for only 2016 and crop yield from 2014 to 2017. The design was a randomized split-plot in two replications comprising two factors. The main plot treatment was sowing date and the split-plot treatment was compaction. The sowing dates included early (A1), normal or timely (A2) and late (A3) sowing dates. The compaction treatments applied each year were no compaction (B0) and compaction by a MF 4225 tractor weighing 4.5 Mg with one pass (B1). Compaction was done wheel-by-wheel. Prior to the experiment in 2016, the field was plowed to ~20 cm depth the previous autumn with

a reversible plow with two moldboards. In A1, plots were either compacted or not compacted, and harrowed and seeded on the same day on April 11, 2016 when the soil was wet to represent the worst-case scenario when farmers will sow early in the spring. In A2, plots were treated two weeks after the A1 treatment (April 25, 2016) when the soil was expected to be in semi-moist condition. Finally, in A3, the treatment was imposed on May 9, 2016 when the soil was expected to be dry. The six treatment combinations were A1+B1, A1+B0, A2+B1, A2+B0, A3+B1 and A3+B0. In all the experimental plots, secondary tillage was done to a depth of ~5 cm using a Ferraboli rotary power harrow (rotorharv). A small grain cereal crop was established on each of the experimental plots: Wheat (*Triticum aestivum* L.*)* in 2014, barley (*Hordeum vulgare* L.) in 2015, oats (*Avena sativa* L.*)* in 2016 and barley in 2017. For each year, the crop was harvested at full maturity using a plot harvester. The harvested area was 9 m² (1.5 m × 6 m) for each plot. The grain yield for each experimental plot was recorded.

Sampling was done on May 24–25, 2016 two weeks after the A3 treatment. Two sets of intact soil cores of different sizes (580-cm³ and 100-cm³) were sampled. The 580-cm³ soil cores were sampled from two sampling positions at 5–15 cm, whereas the 100-cm³ soil cores were sampled from two sampling positions as well as from two depths, ~1–5 cm and at ~5–10 cm. Bulk soil was taken from the two sampling positions and depths (**Fig. 4**).

Fig. 4. Field sampling of soil cores and bulk soil.

At all the field sites, 100-cm³ the intact soil cores and the 580-cm³ (only at Ås) were retrieved by pushing metal cylinders into the soil and carefully removing them to avoid disturbing the soil cores. The cores were then trimmed using a knife and were immediately sealed with tight plastic lids to both ends of the cyliders to prevent evaporation and disurbances during transportation. The bulk soil samples were extracted using a spade or a specially constructed metal shovel

(Schjønning *et al.*, 2002) and were placed in plastic boxes and covered with lids. All soil samples were stored in a 2 ºC room until laboratory analyses.

3.1.4 Experimental results from tillage in Hungarian and Swedish soils (**Paper 5**)

Data on fragment size distribution from tillage experiments published by Dexter and Birkas (2004) and by Keller et al. (2007) were used to validate the new approach proposed in this work for determining θ_{WTL}. The studies investigated the influence of water content on soil fragment size distribution after tillage by a moldboard plow. In the Hungarian study, the tillage experiment was carried out on five soils classified as Calcic Chernozems according to the WRB classification system (Dexter & Birkas, 2004). For the Swedish study, tillage was performed on four soils classified as Eutric Cambisols (Keller et al., 2007). Texture and further details of the soils investigated in this work are presented in **Table 2**.

Table 2. An overview of the investigated sites/soils in the PhD work.

Field sites	Coordinates	Soil class (WRB)	Soil or Treatment	Clay (<2 μm)	Silt (20–20 μm)	Sand (20–2000 μm)	SOC	Paper
				kg kg⁻¹				
Highfield, UK	51°80′ N, 00°36′ W	Chromic Luvisol	BF	0.27	0.25	0.48	0.009	**2 & 5**
			A	0.26	0.26	0.48	0.017	
			LA	0.26	0.26	0.48	0.022	
			G	0.26	0.27	0.47	0.033	
Askov, Denmark	55°28′ N, 09°07′ E)	Aric Haplic Luvisol	UNF	0.09	0.09	0.81	0.010	**2**
			½NPK	0.10	0.10	0.80	0.011	
			1NPK	0.10	0.09	0.81	0.011	
			1½AM	0.10	0.10	0.81	0.013	
Lerbjerg, Denmark	56°22′ N, 9°59′ E	Luvisols	L12	0.12	0.04	0.84	0.014	**3 & 5**
			L22	0.22	0.07	0.71	0.014	
			L29	0.29	0.09	0.62	0.014	
			L45	0.45	0.12	0.43	0.016	
Ås, Norway	59°39′47″ N 10°45′49″ E	Luvic Stagnosol (Siltic)	–	0.22	0.29	0.44	0.026	**4**
Carpathian Basin Hungary[1]	–	Calcic Chernozems	Soil 1 [a]	0.35	0.42	0.23	0.019	**5**
			Soil 2 [a]	0.40	0.28	0.32	0.020	
			Soil 3 [a]	0.50	0.26	0.24	0.019	
			Soil 4 [a]	0.60	0.33	0.07	0.020	
			Soil 5 [a]	0.35	0.38	0.27	0.020	
Uppsala, Sweden[2]	–	Eutric Cambisols	Sälby 1	0.22	0.40 [b]	0.33 [c]	0.021	**5**
			Sälby 2	0.36	0.46 [b]	0.10 [c]	0.022	
			Ultuna 1	0.43	0.28 [b]	0.24 [c]	0.011	
			Ultuna 2	0.54	0.29 [b]	0.10 [c]	0.017	

[a]Size fraction not stated.

[b]Size fraction of Silt: 2–50 μm

[c]Size fraction of Sand: 50–2000 μm

[1]Data from Dexter and Birkas (2004) and [2] data from Keller et al. (2007).

3.2 Measurement techniques

3.2.1 Field measurements

Penetration resistance (PR) was measured in the field for the Ås, Norway soil. The PR was measured in and below the seedbed layer on July 4, 2016 down to 27 cm depth to determine soil strength. For each experimental plot, fifteen replicate measurements were made using a hand-held cone penetrometer at an average soil water content of 0.28 m^3 m^{-3}. The PR measured per plot were used to compute the geometric mean PR at different depths in and below the seedbed layer.

3.2.2 Laboratory measurements

When needed, the bulk soil samples were gently fractured along natural planes of weakness and were spread out on a table in ventilated room to air-dry. Some of the air-dry soil samples were mechanically crushed and sieved to <2 mm to determine texture and SOC content (**Table 2**).

To obtain soil water retention data, the 100-cm^3 soil cores were successively drained on tension tables at −10, −30 and −100 hPa matric potentials. Thereafter, the samples were moved to vacuum pots and pressure plate apparatus to successively establish the matric potentials of −300 and −1000 hPa, respectively according to the methodology described by Dane and Hopmans (2002). Water content at −15,000 hPa (wilting point) was determined on air-dry <2mm samples using WP4-T Dewpoint Potentiometer (Scanlon *et al.*, 2002). Wilting point is the minimum amount of soil water content below which plant root cannot extract water, hence plant will wilt (Kirkham, 2014).

From the soil water retention information pore characteristics, soil total porosity, volumetric water content and air-filled porosity (ε_a) were determined. In addition to pore characteristics derived from the soil water retention data, the soil-gas transport properties were determined on the 100-cm^3 soil cores at −100 hPa by measuring air permeability (k_a) (only in **Papers 3 & 4**) and gas diffusivity (*Dp*) (only in **Paper 4**). Air permeability was measured using the Forchheimer approach recently proposed by Schjønning and Koppelgaard (2017). Gas diffusivity was measured by a non-steady method according to Taylor (1949) and as described by Schjønning (1985). Relative gas diffusivity (*Dp/Do*) was obtained by relating Oxygen (O_2) diffusion in the soil sample to that in the free air. Air-filled porosity was related to k_a or *Dp/Do* to obtain pore continuity or organization indices (Blackwell *et al.*, 1990) and pore tortuosity (Ball, 1981) of soil pore system. Bulk density was determined upon oven drying the soil cores at 105 °C for 24 h.

The conditions describing soil workability were assessed from the quantitative measurements of soil fragmentation (fragment size distribution), tensile strength properties as a function of fragment size and matric potential, and the estimated range of water contents for tillage (**Paper 3**).

Soil fragmentation provides a quantitative information on ease of fracturing soil when energy is applied. Schjønning et al. (2002) proposed a soil drop test, which is a modification of the original drop-shatter test method by Hadas and Wolf (1984). Soil drop test is best done in the field. However, it is possible to perform the test in the laboratory on intact soil cores. Unlike in the field, the test can be performed in the laboratory on an intact soil adjusted to different matric potentials. The soil drop test was performed on the 580-cm^3 intact soil cores (**Paper 4**) at −100, −300 and −1000 hPa. Briefly, after equilibrating the soil cores at the specific matric potential, each soil core was dropped from a predetermined height (200 cm) onto a concrete floor covered with a plastic sheet to avoid losing the soil fragments. The fragmented soil was collected and left to air-dry. Thereafter, the soil was sieved through a nest of sieves with apertures of 16, 8, 4 and 2 mm to determine fragment size distribution. The amount of fragmentation was expressed as the geometric mean

Fig. 5. Soil drop test on soil cores in the laboratory.

diameter (GMD). The soil drop test is simple and easy to perform and has been proposed as soil friability index (Snyder *et al.*, 1995). Nevertheless, it is sensitive to water content and texture and energy input used in the test is low compared to what is used during tillage operations (Munkholm. *et al.*, 2002b).

Tensile strength (*Y*) may be defined as the maximum stress required to fracture a soil aggregate. It is a useful measure of the strength of individual soil aggregate because it is a sensitive measure of soil physical conditions (Dexter & Kroesbergen, 1985). Tensile strength can be assessed with a crushing test. This was achieved by crushing some of the air-dry soil samples using the roller method (Hartge, 1971). The crushed soil was sieved through a set of sieves to obtain the following aggregate size fractions: 8–16, 4–8, 2–4 and 1–2 mm. Some of the 8–16 mm (**Papers 2 & 4**) and 8–16, 4–8 and 2–4 mm aggregates (**Paper 3**) were capillary-
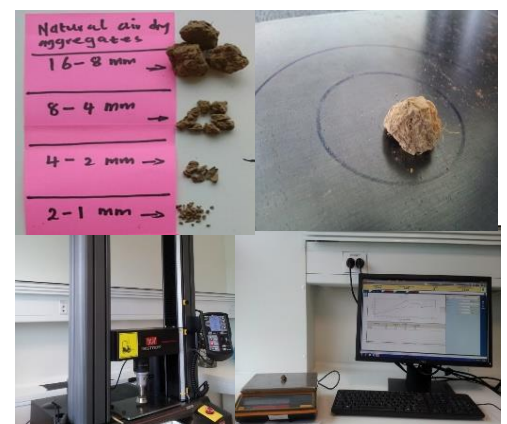
Fig. 6. Measurement of tensile strength of soil aggregates in the laboratory.

adjusted to −100, −300 and −1000 hPa using tension tables, vacuum pots and pressure plates, respectively (Dane & Hopmans, 2002). For the Askov soil samples, the aggregates were divided into three groups based on their moisture status: air-dry, air-dry rewetted to −100 hPa and field moist aggregates (Jensen *et al.*, 2017). Tensile strength of each aggregate was measured in an indirect tension test. It is called "indirect" because the tensile stress is produced by applying a compressive stress, which causes tensile deformation perpendicular to the loading direction. The remaining of the crushed aggregates were collected and oven-dried at 105° C for 24 h to determine their water content. According Dexter and Kroesbergen (1985), *Y* for spherical particles of incompressible material can be calculated as:

$$Y = 0.576F/d^2 \qquad [4]$$

where *F* is the maximum force (N) required to fracture the aggregate and *d* (m) is the effective diameter of the spherical aggregate obtained by adjusting the aggregate diameter according to the individual masses (Dexter & Kroesbergen, 1985):

$$d = d_1(m_0/m_1)^{1/3} \qquad [5]$$

where d_1= is the diameter of aggregates defined by the average sieve sizes, m_0 is the mass (g) of the individual aggregate and m_1 is the mean mass (g) of a batch of aggregates of the same size class.

Perfect and Kay (1994) proposed using specific rupture energy (E_{sp}) for statistical characterization of aggregate strength in tillage studies. They argued that E_{sp} is more appropriate for estimating the strength of dry aggregates than *Y* because it involves no assumption on mode of failure. Munkholm. and Kay (2002) indicated that E_{sp} is also useful for estimating the strength and fragmentation of wet aggregates.

Rupture energy (E_r) was calculated from the area under the stress-strain curve up the point of tensile failure (Vomocil & Chancellor, 1969):

$$E_r \approx \Sigma_i F(s_i)\Delta s_i \qquad [6]$$

where $F(s_i)$ denotes the mean force at the *i*th subinterval and Δs_i the displacement length of the *i*th subinterval. The specific rupture energy (E_{sp}) was defined on gravimetric basis from the equation:

$$E_{sp} = E_r/m \qquad [7]$$

where m is the mass of the individual aggregates.

Quantifying soil friability gives information on ease of producing optimal seedbed with a desirably small fragment size for crop germination and establishment of plants (Munkholm, 2011). Soil friability index (k_Y) was quantified as the slope of the plot of natural logarithm (Ln) of Y for all size fractions and natural logarithm of aggregate volume (Utomo & Dexter, 1981):

Ln (Y) = -k Ln (V) +b [8]

where k is an estimate of friability, b is the intercept of the regression and denotes the predicted Ln (Y) (kPa) of 1 m³ of bulk soil, and V (m³) is the estimated aggregate volume. Soil friability was classified according to the friability classification of Imhoff *et al.* (2002) where F<0.1 = not friable, 0.1–0.2 = slightly friable, 0.2–0.5 = friable, 0.5–0.8 = very friable and >0.8 = mechanically unstable (**Papers 3 & 4**).

Young's modulus (E) was estimated to obtain a quantitative measure of elasticity of the aggregates (only for the Highfield soil in **Paper 2**) using a macro program. Young's modulus was calculated from the stress (σ) and strain (ε) of aggregate:

$E=\sigma/\varepsilon$ [9]

The effective stress (σ_e) at −100, −300, −1000 hPa, and at air-dry state was calculated according to Towner and Childs (1972) (only in **Papers 3 & 5**). According to the authors in the absence of an external mechanical stress, σ_e has two components matric suction (ψ) and surface tension (γ). The contribution of γ to soil strength is important when the degrees of saturation (χ) is <0.3 (Vepraskas, 1984). For the soil investigated in this PhD work, χ ranged from 0.05 to 0.95 therefore, both ψ and γ were used:

$$\sigma e = \chi\psi + \frac{0.3}{\alpha}\left[\left(\frac{\psi_2+\psi_1}{2}\right)(\chi_1-\chi_2)\right]$$ [10]

where χ_1 is the initial degree of saturation, and χ_2 is the final degree of saturation due to change in matric suction. The first term on the right-hand side is generated by pore water pressure and the second term by the surface tension forces.

χ was calculated according to Dexter *et al.* (2007):

$$\chi = \left(\frac{\theta - \theta_{RES}}{\theta_{SAT} - \theta_{RES}} \right) \tag{11}$$

where θ is the gravimetric water content at a given matric suction, θ_{RES} is the residual water content and θ_{SAT} is the water content at saturation.

$$\alpha = \left(\frac{\theta - \theta_{RES}}{\theta_{SAT}} \right) \tag{12}$$

The water contents for tillage were determined using the water retention approach (WRA) (**Papers 2 and 5**), and the consistency approach (CA) (**Papers 2–5**).

The water contents for tillage estimated using WRA is based on fixed points (water contents) generated from modeled water retention characteristics using the van Genuchten (1980) equation. The following were estimated according to Dexter and Bird (2001) and Dexter et al. (2005):

The gravimetric water content (θ, kg kg^{-1}) corresponding to each matric potential (hPa) was calculated by fitting the van Genuchten equation with the Mualem (1976) restriction of $m=1-1/n$ to each set of water retention data obtained from Highfield, Askov and Lerbjerg soils:

$$\theta = (\theta_{SAT} - \theta_{RES}) \left[1 + (\alpha h)^n \right]^{1-(1/n)} + \theta_{RES} \tag{13}$$

where θ_{RES} is the residual water content, $h=\infty$, and α is a scaling factor for h. θ_{RES} was set equal to zero. Values of n were obtained using the curve-fitting program, RETC (van Genuchten *et al.*, 1991).

The wet tillage limit (θ_{WTL}) was estimated using **Eq. 1**

The optimum water content for tillage (θ_{OPT}) was estimated as water content at the inflection point of the soil water retention curve (θ_{INFL}) using **Eq. 2**.

The matric potential at the dry tillage limit (h_{DTL}) was estimated as proposed by Dexter et al. (2005):

$$h_{DTL} \approx \frac{2}{\alpha} \left[\frac{1}{1-(1/n)} \right]^{1/n} n^{1.1} \tag{14}$$

The corresponding water content at the dry tillage limit (θ_{DTL}) was calculated by inserting h_{DTL} from **Eq.14** into equation **Eq.13** yielding **Eq. 3**.

The range of water contents for tillage using the water retention approach ($\Delta\theta_{RANGE}$ (water retention)) was calculated as:

$$\Delta\theta_{RANGE}\text{(water retention)} = \theta_{WTL} - \theta_{DTL} \qquad [15]$$

The consistency approach is based on a combination of soil plastic limit and an estimate of tensile strength of aggregates in the 8–16 mm size class at different water contents.

θ_{WTL} and θ_{OPT} were determined according to Dexter and Bird (2001):

$$\theta_{WTL} = \theta_{PL} \qquad [16]$$

$$\theta_{OPT} = 0.9\,\theta_{PL} \qquad [17]$$

θ_{DTL} was graphically determined as water content at which the strength of soil is twice the strength at θ_{OPT} from the relation between natural logarithm of tensile strength of 8–16 mm soil aggregates and gravimetric water content measured at different matric potentials (Munkholm. et al., 2002a).

The range of water contents for tillage based on the consistency approach ($\Delta\theta_{RANGE}$ (consistency)) was calculated as:

$$\Delta\theta_{RANGE}\text{(consistency)} = \theta_{WTL} - \theta_{DTL} \qquad [18]$$

3.2.3 Simulation of soil workability and number of workable days

Weather data (daily dry bulb temperature, wet bulb temperature, wind speed, maximum air temperature, minimum temperature, soil temperatures, relative humidity, rainfall, and solar radiation covering the period 2014 to 2018 were obtained to simulate soil water content and the number of workable days.

Soil workability from 1 to ~10 cm depth for the BF, A, LA and G treatments, and the L12, L22, L29 and L45 were determined using the wet and dry tillage limits estimated by WRA, CA and the new approach (NA) proposed in this PhD thesis (more details on NA is provided in section 5). Briefly, the DAISY model was used to calculate the variation in the soil water content at three depths: 3, 6 and ~10 cm over the simulation period. DAISY uses the weather data and soil information to model the response of a one dimensional soil column and outputs as well as the soil matric

potential (Edwards et al., 2016). A binary decision variable was produced for each soil and depth, being 1 if the soil water content is within the range of the wet and dry tillage limits and elsewise 0. An overall binary decision variable for soil workability was determined by considering the binary variables for all the three layers, being 1 if the decision variables for all the three layers are 1, and elsewise 0 (Edwards et al., 2016).

Table 3. Overview of measurements or estimated parameters carried out on soils from the different field sites.

Field sites	Soil physicochemical properties					Soil fragmentation and strength properties						Estimation of water contents for tillage			Paper
	TA	SWRC	k_a	Dp	PL	Soil drop test	Y	E_{sp}	E	k_Y	σ_e	WR approach	Consistency approach	New approach	
Highfield, UK	+	+	−	−	+	−	+	+	+	+	+	+	+	+	**2 & 5**
Askov, Denmark	−	−	−	−	+	−	−	−	−	−	−	+	+	−	**2**
Lerbjerg, Denmark	+	+	+	+	+	−	+	+	−	+	+	+	+	+	**3 & 5**
Ås, Norway	+	+	+	−	+	+	+	+	−	+	−	−	+	−	**4**
Uppsala, Sweden	−	−	−	−	−	−	−	−	−	−	−	−	−	+	**5**
Carpathian Basin, Hungary	−	−	−	−	−	−	−	−	−	−	−	−	−	+	**5**

TA, texture analysis; SWRC, soil water retention characteristics; k_a, air permeability; Dp, gas diffusivity; PL, Plastic limit; Y, tensile strength; E_{sp}, specific rupture energy; E, Young's modulus; k_Y, Friability index; σ_e, effective stress; WR, Water retention. Negative symbol indicates the parameter was not measured or estimated in the PhD work, positive symbol indicates the parameter was measured or estimated in the PhD work.

3.3 Statistical analyses

Data obtained for non-normally distributed variables (k_a, PO_1, σ_e, Y, E_{sp} and E) were log-transformed to yield normality. Results are reported as the geometric mean for the non-normally distributed variables, and as arithmetic mean for the normally distributed variables (θ, ε_a, Dp/Do, τ, k_Y). Statistical analyses in **Papers 2 & 4** were carried out in R software package (R Core Team, 2017). The Highfield data were fitted by a linear mixed effect model, which comprised treatment as fixed and block as random factors. The Askov data were fitted by a linear model, which comprised block as a fixed effect. Finally, the Ås data were fitted by a generalized linear model. Statistical comparison were made using a pairwise comparison (Tukey test). In the case of the BF treatment in Highfield, which was not included in the original randomized block design, statistical comparison with counterpart treatments were done using a paired t-test. For the Lerbjerg soil without no true field replicates, data analyses were carried out in MS Excel. Analyses were based on observed trends obtained from the relationship between the investigated soil properties. For all the studies, the criterion used for statistical significance was $p < 0.05$.

4 Results and discussion

4.1 Quantification of soil workability and fragmentation

Soil workability is an important indicator in tillage whereas soil fragmentation is a primary aim in tillage during seedbed preparation. In essence, a workable soil should be easy to fragment during tillage to create a favorable seedbed for crop establishment and growth. The ease of tilling soil implies that soil should be friable, and should be neither too wet nor too dry. The conditions describing the ease of crumbling can be assessed from the quantitative measurements of tensile strength characteristics as a function of aggregate size and matric potential (**Papers 2–4**; Munkholm. & Kay, 2002; Munkholm. et al., 2002a), fragment size distribution as a function of water content or matric potential (**Paper 4**; Munkholm. et al., 2002b; Dexter & Birkas, 2004; Keller et al., 2007) and the estimated range of water contents suitable for tillage (Paper 2–4; Dexter & Bird, 2001). Soil strength characteristics, friability and water contents for tillage are affected by SOC and clay contents, and the state of soil structure as shown in **Fig. 1**, which in turn affect soil workability and fragmentation in tillage. These are discussed more in detail in **Sections 4.1 & 4.2** below.

4.1.1 Soil strength and fragmentation: the role of SOC, clay, matric potential and compaction

Soil organic carbon content is a key soil property affecting many soil physical properties and functions. Soil organic carbon affects soil mechanical properties such as soil strength, bulk density, inter-aggregate or structural porosity, and enhances better soil fragmentation during tillage (Abdollahi *et al.*, 2014).

To assess the role of SOC on soil strength properties, soils with similar texture and a range of SOC in the topsoil were used to overcome the risk of confounding interaction between texture and SOC on the investigated parameters (**Paper 2**). Results from the Highfield and Askov soil showed that in the air-dry state, tensile strength (Y) and Young's modulus (E) of aggregates significantly decreased with increasing SOC (**Fig. 7**).

The negative relationship between SOC and Y or E can be explained by the role of the SOC in improving soil structural porosity. At low water content such as in the air-dry state the structural pores are typically air-filled, which facilitate crack propagation and crack elongation when stress is applied, resulting in soil fragmentation during tillage (Dexter & Richard, 2009). The positive relationship between SOC and specific rupture energy (E_{sp}) can be ascribed to increased elasticity of aggregates with increasing SOC (**Paper 2**).
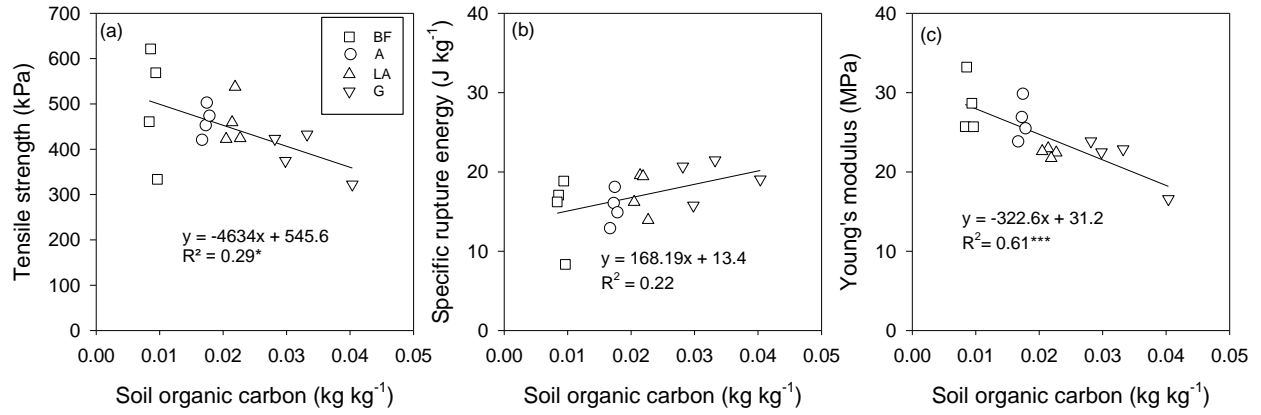
Fig. 7. (a) Tensile strength, (b) specific rupture energy and (c) Young's modulus of air-dry aggregates calculated as geometric means across the four aggregate classes (8−16, 4−8, 2−4 and 1−2 mm) for each plot as a function of soil organic carbon. Bare fallow (BF), Arable (A), Ley-arable (LA) and Grass (G) treatments. *$p < 0.05$ and ***$p < 0.001$ (***Paper 2***).

In the wet state, aggregates of the soil with large SOC content are stronger than those with small SOC (Munkholm. et al., 2002a). At −100 hPa, aggregates of the G treatment with large SOC were stronger in terms of E_{sp} than the counterpart BF soil with small SOC (**Paper 2**). This may be attributed to the influence of SOC including organic binding and bonding materials such as polysaccharides fungal hyphaes and roots (Tisdall & Oades, 1982). Previous study of the BF, A and G treatments found more diverse and active root biomass in the G treatment compared to the A treatment (Hirsch *et al.*, 2009). Findings here indicate that with increase in SOC, soil strength is reduced in the air-dry state implying that soil clods or large fragments are easily fragmented by tillage operations, whereas in the wet state, soil becomes relatively stronger. That is, large SOC reduces the tendency of soil slumping under its own weight when wet, e.g., during the winter (**Paper 2**) or due to external stresses, e.g., field traffic. This implies that a SOC-enriched soil is workable under wetter conditions compared to a SOC-depleted soil. This is also illustrated by the large θ_{WTL} for the G soil (0.34 kg kg^{-1}) compared to the BF soil (0.19 kg kg^{-1}) (this is discussed in the subsequent section).

Clay is a basic soil constituent and governs soil physical, chemical and biological properties and processes. The degree of packing of clay mineral particles influences soil structure and inter-particle bonding, which in turn affects pore structure characteristics. The relationship between soil structural characteristics and clay content is shown in **Fig. 8a−f** for the Lerbjerg clay gradient soil. The volume of pores < 30 μm linearly and significantly increased with increasing clay content (**Fig. 8a**). Similar positive and significant linear increase was observed between tortuosity (τ) and

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clay content (**Fig. 8e**). The k_a linearly and significantly decreased with increasing clay content (**Fig. 8c**). Similar linear negative relationship was observed between PO_1 and clay content, although not statistically significant (**Fig. 8d**). The volume of pores >30 μm and Dp/Do both showed a sharp decrease from L1 to L3, and a moderate decrease from L4 to L6 (**Fig. 8b and f**).
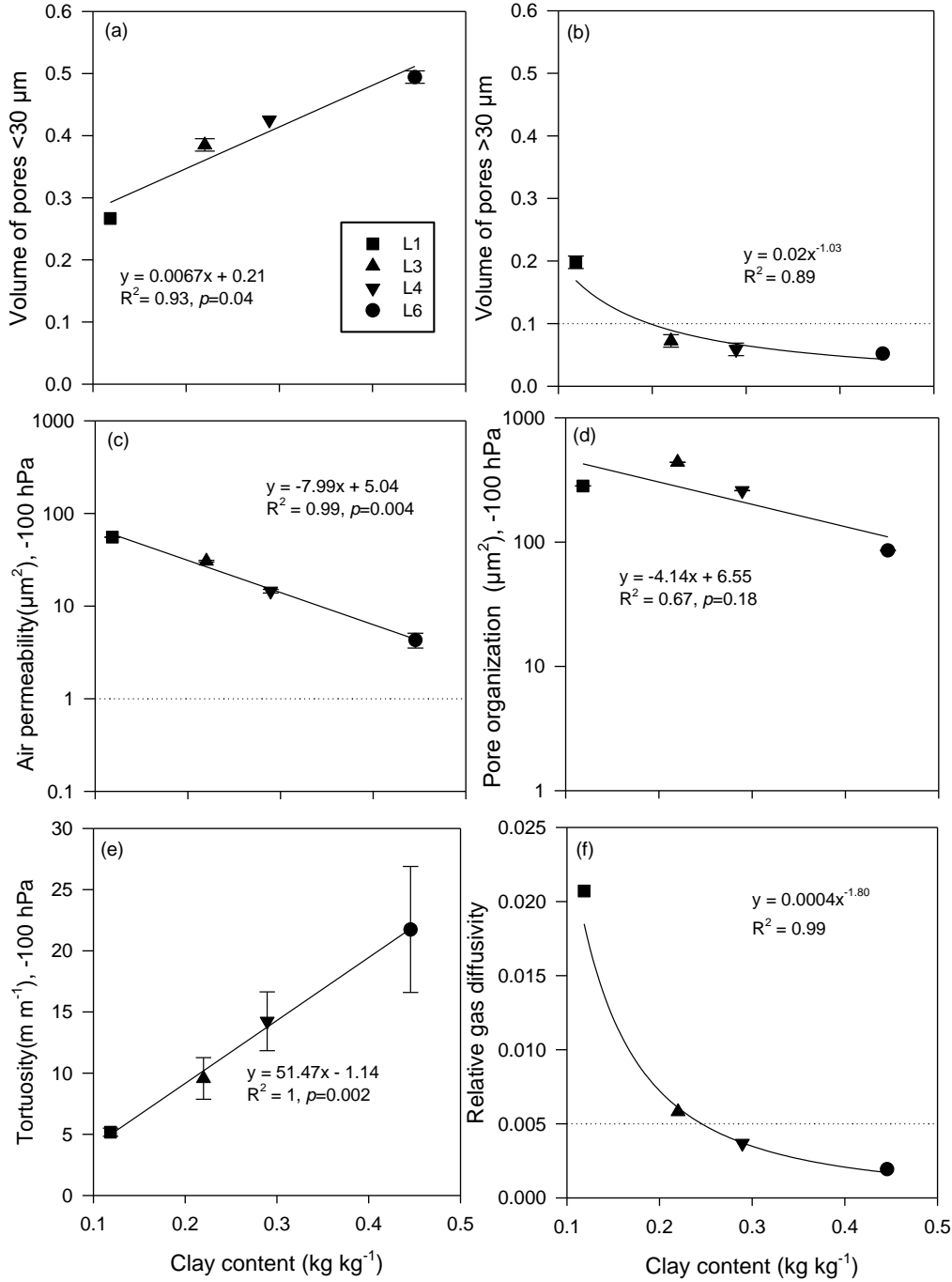
Fig. 8. (a) Volume of pores <30 μm, (b) volume of pores >30 μm, (c) air permeability, (d) pore organization index ($PO_1 = k_a/\varepsilon_a$), (e) tortuosity and (f) relative gas diffusivity at −100 hPa as a

function of clay content for L12, L22, L29 and L45 with 0.12, 0.22, 0.29 and 0.45 kg kg⁻¹ clay content, respectively. Solid lines indicate regression and dotted lines indicate frequently-stated lower threshold values of air-filled porosity (volume of pores >30 μm), air permeability and relative gas diffusivity. Please note the different axes scales. Error bars indicate the standard error. (***Unpublished data***).

Clay content also influences soil strength properties. Results from the Lerbjerg gradient showed that Y and E_{sp} increased with increasing clay content and with decreasing water content (i.e. more negative matric potential). Increase in strength with increasing clay content may be explained as Y is largely dependent on the random distribution of flaw planes in a soil (Braunack *et al.*, 1979). Increased clay content tends to increase the volume of intra-aggregate pores (as evidenced by increasing volume of pores <30 μm with increasing clay content (**Fig. 8a**). Grant (1989) noted that a soil with large clay content tends to have more contact points and a more uniform pore size distribution and therefore, have fewer sites for the propagation of failure zones. Increase in strength with decreasing water content or matric potential has been explained in terms of σe (Terzaghi, 1923). For the clay gradient, both Y and E_{sp} increased with increasing σe for the range of matric potentials studied (**Fig. 9a and b**). Increase in strength due to high clay content or increasing effective stress may reduce soil workability because it is an indication that soil clods are stronger and high energy will need to be expended for soil fragmentation (**Paper 3**).
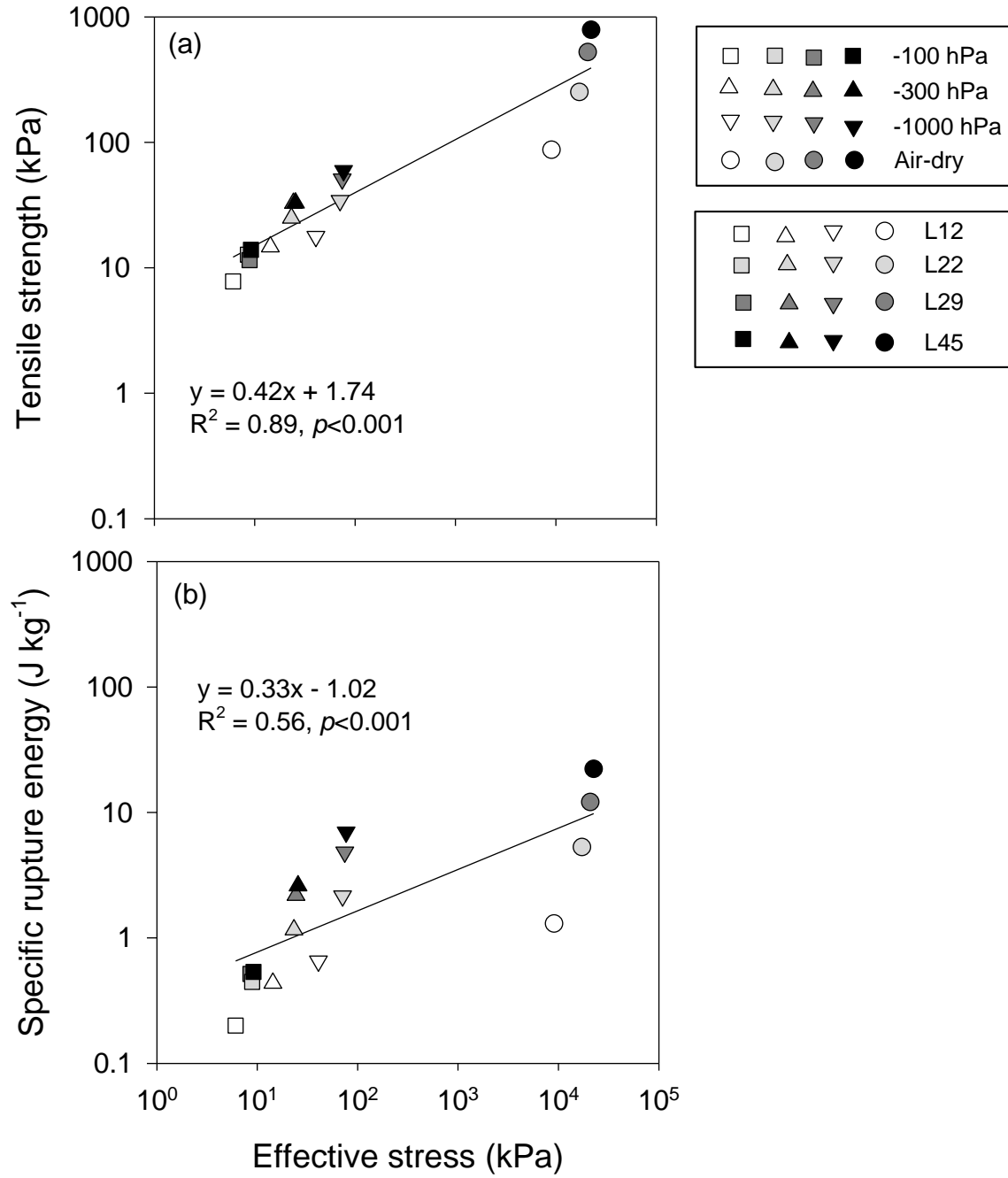
Fig. 9. Geometric mean values of (a) tensile strength and (b) specific rupture energy calculated as geometric means across all size fractions as a function of the geometric mean of effective stress. Symbols represent means of L12, L22, L29 and L45 at −100, −300, −1000 hPa and at air-dry state. (***Paper 3***).

Tensile strength and soil fragmentation are largely dependent on soil pore structural characteristics and presence of micro-cracks. As shown in **Fig. 10** for the soil from Ås, Norway, the fragment size distribution from the soil drop test negatively and significantly decreased with increasing ε_a at −100 hPa (**Paper 4**).

Tensile strength decreases with increasing air-filled macroporosity and pore continuity, but increases with increasing τ of the pore system (Munkholm. et al., 2002b). This was confirmed by the Lerbjerg soil. It was found that at −100 hPa as ε_a increased from L45 to L12, both Y and E_{sp} decreased accordingly. Conversely, Y or E_{sp} both increased with increasing τ, albeit not statistically significant in neither case (**Fig. 11a–f**) (**Paper 3**). The findings indicate that soil management that alters the soil structure may consequently affect soil strength and fragmentation. For instance, soil compaction caused by

$$y = -219.98x + 62.83$$
$$R^2 = 0.40*$$

Fig. 10. Relationship between geometric mean diameter and air-filled porosity at −100 hPa. Lines indicate regression lines. *$p<0.05$ (***Unpublished data***).

field traffic densifies soil and reduces soil macroporosity, which in turn affects other physical properties and soil functions such as air and water flow in the soil essential for plant growth.

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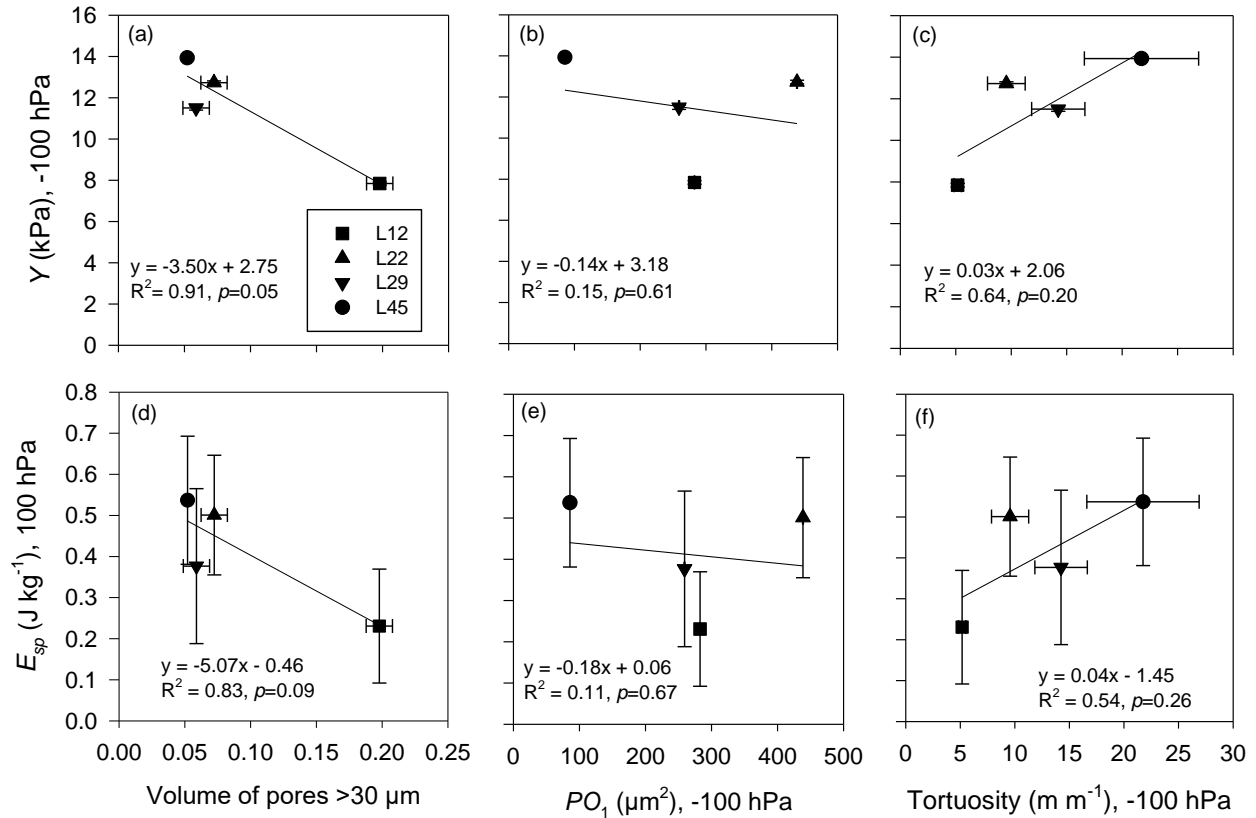
Fig. 11. Tensile strength (Y) and specific rupture energy (E_{sp}) calculated as the geometric mean of 2–4, 4–8 and 8–16 mm size fractions at −100 hPa as a function of (a and d) volume of pores >30 µm, (b and e) pore organization ($PO_1 = k_a/\varepsilon_a$) and (c and f) tortuosity at −100 hPa. Error bars indicate the standard error (***Paper 3***).

Even though tillage is carried to alter fragment size distribution and to improve soil conditions for crop establishment, emergence and growth of seedlings (Braunack & Dexter, 1989a; Braunack & Dexter, 1989b), when performed in less-than-ideal soil moisture conditions, tillage can be destructive to soil structure. For instance, when soil is too wet, tillage may result in kneading, a phenomenon where small particles are squeezed together to form large soil clods. The clods become very strong upon drying. Moreover, there is a risk of soil compaction due the stresses exerted by wheels of machinery and tillage implement. Therefore, field traffic or cultivating in wet soil conditions can destroy the soil structure, which consequently affects seedbed mechanical and physical properties. From the soil investigated in Ås, Norway, Compaction (B1) and the Early sowing (A1) treatments or their combination (A1+B1) resulted in increased Y and PR in and below the seedbed layer (**Paper 4**). The strong aggregates for the B1 and A1 is further illustrated by the generally, high E_{sp} at both 1–5 and 5–10 cm depth (**Table 4**)

Table 4. Geometric means of specific rupture energy of 8–16 mm soil aggregates.

Depth (cm)	Treatment	Specific rupture energy (J kg^{-1})			
		−100 hPa	−300 hPa	−1000 hPa	Air-dry
1–5	A1+B1	0.35	0.94	1.99	4.7
	A1+B0	0.24	1.26	1.65	3.7
	A2+B1	0.22	0.93	1.36	2.7
	A2+B0	0.16	0.59	1.18	4.0
	A3+B1	0.24	0.42	1.31	1.9
	A3+B0	0.22	0.56	1.19	1.9
	Averages across compaction				
	B1	0.27	0.71	1.52	2.9
	B0	0.21	0.75	1.32	3.0
	Averages across sowing times				
	A1	0.29	1.09b	1.81	4.2b
	A2	0.19	0.74b	1.27	3.3b
	A3	0.23	0.48a	1.24	1.9a
	Averages across sowing times				
5–10	A1+B1	0.35	1.99b	3.30b	4.0
	A1+B0	0.26	1.14ab	1.52a	3.5
	A2+B1	0.24	0.51a	0.92a	3.3
	A2+B0	0.18	1.01ab	0.82a	2.4
	A3+B1	0.28	1.10ab	1.37a	3.1
	A3+B0	0.33	0.77ab	1.50a	3.0
	Averages across compaction				
	B1	0.29	1.03	1.61b	3.5
	B0	0.25	0.96	1.23a	2.9
	Averages across sowing times				
	A1	0.30	1.50b	2.24c	3.7
	A2	0.21	0.72a	0.87a	2.8
	A3	0.30	0.92ab	1.44b	3.0

Values with different letters are significantly different at $p<0.05$. A1, Early sowing date; A2, Normal sowing date; and A3, Late sowing date; B0, control and B1, compaction with a single pass by a tractor weighing ~4.5 Mg (***Unpublished data***).

An assessment of soil friability obtained from the relationship between *Y* and the volume of aggregates showed that the G treatment with large SOC increased soil friability compared to the other treatments, although not statistically significant (**Fig. 12**). A high value of friability index shows that large aggregates are weaker than small aggregates due to a high probability of the presence of flaw planes for tensile failure in the former compared to the latter (Braunack et al., 1979).
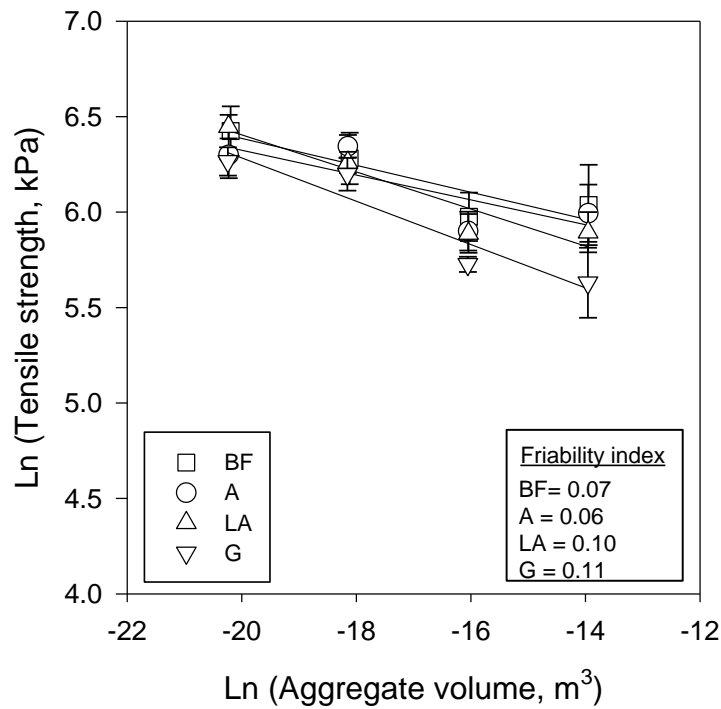
Fig. 12. Natural logarithm (Ln) of tensile strength (kPa) as a function of Ln aggregate volume (m³), for air-dry aggregates. Soil friability index (k_Y) determined as the slope of the regression. Error bars indicate standard errors (***Unpublished data***).

As outlined in **Section 1**, soil friability is influenced by water content or matric potential. Results from the Lerbjerg soil showed that for the L12, k_Y tended to increase from −100 hPa to −300 hPa and then decreased from −1000 hPa to air-dry, whereas for L45, k_Y increased from −100 hPa to −1000 hPa and then decreased for air-dry. For both L22 and L29, k_Y increased from −300 hPa to −1000 hPa and decreased at air-dry state (**Fig. 13**). Evidence here showed that it is important to determine the optimum water content for tillage by measuring k_Y at several points on the water retention curve and over a wide range of water contents or matric potentials because friability does reach a maximum (**Paper 3**).

Fig. 13. Friability (k_Y) as a function of matric potential. L12, L22, L29 and L45 have clay content of 0.12, 0.22, 0.29 and 0.45 kg kg⁻¹, respectively (***Unpublished data***).

Evaluating soil friability from the soil drop test indicated that in general, fragmentation was poor for all treatments and at all matric potentials studied. Nevertheless, the A1+B1 soil showed the worst fragmentation, indicated by high GMD values, large proportion of large fragments and small proportion of small fragments. This implies that, in practice, larger number of successive seedbed harrowing, including their negative impact on soil mechanical and physical properties would be required to fragment the soil into a suitable seedbed for spring-sown small grain cereal crops (**Paper 4**).

Multiple factors affect the final yield of crops (Perez-Bidegain *et al.*, 2007) and the seedbed physical properties is one of the essential factors. This is because seedbed consisting of, for example, large and strong fragments can delay crop emergence, root proliferation and penetration, which in turn adversely affect crop yield. Although not significant, the A1 treatment reduced yield of small grain cereals by 4% in 2014–2017 compared to the timely sowing date (A2). The late sowing (A3) significantly decreased yield of cereal crops in 2014 and 2015 compared to both the A1 and A2 treatments, but this may mainly be ascribed to a shorter growing season rather than an influence of soil physical properties (**Paper 4**).

4.1.2 Soil water contents for tillage: the role of SOC, clay and compaction

This section assesses soil workability based on estimating the water contents for tillage and quantifies the influence of SOC and clay contents, and compaction and sowing date on the range of water contents for tillage.

Soil organic carbon affects the water contents for tillage primarily through its influence on soil structure, water holding capacity (Murphy, 2015), and increased particle bonding. The latter increases soil strength in the wet state as discussed in **Section 4.1.1**, which in turn increases θ_{WTL}. Soil organic carbon influences clay dispersion in water —a soil with small SOC content tends to have higher dispersion of clay than a soil with large SOC content (Watts & Dexter, 1997; Jensen et al., 2017). Cementation and crusting of dispersed clay upon drying results in 'hard-setting soil' (Mullins *et al.*, 1987) characterized by hard and structureless soil mass, which typically affects θ_{DTL}. For the Highfield and Askov soils investigated, it was found that large SOC content (G and 1½AM soils) increased both the wet and dry tillage limits compared to the soil with small SOC content (BF and UNF) (**Paper 2**). For example, based on CA, the θ_{WTL} and θ_{DTL} for G corresponded respectively to ~ −300 and ~ −2500 hPa, and ~ −900 and ~ −2100 hPa for the BF soil. This indicates that the G soil is workable in a wetter or drier condition compared to the BF soil.

Both WRA and CA showed that $\Delta\theta_{RANGE}$ was wider for the G soil compared to the BF, and for the 1½AM compared to the UNF soil. For the Highfield soil, the increase in $\Delta\theta_{RANGE}$ from BF to G was more than a factor of 3, and about a factor of 1.2 from UNF to 1½AM. There was a positive linear and a significant relationship between $\Delta\theta_{RANGE}$ and SOC contents for the Highfield and Askov soils — explaining 54–87% of the variation in $\Delta\theta_{RANGE}$ (**Paper 2**), consistent with the findings of Munkholm. et al. (2002a).

Clay content influences the water contents for tillage by increasing θ_{WTL} and θ_{DTL}, and decreasing the $\Delta\theta_{RANGE}$ (Dexter & Bird, 2001). Increase in θ_{WTL} and θ_{DTL} with increasing clay content can be explained as due to increasing the volume of intra-aggregate pores whereas, a decrease in $\Delta\theta_{RANGE}$ may be ascribed to a reduced macroporosity (**Paper 1**). Based on CA, θ_{WTL} and θ_{DTL} for L12 with small clay content were 0.21 and 0.09 kg kg^{-1}, respectively. These corresponded to approximately −65 and −3600 hPa, respectively. For the L45 with large clay content, θ_{WTL} and θ_{DTL} were 0.29 and 0.24 kg kg^{-1} corresponding to approximately −1900 and −4100 hPa, respectively. $\Delta\theta_{RANGE}$ reduced by a factor of ~2 from L12 to L45 (**Paper 3**).

Tillage affects the water contents for soil workability through its effects on soil structural changes. Traffic and tillage in less suitable soil moisture conditions cause alteration due to compaction and kneading, which can be detrimental to the soil structure. Soil structural degradation in the topsoil caused by tillage in too wet conditions has been shown to persist until the following autumn (Munkholm. & Schjønning, 2004). For the soil investigated in Ås, Norway, compaction reduced $\Delta\theta_{RANGE}$ by 10% compared to the control treatment. Further, the early sowing date and late sowing date reduced $\Delta\theta_{RANGE}$ by 20 and 18%, respectively compared to the timely sowing date, although not statistically significant (**Paper 4**). Findings here showed that compaction and/or tillage-induced soil structural degradation may complicate scheduling of operations because it can potentially reduce the $\Delta\theta_{RANGE}$ for subsequent tillage operations.

The results from **Papers 2−4** confirmed the hypotheses postulated in this work:(i) increasing SOC content increases the range of water contents for soil workability, (ii) increasing clay content decreases the range of water contents for soil workability, and (iii) tillage operations in less-than-ideal soil conditions adversely affects seedbed physical properties and soil workability. **Table 5** summarizes the overall influence of SOC, clay content and tillage management on the water contents for tillage discussed in **Section 4.1.2**.

Table 5. An overview of overall influence of soil organic matter and clay contents, and compaction on the water contents for tillage based on the consistency approach.

Attribute	Overall trend			Reason	Paper
	θ_{WTL}	θ_{DTL}	$\Delta\theta_{\text{RANGE}}$		
Soil organic carbon	↑	↑	↑	Improved macroporosity and high absorptive capacity for water	2
Clay content	↑	↑	↓	Reduced macroporosity	3
Timing of tillage					
Early	↓	↓	↓	Soil is wet: degradation of soil structure —reduced porosity.	4
Timely/normal	↑	↑	↑	Soil moisture is optimal: less destruction to soil structure — improved soil porosity	
Late	↘	↘	↓	Soil is dry: risk of crusting and cementation, and consequently densification due to too fine particles	
Compaction	↓	↓	↓	Degradation of soil structure — reduced porosity	

θ_{WTL}, Wet tillage limit; θ_{DTL}, dry tillage limit; and $\Delta\theta_{\text{RANGE}}$, the range of water contents for tillage

4.2 Influence of SOC on $\Delta\theta_{\text{RANGE}}$ of a field with variable clay content

Good soil management is key for maintaining or increasing the window of water content for soil workability (Hallett & Bengough, 2013). It involves management practices that improve soil structure which will also improve soil physical conditions for tillage such as increasing SOC and preventing practices that deteriorate soil structure such as compaction due to field traffic. The study on Lerbjerg soil with variable clay content showed that $\Delta\theta_{\text{RANGE}}$ varies for different parts of the field (**Paper 3**). For such soils, the aim is to make $\Delta\theta_{\text{RANGE}}$ overlap so that a farmer can perform tillage in 'one go'. Since we know that SOC increases $\Delta\theta_{\text{RANGE}}$ (**Paper 2**), one option could be to increase SOC in the different parts of the field.

This section illustrates how increase in SOC can influence $\Delta\theta_{\text{RANGE}}$ of the Lerbjerg field with clay gradient. In other words, it demonstrates how increase in SOC can increase $\Delta\theta_{\text{RANGE}}$ and overlap the matric potentials of the tillage limits across the L12, L22, L29 and L45. To do this, data from the Highfield soil were used to estimate how much θ_{WTL}, θ_{DTL} per unit change in SOC.

For the exercise here, it was assumed that the soil in Lerbjerg behaves similar to the Highfield soil in terms of SOC effects on tillage limits. The Lerbjerg data were inserted into the obtained expressions indicating the estimated changes**. Table 6** shows how the matric potential for tillage limits of the L12 to L45 would change if the current measured SOC at 10 cm depth (topsoil layer) were increased by 5, 10, 20, 30, 50 and 100%.

As expected, the θ_{WTL} and θ_{DTL} for the L12, L22, L29 and L45 increased with increasing SOC content. In general, increase in SOC by 5 to 100% from the current levels did not change θ_{WTL} much for the L12 to L45 (**Table 6**). The $\Delta\theta_{\text{RANGE}}$ did not change when SOC was increased by 5% or by 10% from the current levels, but did so from 20% to 100%. This can be interpreted as a small increase in SOC may have only a subtle increment in $\Delta\theta_{\text{RANGE}}$ particularly for a soil with large clay content. Findings here imply that a farm manager of the investigated field or similar fields with high clay variability would need to increase SOC by several tons per hectare to remarkably improve θ_{WTL} and $\Delta\theta_{\text{RANGE}}$. This can be done by for example, by amending soil with organic manure and residues. Assuming two general values: 5% dry matter and 45% carbon in dry matter (Taghizadeh-Toosi *et al.*, 2014), the quantity of fresh organic source (manure or slurry) inputs required to increase the SOC by 5, 10, 20, 30, 50 and 100% from the current levels are shown in **Table 6**. A fresh-weight application rate of 36, 38, 35 and 34 t ha⁻¹ will need to be applied to increase the present levels of SOC of L12, L22, L29 and L45 by 5%. However, this increase in SOC did not really change the $\Delta\theta_{\text{RANGE}}$. As mentioned elsewhere, between 20 and 100% of the present level of SOC is needed to really increase $\Delta\theta_{\text{RANGE}}$, but this will need between 131 and 636 t ha⁻¹ of fresh organic source.

It needs to be emphasized that the estimated application rates shown here assumed all the SOC in the organic manure or slurry resides in the soil. It has been shown that the long-term C retention in soil is about 14% for animal faeces (manure) (Thomsen *et al.*, 2013). This suggests that, much more (~7 times more) fresh organic manure or slurry than the quantities estimated here would need to be applied to compensate for SOC losses in the soil. In practice, high application rate may not be feasible because large quantities of manure might be scarce. Assuming a farmer can produce or obtain this large quantities, bringing the manure to the field can lead to soil compaction due to field traffic. It needs to be emphasized that farmers' application of organic

manure can be restricted by regional or country specific environmental regulations and norms on reducing nutrient losses from agricultural fields.

Table 6. Changes in water contents for tillage (wet tillage limit, θ_{WTL}, dry tillage limit, θ_{DTL} and range of water contents for tillage, $\Delta\theta_{RANGE}$) assuming SOC increases from 5% to 100% at 10 cm depth. θ_{WTL}, θ_{DTL} *and* $\Delta\theta_{RANGE}$ estimated using the consistency approach.

Attribute	Soil	SOC (kg kg⁻¹)	SOC (t ha⁻¹)	Quantity of fresh organic manure* (t ha⁻¹)	Water content (kg kg⁻¹)			Matric potential (hPa)	
					θ_{WTL}	θ_{DTL}	$\Delta\theta_{RANGE}$	θ_{WTL}	θ_{DTL}
Current	L12	0.014	19.1	-	0.21	0.09	0.12	−65	−3586
	L22	0.014	20.4	-	0.23	0.15	0.09	−479	−4670
	L29	0.014	18.9	-	0.25	0.19	0.06	−1221	−3413
	L45	0.016	19.3	-	0.29	0.24	0.06	−1846	−4118
5% increase in SOC	L12	0.014	19.9	36	0.22	0.09	0.12	−64	−3760
	L22	0.015	21.3	38	0.24	0.15	0.09	−463	−4818
	L29	0.014	19.7	35	0.25	0.19	0.06	−1210	−3507
	L45	0.017	20.1	34	0.30	0.24	0.06	−1830	−4224
10% increase in SOC	L12	0.015	20.8	71	0.22	0.09	0.13	−64	−3942
	L22	0.016	22.2	75	0.24	0.15	0.09	−448	−4971
	L29	0.015	20.4	69	0.26	0.19	0.06	−1199	−3604
	L45	0.017	20.8	67	0.30	0.24	0.06	−1815	−4333
20% increase in SOC	L12	0.016	22.3	139	0.23	0.10	0.13	−62	−4335
	L22	0.017	23.8	147	0.25	0.15	0.10	−419	−5290
	L29	0.017	22.0	136	0.26	0.20	0.07	−1177	−3804
	L45	0.019	22.3	131	0.31	0.25	0.06	−1783	−4558
50% increase in SOC	L12	0.020	26.7	331	0.25	0.11	0.14	−59	−5761
	L22	0.021	28.5	350	0.28	0.17	0.11	−343	−6379
	L29	0.021	26.3	321	0.29	0.21	0.08	−1113	−4476
	L45	0.024	26.3	303	0.34	0.26	0.08	−1693	−5308
100% increase in SOC	L12	0.027	33.0	605	0.29	0.13	0.16	−53	−9257
	L22	0.029	35.1	636	0.32	0.19	0.13	−246	−8713
	L29	0.028	32.3	584	0.33	0.23	0.10	−1015	−5869
	L45	0.032	31.5	529	0.39	0.29	0.10	−1552	−6841

One practical solution to achieve high SOM inputs while reducing potential losses is to add organic inputs in the form of 'charred organic carbon' (biochar). Biochar is very stable in soil environment and contributes to carbon storage, i.e. carbon sequestration. Incorporating biochar into soil also improves SOC content, soil fertility and physical quality (Sohi *et al.*, 2010). Testing this in a field experiment could be a subject for future studies.

5 A new approach for estimating the water contents for tillage

Knowledge and a reliable estimate of the water contents for tillage is of utmost importance for scheduling tillage operations in terms of when 'to go' and 'not to go' to the field (**Paper 1**). This is because carrying out tillage operations in an ideal soil conditions is crucial to avoid tillage-induced soil structural degradation, creating an undesirable seedbed for crop establishment, and using high-energy input because soil is not workable. Different approaches have been proposed in the literature for estimating the water contents for tillage. As discussed in **section 2**, the water retention approach (WRA) and the consistency approach (CA) have been used as state-of-the-art approaches for estimating the water contents for tillage.

The WRA is based on fixed points generated from modeled water retention characteristics using the van Genuchten (1980) equation whereas CA is based on a combination of soil plastic limit and an estimate of tensile strength of aggregates in the 8–16 mm size class at different water contents. WRA implies soil has a uni-modal pore size distribution. Therefore, WRA may not be appropriate for estimating the water contents for tillage for soils with bi-modal pore size distribution (Dexter *et al.*, 2008) such as arable top-soils which may be induced by SOC and tillage management. As for CA, θ_{WTL} is estimated from remolded soil, i.e. destroying the soil structure and therefore, does not represent soils with intact structure. Moreover, the approach provides an arbitrarily way for determining θ_{DTL}. There is a need to revisit WRA and CA to outline their robustness for different soils. More importantly, there is still a strong need to develop new approaches to quantify the water contents for tillage. To contribute to this development, a new approach (NA) is proposed for estimating θ_{WTL} and θ_{DTL}. The NA was compared with the WRA and CA using a soil with a range in SOC content and a soil with a range of clay content. Finally, to provide practical information on the range of water contents for tillage, a simulation was done to quantify the number of workable days along SOC and clay gradient in the spring and the autumn.

In the newly proposed approach, θ_{WTL} is estimated as water content at soil air-filled porosity of 0.10 $m^3 m^{-3}$. At this set lower limit of air-filled porosity, for most soils, it is mainly the structural pore space which will be partially air-filled whereas the matrix pores will be water-filled. The air-filled structural pores and micro-cracks elongate and coalesce under applied stress to induce soil fragmentation (Dexter & Richard, 2009). The θ_{DTL} is estimated from a fixed tensile strength value of 50 kPa for all soils which is different from the approach proposed by Dexter and Bird (2001) who estimated the dry tillage limit as "the water content at which the strength of soil is twice the strength at the optimum water content". The value was based on Soil Science Division Staff (2017) classification of resistance to rupture of a 25 to 30 mm blocklike soil specimen. The θ_{DTL} can be

determined as follows: (1) determining the effective stress at predefined measured points on the water retention curve, (2) estimating effective stress at 50 kPa, (3) estimating the matric potential at 50 kPa, and (4) determining the water content at the estimated matric potential (**Paper 5**).

The θ_{OPT} can be determined from fitting the water retention data to the double-exponential equation (DE) proposed by Dexter et al. (2008). The pore size distribution predicted by the DE obtained by numerical differentiation is plotted as a function of matric potential (in pF=$\log_{10}$ hPa). The θ_{OPT} is graphically determined as the water content at the break point between matrix and structural pores (**Paper 5**). Examples of how θ_{OPT} is graphically determined are presented in **Fig. 14**.
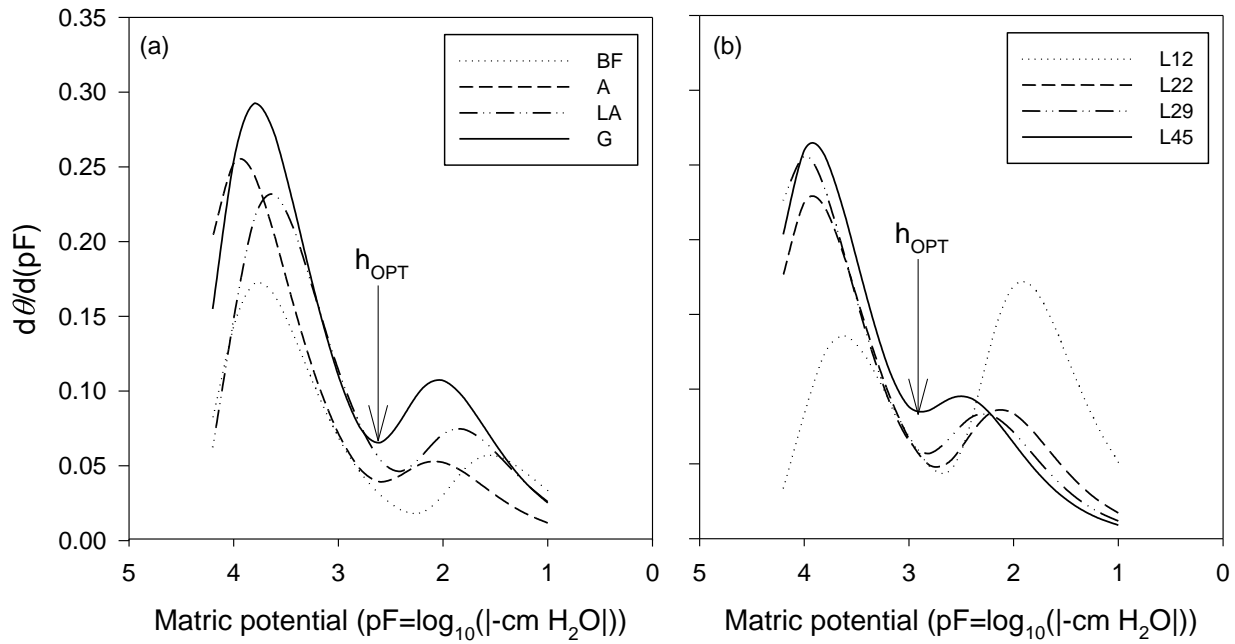
Fig. 14. Pore size distribution (dθ/d (pF) as a function of matric potential (in pF) for (a) Highfield soil and (b) Lerbjerg soil. Bare fallow (BF), Arable (A), Ley-arable (LA) and Grass (G) treatments. L12, L22, L29 and L45 have clay contents of 0.119, 0.220, 0.289 and 0.446 kg kg^{-1}, respectively. Arrows show how the matric potential (*h*) at the optimum water content for tillage (θ_{OPT}) is determined graphically (**Paper 5**).

5.1 A comparison of the approaches for estimating the water contents for tillage

For the Highfield soil, except for BF, θ_{WTL} estimated by the NA were generally wetter than those estimated by WRA and CA. In the case of the Lerbjerg soil, the estimates by NA were identical to those by WRA, but in general, slightly wetter than the estimates provided by CA (**Table 7**). The discrepancies in the estimates provided by NA on one hand and CA on the other hand can be explained as, unlike NA, CA estimates θ_{WTL} as the plastic limit, which involves remolding the soil. Therefore, water content at plastic limit may not reflect the water content for a soil with an intact soil structure (**Paper 5**). The optimum water contents for tillage (θ_{OPT}) was estimated using the double-exponential function (DE) proposed by Dexter et al. (2008). The estimates provided by DE were slightly wetter than those for WRA and CA. Interesting, θ_{OPT} estimated by WRA, CA and DE were generally identical to water content at −300 hPa matric potential (**Table 7**). Recently, Jensen *et al.* (2019) recommended using DE for predicting soil water retention. They argued that unlike the van Genuchten (1980) model (which is applied in the WRA), DE is more flexible and provides adequate description of bi-modal pore size distribution, which can be induced by management effect such as SOC and tillage. Here, it is suggested that the DE should be used for estimating θ_{OPT} in accordance to Dexter and Richard (2009). In cases where information on water retention data for a given soil is scarce, water content at −300 hPa matric potential may be used as θ_{OPT} (**Paper 5**). In general, θ_{DTL} estimated by NA were wetter than that by WRA and CA, but with a few exceptions for the A treatment in Highfield and L12 in Lerbjerg. For these soils, WRA provided unrealistic estimates of the θ_{DTL} for the A treatment, and θ_{WTL} for the L12 compared to the CA and NA (**Table 7**). However, it is not known which of the approaches provides the correct estimates of the water contents for tillage.

Table 7. Soil water contents for tillage (the wet tillage limit, θ_{WTL}; the optimum water contents for tillage, θ_{OPT}; and the dry tillage limit, θ_{DTL}). θ_{WTL} and θ_{DTL} for the Highfield and Lerbjerg soil estimated using the water retention approach, the consistency approach and the new approach. θ_{OPT} was estimated using the water retention approach, the consistency approach and the double-exponential function.

Soil/Treatment	Wet tillage limit			Optimum water content for tillage				Dry tillage limit		
	Water retention approach	Consistency approach	New approach	Water retention approach	Consistency approach	Water content at −300 hPa	Water content at break-point[a]	Water retention approach	Consistency approach	New approach
	kg kg^{-1}									
BF	0.27	0.19	0.25	0.24	0.18	0.20	0.21	0.21	0.16	0.18
A	0.23	0.24	0.27	0.18	0.21	0.26	0.26	0.08	0.18	0.24
LA	0.33	0.25	0.36	0.28	0.23	0.30	0.30	0.22	0.20	0.25
G	0.36	0.34	0.41	0.29	0.31	0.37	0.35	0.18	0.24	0.30
L12	0.27	0.21	0.26	0.24	0.19	0.15	0.14	0.19	0.09	0.08
L22	0.27	0.23	0.25	0.23	0.21	0.24	0.23	0.20	0.15	0.21
L29	0.31	0.25	0.28	0.27	0.22	0.28	0.27	0.24	0.19	0.26
L45	0.38	0.29	0.37	0.34	0.26	0.37	0.35	0.30	0.24	0.35

[a] Water content at the break-point between textural and structural porosity.

Bare fallow (BF), Arable (A), Ley arable (LA) and Grass (G); L12, L22, L29 and L45 have clay contents of 0.119, 0.220, 0.289 and 0.446 kg kg^{-1}, respectively (***Paper 5***).

5.2 Workable days in spring and autumn as a function of SOC and clay contents

In simulating soil workability and number of workable days, a soil is considered workable when the simulated water contents for all the depths investigated were within the wet and dry tillage limits. The limits are based on those estimated by WRA, CA and NA. The average workable days in the spring and the autumn from 2014 to 2018 are shown in **Table 8**. Soil organic carbon and clay contents have a strong influence on workable days which is consistent with the findings showing the strong effect of SOC on the range of water content for tillage (Dexter & Bird, 2001; **Paper 2**), and clay content vs. the range of water content for tillage. The average workable days in the autumn and spring varies for each soil and the approach for estimating the wet and dry tillage limits. The number of workable days in spring and autumn seasons over the five-year period were more for the G and LA in Highfield compared to the BF and A treatments, and for the L12 and L22 than the L29 and the L45, except for the WRA (**Table 8**). The number of workable days largely depends on the approach used to estimate θ_{WTL} and θ_{DTL}. The limits estimated by CA produced fewer number of days than WRA and NA. This could be attributed to the fact that, the simulated soil water contents over the period from 2014 to 2018 were wetter than the upper workability limit estimated by CA (**Paper 5**).

Table 8. Average yearly workability during the spring and autumn over 2014–2018 for the investigated soils in Highfield and Lerbjerg. Workability limits were estimated using the water retention approach (WRA), the consistency approach (CA) and the new approach (NA).

Site	Soil/treatment	Workability limits-WRA		Workability limits-CA		Workability limits-NA	
		Workable days in spring	Workable days in autumn	Workable days in spring	Workable days in autumn	Workable days in spring	Workable (days) in autumn
Highfield	BF	7 (0–10)	10 (2–25)	0 (0)	0 (0)	3 (0–9)	2 (0–7)
	A	0 (0)	0 (0)	1 (0–4)	0 (0)	0 (0–1)	4 (0–11)
	LA	15 (0–32)	15 (5–28)	0 (0)	0 (0)	56 (39–76)	39 (37–41)
	G	21 (0–44)	17 (6–31)	13 (0–38)	7 (1–21)	63 (41–76)	40 (31–45)
Lerbjerg	L12	1 (0–2)	1 (0)	35 (0–69)	37 (23–45)	36 (0–71)	38 (24–45)
	L22	13 (0–20)	11 (4–15)	47 (0–66)	34 (21–44)	8 (0–13)	8 (3–11)
	L29	10 (0–15)	10 (3–13)	32 (0–46)	24 (17–31)	1 (0–3)	1 (0–1)
	L45	22 (0–36)	17 (10–25)	0 (0–1)	0 (0)	0 (0)	0 (0)

Bare fallow (BF), Arable (A), Ley arable (LA) and Grass (G); L12, L22, L29 and L45 have clay contents of 0.119, 0.220, 0.289 and 0.446 kg kg^{-1}, respectively. The range in the parenthesis refer to the minimum and maximum number of workable days in the period 2014 – 2018 (***Paper 5***).

5.3 Drawbacks of the new approach for estimating water contents for tillage

Although the new approach accounts for the soil structure and estimates θ_{DTL} using an absolute strength threshold value (50 kPa), measurements of tensile strength and water retention points in the wet and dry regions can be time consuming. In spite of this, the approach can be useful for extending our knowledge in predicting the soil workability for tillage operations. Further, as for WRA and CA, NA in some cases estimated 'zero' and 'one' workable day for the investigated soils, which may be unrealistic. However, as mentioned elsewhere, which approach provides the correct estimates of the water content for tillage still remains an open question and this could be an important subject for further studies. Even though NA gives quantitative threshold of the stress required for soil fragmentation, the fixed strength value for estimating θ_{DTL} used for all soils is still somewhat arbitrary. Field validation of the proposed approach is necessary to know its general applicability.

In terms of ease of measuring wet tillage for the different approaches, as for the WRA, NA requires more water retention data for estimating θ_{WTL}. Conversely, the plastic limit used in CA as the wet tillage limit is relatively simple, fast and cheap to estimate θ_{WTL} (**Paper 5**).

6 Practical measures for improving the workability of soil during tillage

The workability of soils can be improved by improving soil structure. One option for improving soil structure is to increase SOC, which in turn increases the range of water contents for tillage (**Paper 2**). It was also shown that increase in SOC can reduce cultivation problems in agricultural soils with a wide range in clay contents (**Paper 3**). Managing tillage, for example, reduced tillage practices can help to conserve SOC because tillage accelerates soil organic matter mineralization (Stockmann *et al.*, 2013). If tillage cannot be avoided, SOC can be increased by adding inputs (organic manures and mineral fertilizers). However, it was shown that this is not easy to do. The addition of charred organic carbon can help reduce the potential loss of SOC.

Adjusting tillage intensity in fields with variable soil workability can potentially improve soil fragmentation during tillage. Recently, Daraghmeh *et al.* (2019) showed that soil fragments produced under a high-intensity tillage using a rotavator were stronger than those for the low-intensity tillage. They attributed this to destruction of air-filled structural porosity, and higher dispersion of clay for the high-intensity tillage compared to the low-intensity tillage. Adjusting intensity of tillage 'on-the-go' will ensure that the appropriate intensity is applied according to site-specific soil workability in field with variable range of water contents for tillage. This could be studied in the future.

7 Conclusions

This PhD work quantified the influence of SOC and clay contents, and compaction and sowing date on soil workability and fragmentation. Workability and fragmentation were assessed from the quantitative measurements of tensile strength characteristics, fragment size distribution as a function of matric potential, and the estimated water contents for tillage. The main conclusions are:

Soil organic carbon (SOC) improves soil structure, which enhanced soil fragmentation and increased the range of water contents for tillage ($\Delta\theta_{RANGE}$). Results suggest that management practices that increase SOC are fundamental for increasing the range of water contents for tillage to produce the desired tilth for crop establishment.

Results showed that tensile strength is highly influenced by both clay content and matric potential. Increase in clay content decreased $\Delta\theta_{RANGE}$. Findings emphasized that, a soil with a clay gradient exhibits variable $\Delta\theta_{RANGE}$. Therefore, a uniform tillage operations of a texturally variable field might not be the best management option because spatio-temporal variability of a field matters.

Field traffic and tillage in less-than-ideal soil condition because soil is too wet or too dry not only affected seedbed physical properties for the current grown crop, but can potentially reduce soil workability for subsequent tillage operations, which might complicate scheduling of operations, particularly in colder climates where the growing period for cereals is short.

The average workable days in the spring and in the autumn estimated from the consistency approach and the new approach decreased with increasing clay content although the reverse was found for the water retention approach. More importantly, findings suggest that average yearly soil workability also depend on the approach used for estimating soil workability limits.

The new approach for estimating the wet tillage limit, the optimum water content for tillage and the wet tillage limit provided estimates of the range of water contents for tillage for soil with a range of soil organic carbon content and soil with a clay gradient. This opens a possibility for evaluating the approach in laboratory and in field conditions on a range of soil textures and in different climates to establish its general applicability.

8 Perspectives for future studies

This study demonstrated that SOC has a positive effect on soil workability and fragmentation—it increases the $\Delta\theta_{RANGE}$. It is important to investigate the influence of SOC on $\Delta\theta_{RANGE}$ of soils, e.g., different textures and climatic conditions.

In this thesis, the limits of water contents for soil workability of the investigated soils were estimated mainly from laboratory measurements. There is a need for field experiments to test these limits on similar soils to establish applicability of the defined limits.

Further studies on how to make results on soil workability and fragmentation more usable and accessible to farmers will be an important step forward towards sustainable use of soil for agricultural production. Findings from this PhD work could be used to develop a decision support system (DSS) or a simple decision support App for rapid use by farmers to determine soil workability in their fields.

There is a need for more laboratory and field studies to evaluate the new approach for estimating the water contents for tillage for a range of soils, under different management and different climatic conditions. Such studies are essential to illustrate the practical value and general applicability of the new approach. Also, the absolutes value of 0.10 m^3 m^{-3} used to estimate the wet tillage limit and 50 kPa used to estimate the dry tillage limit may need to be refined in the future.

9 Research contributions to advancement of science and practical application of the results in farm management

The findings of the study contribute to advancement of science by providing a quantitative information on the influence of SOC and clay contents on soil workability and fragmentation. It also proposed a new approach for estimating the water contents for tillage, which would be useful for improving the prediction of soil workability and fragmentation in tillage. The main implications of the findings from the agronomic point of view are:

For the same soil type, increase in SOC increased the θ_{WT} and θ_{DTL}, and consequently increased the range of water content over which soil is workable. It is worth noting that the large value of SOC associated with the Grass treatment in Highfield is partly because it has not been cultivated. That is, cultivating the soil will lead to a drastic decline in SOC over time (**Paper 2**).

In practice, there can be a remarkable field-to-field and within-field variations of soil characteristics, which in turn affect the range of water contents for tillage. Findings from the Lerbjerg soil emphasized that soil workability and fragmentation can vary in a field with a variable soil texture. This implies that in such a field, a uniform tillage operation might not be the best management option unless operations are properly scheduled. The following might be options available for tillage management: (i) A farmer would have to divide his/her a field into subfields, i.e. based on clay content. He or she can then till the field at different times for each soil according to according to site/location-specific soil workability. However, detailed soil mapping of the field is required for delineating soil workability within fields according to clay variability. (ii) The timing of tillage should be made to synchronize with when $\Delta\theta_{RANGE}$ for the whole field (L12, L22, L29 and L45) overlaps. (iii) Another option available to a farmer is to improve the soil physical quality by reducing compaction and increasing SOC content. The latter in turn improve soil conditions for tillage through increasing $\Delta\theta_{RANGE}$ and overlap of matric potentials of tillage limit across the field as illustrated in **section 4.2**.

In colder climatic regions where the growing period for cereals is short, cultivation in less-than-ideal moisture conditions such as early spring when soil is still wet can limit the ability of a soil to produce favorable seedbeds for crop establishment during tillage. Further, although the machinery used in the experiment at Ås, Norway was small compared to what farmers may customarily be using today, the adverse effects of traffic and tillage in wet conditions on soil physical properties such as soil fragment size distribution and the tensile strength of aggregates were still detected in many instances. Large tires with low inflation pressure will help reduce the

risk of structural degradation of soil during tillage in wet conditions, even when light machinery is used.

Overall, the quantitative information on the effect of SOC and clay contents, and tillage management on the water contents for tillage can be useful for developing a DSS for field readiness, which comprises soil workability as studied in this thesis and soil trafficability—ability of a soil to support and withstand field traffic (Rounsevell, 1993). The DSS could be used as an integral part of future farm management system for tillage planning and operations for scheduling tillage operations, which will allow farmers to cultivate soils within the window of workability. This can be useful to reduce the risk of traffic and tillage-induced soil structural degradation as discussed in this thesis. It can also reduce energy require during tillage, which saves fuel. These benefits are indispensable for sustainable use of soils and improving environmental quality in modern agriculture.

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11 Supporting papers

Paper 1

Predicting soil workability and fragmentation in tillage: a review

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Predicting soil workability and fragmentation in tillage: a review

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Abstract

Soil workability and friability are required parameters to consider when creating suitable seedbeds for crop establishment and growth. Knowledge of soil workability is important for scheduling tillage operations and for reducing the risk of tillage-induced structural degradation of soils. A reliable evaluation of soil workability implies a distinctive definition of the critical water content (wet and dry limits) for tillage. In this review, we provide a comprehensive assessment of the methods for determining soil workability, and the effects of soil properties and tillage systems on soil workability and fragmentation. The strengths and limitations of the different methods for evaluating the water content for soil workability, such as the plastic limit, soil water retention curve (SWRC), standard Proctor compaction test, field assessment, moisture-pressure-volume diagram, air permeability and drop-shatter tests are discussed. Our review reveals that there is limited information on the dry limit and the range of water content for soil workability for different textured soils. We identify the need for further research to evaluate soil workability on undisturbed soils using a combination of SWRC and the drop-shatter tests or tensile strength; (i) to quantify the effects of soil texture, organic matter and compaction on soil workability; and (ii) to compare soil water content for workability in the field with theoretical soil workability, thereby improving the prediction of soil workability as part of a decision support system for tillage operations.

Keywords: Wet tillage limit, dry tillage limit, plastic limit, soil water retention curve, soil properties, tillage systems

Introduction and review of objectives

Tillage plays an important role in arable farming. It is used to incorporate organic materials into soil and to control weeds. In the preparation of seedbeds, tillage is used to improve soil structures (i.e. tillage-induced soil fragments) for crop establishment. Tillage comprises primary or secondary tillage. Primary tillage involves digging, stirring and turning over the soil, such as during ploughing. Secondary tillage is often carried out after primary tillage (usually at a shallow depth) to break down large soil fragments (produced during primary tillage), primarily to prepare seedbeds. This review focuses on secondary tillage for seedbed preparation.

Even though the desired aggregate size of soils in seedbeds varies because of crop-specific requirements, in general, seedbeds consisting of small soil fragment sizes provide suitable conditions for seed establishment, emergence and root growth (Braunack & Dexter, 1989a). Russell (1973) defined small soil fragments that create ideal seedbeds as those between 0.5–1 and 5–6 mm in size. Good seedbeds for crop establishment consist of more than 50% of the soil fragments that are < 5 mm in size. Such fine seedbeds increased the number of plants and crop yield by 5% compared to the coarse seedbeds for silty soil in Sweden (Håkansson *et al.*, 2002). Braunack and Dexter (1989b) showed that the seedbeds consisting of fragment sizes between 0.5 and 8 mm had high inter-aggregate aeration and are less erodible and compactible.

Seedbeds dominated by coarse fragments or clods – aggregates with diameter > 32 mm (Keller *et al.*, 2007) or > 38 mm (Lyles & Woodruff, 1962) – are useful for

controlling erosion, but have less agronomic value in terms of crop establishment (Dexter & Birkas, 2004). This is because coarse soil fragments can reduce soil-seed and soil-root contact areas, which in turn affect seed germination and root growth. Moreover, large soil fragments increase mechanical impedance because of crusting (particularly in soils with small soil organic matter – SOM – contents) and decrease intra-aggregate aeration which may affect seedbed performance in relation to crop growth (Braunack & Dexter, 1989a). Although finer soil fragment sizes (< 1 mm) can improve the yield of oats and the nitrogen uptake of barley (Edwards, 1958), seedbeds dominated by too fine (dust) particles are highly erodible, vulnerable to surface crusting and have poor aeration (Farres, 1978; Braunack & Dexter, 1989b). This implies that an ideal seedbed for crop establishment should not consist of fragments that are either too fine or too coarse. In practice, there is often conflicting requirements for seedbed preparation in terms of fragment sizes required for seedbeds (Braunack & Dexter, 1989a). Braunack and Dexter (1989a) argued that there is often a compromise between the conditions for plant growth and properties for traction and tillage. Seedbeds consisting of both fine and coarse soil fragments help to improve water retention and aeration, soil-seed and soil-root contact areas, and to reduce the erodibility of very fine soil aggregates (Braunack & Dexter, 1989a).

In practice, soil conditions for seedbed preparation are mostly based on qualitative field assessment by farmers, who often crumble soil to see how it breaks. Although the qualitative assessment of farmers can be done with fair precision, the results are subjective because the method is intuitive and therefore operator dependent (Cadena-Zapata, 1999). Tillage operation based on intuitive assessment of soil conditions may result in high energy requirements or delay in operations (Cadena-Zapata *et al*., 2002). There is also the

risk that tillage operations are executed at periods when the soil is not workable. Workability is a desirable soil condition during tillage. Workability refers to the condition of the soil when tillage operations can be executed without causing structural damage. When preparing seedbeds, soil is considered workable when tillage operations produce suitable seedbeds for crop establishment without smearing or compaction (Rounsevell & Jones, 1993; Müller *et al*., 2011). It depends on a combination of tillage systems and factors including soil water content, bulk density, texture, clay and SOM. Soil water content is one of the most influential factors that affect the readiness of soil for field operation. Soil readiness is the combination of soil workability and trafficability, that is, the ability of soils to support and withstand field traffic without soil degradation (Rounsevell, 1993; Edwards *et al*., 2016).

Soil is workable within a range of water content ($\Delta\theta_{RANGE}$); under these conditions, tillage operations produce the desirable seedbeds. In this paper, we refer to $\Delta\theta_{RANGE}$ also as a 'satisfactory' or 'safety' range of water content for soil workability. This range is the difference between the upper (wet) tillage limit (WTL) and the lower (dry) tillage limit (DTL) (Figure 1). Knowledge of soil workability and trafficability can be used to estimate the number of days when soils can be worked without causing damage as a result of compaction (Earl, 1997). In this review, we focus only on soil workability and fragmentation.

Quantitative information on the optimum water content for tillage (θo_{PT}), WTL, DTL and $\Delta\theta_{RANGE}$ can be used by farmers and environmental managers to improve their decision support system for planning and optimizing tillage operations (Bochtis *et al*., 2014). This can help to improve post-tillage soil structures as well as reduce the risk of tillage-induced soil degradation and the energy requirement for tillage operations. Tilling soils under too wet conditions
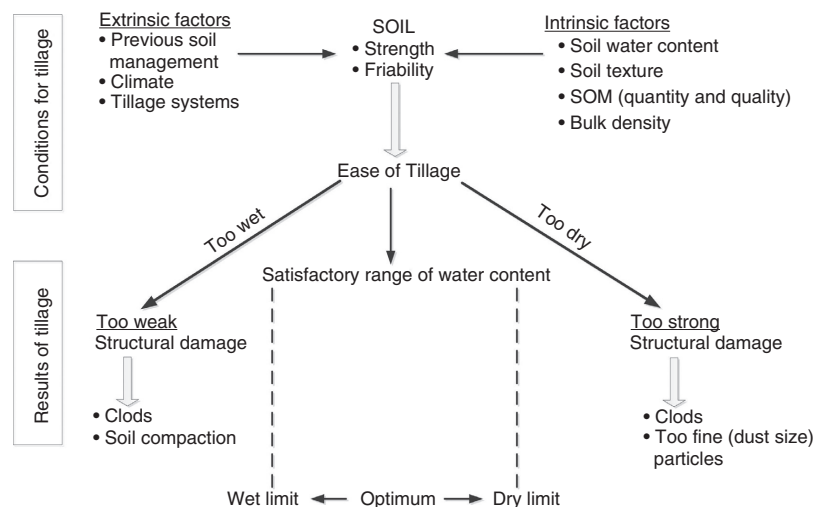
Figure 1 Schematic presentation of the concept of soil workability and factors affecting it.

destabilizes the soil structure, increase the risk of soil compaction and produce poor seedbeds because of the formation of clods (Dexter & Bird, 2001). Likewise, tilling too dry soils requires more energy and produces clods and dust size particles (Hadas & Wolf, 1983) (Figure 1).

Tillage at θ_{OPT} produces the most suitable seedbeds for crop establishment. Wagner *et al.* (1992) obtained the maximum amount of small soil fragment sizes in silty clay loam soils when tillage was done at θ_{OPT}. In addition, tilling at θ_{OPT} reduces the number of passes of tillage implements required during field operations (Hoogmoed *et al.*, 2003). The optimum water content for tillage is defined as the water content where tillage operation produces the maximum number of small aggregates and the minimum number of clods (Dexter & Bird, 2001). Moreover, the specific surface area of fragments produce after tillage is larger at θ_{OPT} (Keller *et al.*, 2007).

Soil fragmentation is the process of crumbling of soil fragments under applied stress (Munkholm, 2002). Friability relates to the concepts of brittle fracture and 'weakest link' in a material; it is a characteristic of a material which describes the ease of crushing, crumbling or rubbing apart the particles of which the material is composed (Christensen, 1930). In the study of soils, friability is defined as the 'tendency of a mass of an unconfined soil to crumble under applied stress into certain size range of smaller fragments' (Utomo & Dexter, 1981). Munkholm (2011) added that 'soil friability is also characterized by an ease of fragmentation of undesirably large aggregates or clods and a difficulty in fragmentation of minor aggregates into undesirable small elements'. Friability is a desirable feature for tillage, and there are different field and laboratory methods for quantifying it [detailed explanation is given in Munkholm (2011)]. Friability depends on soil water content, soil bulk density, texture, aggregate stability, SOM and soil microstructure (Utomo & Dexter, 1981; Watts & Dexter, 1998). At θ_{OPT}, soil friability is at its greatest. Maximum soil fragmentation during tillage also occurs at this point (Utomo & Dexter, 1981). The optimum water content for soil fragmentation is also referred to as θ_{OPT}. Quantification of friability can be used to assess soil workability, management effects on soil structural conditions and soil physical quality. Cadena-Zapata (1999) reported that soils were more workable in friable conditions. It can therefore be argued that soil fragmentation, friability and workability are closely inter-connected.

The concept of least limiting water range (LLWR) has been used to explain the range of water content over which limitations on root growth are minimal (da Silva *et al.*, 1994). Munkholm (2011) reported that maximum soil friability occurred within the LLWR. This author argued that from the perspective of tillage, it is more important to focus on the range of water content as a measure of optimum soil fragmentation rather than just focusing on

θ_{OPT}. This is because soil fragmentation does not show a distinct peak at a specific water content, implying that a gradual change in water content, corresponding to the satisfactory range of water content over which tillage produces fragments of desirable sizes, is more appropriate. This observation indicates that a reliable evaluation of soil workability implies a distinctive definition of the upper and lower water contents for tillage. A number of methods and concepts for determining soil workability have been presented in the literature (Table 1), but these methods have not yet been evaluated to outline their applicability, strengths and disadvantages.

The objectives of the present paper are to (i) evaluate the different methods used to determine θ_{OPT}, WTL, DTL and $\Delta\theta_{RANGE}$, (ii) summarise the effects of soil properties (soil water content, texture, and bulk density) and tillage systems on soil workability and fragmentation and (iii) identify research gaps and future perspectives.

Water content for soil workability and methods of evaluation

Optimum water content for tillage. As already described, θ_{OPT} is the water content where a tillage operation produces desirable seedbeds. Soil strength is weak at θ_{OPT}, which could be attributed to little adhering of soil particles because cohesive forces of capillary bound-water and effectiveness of cemented dispersed materials are at minimum (Mosaddeghi *et al.*, 2009). Tilling soil at θ_{OPT} requires less energy and produces suitable soil fragments for crop establishment and growth. The reason for great soil crumbling at θ_{OPT} is ascribed to the fact that soil fragmentation is as a consequences of the existence of surface of weakness within the soil, which are associated with inter-aggregate pores emptied of water (i.e. air-filled pores) (Dexter & Bird, 2001). The air-filled micro-cracks elongate under mechanical stress resulting in soil fragmentation. We next consider some of the methods and parameters that have been used to determine θ_{OPT}.

Plastic limit. The plastic limit (PL) of a cohesive soil refers to the gravimetric water content between the plastic and semi-solid state of consistency at which a freshly remoulded soil changes from plastic to brittle or friable state (McBride, 2007). Soil water content less than the PL is considered as the optimal condition for seedbed preparation (Kirchhof, 2006). Bhushan and Ghildyal (1972) reported a value of 0.77 θ_{PL} as θ_{OPT} for lateritic sandy loam soils. Dexter and Bird (2001) showed that $\theta_{OPT} = 0.9\ \theta_{PL}$ for most soils. Keller *et al.* (2007) reported that $\theta_{OPT} = 0.7–0.9\ \theta_{PL}$ for soils studied in Sweden. Utomo and Dexter (1981) found that maximum soil friability occurred at water content just below PL, indicating that

Table 1 Soil workability limits reported in the literature

Soil workability limits

Wet limit	Optimum water content	Dry limit	Soils studied	Source
Water content of 24 kg/kg	–	Water content of 18 kg/kg	–	Sitkei (1967)
–	Water content at maximum Proctor density ($\theta_{proctor}$)	–	Silty clay loam and silt loam (Humid continental climate)	Wagner et al. (1992)
Water content at plastic limit	0.9 θPL or θ_{INFL}	Water content at which the strength of soil is twice the strength at the optimum water content	Clay loam to silty clay loam (Temperate)	Dexter and Bird (2001)
Water content at pF 1.9 (−100 hPa) for loam soil and pF 2.1 (−125 hPa) for clay soil	–	Water content at pF 3.1 (−1250 hPa) for the loam soil and pF3.5 (−3162 hPa) for the clay soil	Loam and clay soils (Tropical)	Hoogmoed et al. (2003)
–	0.7 of water content at matric potential of −5 kPa	–	Soils from different geographical regions	Mueller et al. (2003)
Water content of 40 kg/kg	–	Water content of 33 kg/kg	Clay (Temperate)	Gülser et al. (2009)

PL, Plastic limit; pF, It is a logarithm of the absolute value of soil matric potential; θ_{INFL}, Water content at inflection point.

optimum soil workability also occurred at that water content. Tillage operations at water contents greater than PL resulted in plastic deformation of the soil structure (Watts *et al.*, 1996; Dexter & Bird, 2001).

Even though Atterberg's PL can be used to determine θ_{OPT}, it is not appropriate for coarse textured soils that are not plastic. Expressing θ_{OPT} as a function of PL results in a large coefficient of variation simply because it does not take into account the soil structural conditions at the time of tillage (Keller *et al.*, 2007) (Figure 2). Another limitation of PL for determining soil workability is that the water content for tillage is estimated from remoulded soils (i.e. the soil structure is destroyed). Therefore, PL does not take into consideration pre-existing cracks which are important in soil fragmentation (Keller *et al.*, 2007).

Soil water retention curve. Dexter and Bird (2001) defined the optimum water content for soil workability based on the soil water retention curve (SWRC). The authors measured water retention (10–15 000 hPa matric potential) on natural soil aggregates (9–13 mm) sampled from the uppermost soil layer (0–0.1 m depth) of fine silty loam soils from the Highfield long-term experiment at Rothamsted, UK. They proposed that when suction of the modulus of the soil matric potential (h) is plotted against gravimetric water content (θ), the point on the curve where the curvature of the SWRC is zero or

changes sign, θ at this log (h) is called the inflection point (θ_{INFL}). The inflection point has two characteristics: position and slope. First, we discuss θ_{OPT} in relation to 'the position of θ_{INFL}' and then in relation to 'slope of θ_{INFL}'. We will end the section by outlining some of the strengths and limitations of using SWRC to determine θ_{OPT}. Dexter and Bird (2001) proposed that θ_{OPT} corresponds to the water content at the inflection point of SWRC. In other words, $\theta_{OPT} = \theta_{INFL}$. They suggested that θ_{INFL} can be estimated by fitting water retention data to the van Genuchten (1980) retention equation:

$$\theta_{INFL} = (\theta_{SAT} - \theta_{RES})\left[1 + \frac{1}{m}\right]^{-m} + \theta_{RES} \qquad (1)$$

where θ_{SAT} and θ_{RES} are water contents at saturation and the residual water content, respectively, m is a parameter governing the shape of the curve.

Two inflection points (from the wet end to the dry end) could be identified depending on whether the water content is plotted against h or log(h). The first inflection point is interpreted as the breakthrough matric potential where air first enters throughout the soil. The second inflection point corresponds to the matric potential at which the air content of the soil increases the most with increasing log(h). The two inflection points are close together for soils with a narrow
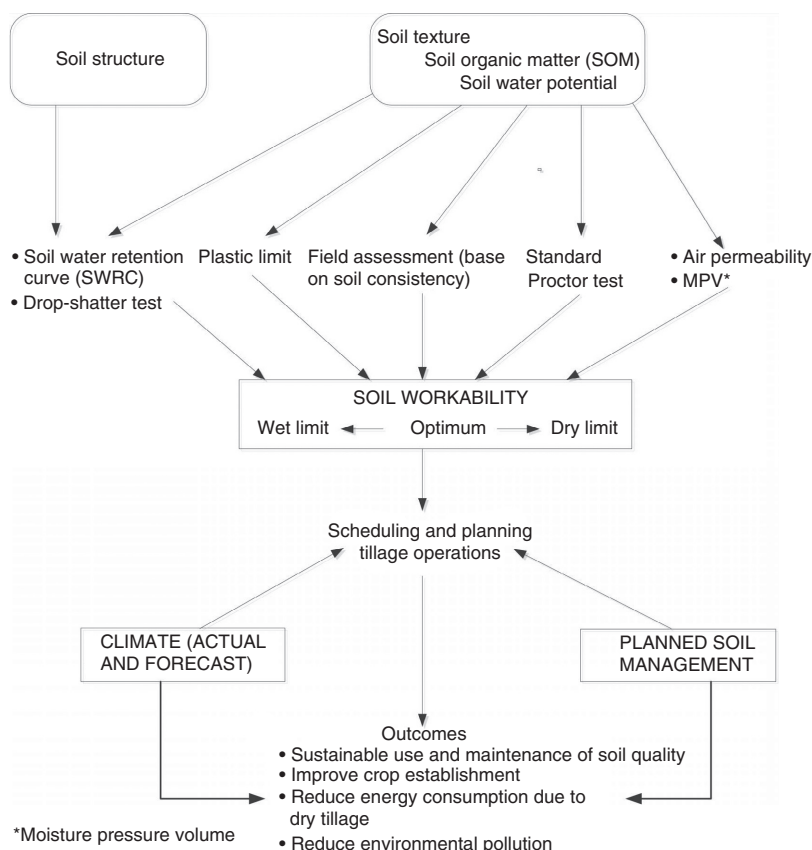
Figure 2 Evaluation of soil workability as part of a Decision Support System.

range of pore size distribution, but the difference increases with the range of pore sizes in the distribution (Dexter & Bird, 2001). The pores emptied of water at inflection point of SWRC are mostly structural pores or micro-cracks (Dexter, 2004a).

Dexter (2004a) also describes SWRC at the inflection point in terms of its slope, $S = d\theta/d(ln\ h)$. It is important to mention that S does not give estimate of θ_{OPT} per se, but is useful in describing soil micro-structure, which can be used as an index of soil physical quality. S can be related to fragment size distribution produced by tillage. Dexter (2004b) found a positive correlation between S and soil friability (both depend on soil micro-structure). Dexter and Birkas (2004) also reported that there is a negative correlation between values of S and the amount of clods produce at θ_{OPT}, which indicates soil workability, as discussed above. The larger the S value, the greater the proportion of smaller soil fragments (< 4 and < 8 mm in diameter), and the smaller the proportion of clods, > 32 and > 64 mm after tillage (Keller *et al.*, 2007). Soils with good physical quality, $S > 0.035$, did not produce large fragments after tillage (Dexter & Birkas, 2004).

Unlike Atterberg's PL, the use of SWRC for determining θ_{OPT} is more appropriate for predicting water-related

properties of structurally intact (undisturbed) soils. A major strength of using the inflection point is that it takes into account the soil structure (Figure 2) and the existence of areas of weakness in the soil which influence soil fragmentation during tillage. Such areas of weakness are associated with pre-existing micro-cracks structure which are often air-filled at low water potential (Dexter & Bird, 2001). Mueller *et al.* (2003) found that θ_{INFL} was larger than θ_{OPT} which may increase the risk of soil deformation because of shearing during tillage. In another study, Müller *et al.* (2011) reported that at θ_{INFL}, soils were too wet and thus, not workable. The authors proposed using a factor of 0.8 for fine-tuning the calculated value at the inflection point downwards. Moreover, in spite of the ability of the water retention curve to predict soil workability, it does not explain why the inflection point corresponds to θ_{OPT} (Dexter & Richard, 2009b).

Standard Proctor procedure. The Proctor density (compaction) test describes the change in soil density with water content. The method uses standardized energy input and compaction procedure (Mueller *et al.*, 2003). Wagner *et al.* (1992) proposed that θ_{OPT} corresponds to the Proctor

critical water content ($\theta_{\mathrm{Proctor}}$) for Kimo silt clay loam and Eudora silt loam soils, where θ is the gravimetric water content. The $\theta_{\mathrm{Proctor}}$ corresponds to 70% of the water content at tension of -5 kPa (Mueller *et al.*, 2003). Mosaddeghi *et al.* (2009) explained that at the drier end of the Proctor density curve when $\theta < \theta_{\mathrm{Proctor}}$, soils have high friction between particles and strength to resist soil compaction by tillage implements. On the other hand, when $\theta > \theta_{\mathrm{Proctor}}$ (wet end of the Proctor density curve), soil compactibility is reduced because water filled pores are not easily compressible. However, there is risk of shear deformation because of low soil strength. The physical explanation of why θ_{OPT} coincides with the $\theta_{\mathrm{Proctor}}$ has been given in terms of particle-to-particle bonding, soil plasticity and fragmentation (Payne, 1988) – at the $\theta_{\mathrm{Proctor}}$, soil particles are cohesive, but non-plastic, which increases soil fragmentation during tillage. The Proctor density test has drawbacks. The fact that θ_{OPT} coincides with the $\theta_{\mathrm{Proctor}}$ shows that at this water content tillage operations can lead to soil compaction (Müller *et al.*, 2011).

Field assessment. Water content for soil workability has been determined by a field assessment method. The method relies on the plastic limit test already discussed. Mueller *et al.* (2003) determined soil workability based on the Atterberg's soil consistency, which refers to the resistance of a material to deformation. The authors assessed workability by pressing, remoulding and rolling soil by hand. The consistency state of the soil was estimated from a score of 1 (dry, hard) to 6 (liquid). The soils were workable at consistency score < 3 where no marked plastic deformation occurred when the soil was pressed between the fingers. Moreover, at consistency score < 3, the soil did not stick to the palm, and it was not possible to roll the soil into a thin wire (Mueller *et al.*, 2003).

Knowledge of the consistency state of soil can be used to assess the water content at which marked deformation and adhesion to tillage implement occur during tillage. Nevertheless, field scoring based on soil consistency state is not very useful for assessing soil fragmentation at θ_{OPT} because it does not provide information about the proportion of small fragments during tillage (Mueller *et al.*, 2003). Moreover, the practicalities of field assessments must also be considered, as in today's modern farming practices it would be extremely time consuming to physically visit many spatially diverse locations to make field assessment of soil workability (Edwards *et al.*, 2016).

Wet tillage limit. The wet tillage limit can be defined as the upper boundary or safety limit (Figure 1) of water content for soil tillage. Tilling soils above the WTL leads to plastic deformation of their structure because the strength of the soil to resist shear deformation under mechanical stress reduces with increasing water content. The water content at the wet tillage limit (θ_{WTL}) corresponds to the water content at PL, that is, $\theta_{\mathrm{WTL}} = \theta_{\mathrm{PL}}$ (Dexter & Bird, 2001). Dexter and Bird (2001) proposed that θ_{WTL} can be calculated from the parameters of the SWRC as followed:

$$\theta_{\mathrm{WTL}} = \theta_{\mathrm{INFL}} + 0.4(\theta_{\mathrm{SAT}} - \theta_{\mathrm{INFL}}) \qquad (2)$$

Determining θ_{WTL} using the water retention curve estimates the upper limit for soil workability using undisturbed soils, that is, it takes into account soil structure in field conditions. Nevertheless, the use of the soil water retention parameters do not give information on fragment size distribution produced by tillage.

Hoogmoed *et al.* (2003) measured WTL on tropical loam and clay soils in Mexico using air permeability test and interpretation of the moisture-pressure-volume (MPV) diagram. Both methods were based on soil compaction and deformation processes under stress. The tests were used to determine the water content where the soils became compacted (after subjecting them to uniaxial compression at a given pressure) because of the decrease in soil strength as the water content increases. Based on the air permeability test, WTL is the water content where compaction results in a drastic drop of convective air flow. For the MPV diagram, WTL corresponds to the bending point of the lowest isobar of the compression pressure (i.e. the point where porosity is least). For the air permeability test, WTL was at pF 2.0 and pF 2.1 for the loam and clay soils, respectively. As for the MPV diagram, WTL was at pF 1.9 and 2.2 respectively for the same soils (Hoogmoed *et al.*, 2003).

Hoogmoed *et al.* (2003) stressed that WTL determined from the two tests yielded values close to the soil consistency test (pF 1.9 for the loam soil and pF 2.2 for the clay soil). One setback of using air permeability test and interpretation of the moisture-pressure-volume diagram to determine WTL is that the methods are based on compaction and deformation of soil and may not be directly applicable to non-compacted soils. Despite this limitation, the methods could be tested on non-tropical soils to outline their general applicability.

Dry tillage limit. The dry tillage limit refers to the soil water content below which soils have a solid and hard consistency state. Dexter and Bird (2001) identified an arbitrary fixed point of DTL as the water content at which the strength of soil is twice the strength at θ_{OPT} (i.e. $2\tau_{\mathrm{OPT}}$ where τ is the soil strength, estimated from the effective stresses). In another study, Dexter

et al. (2005) proposed a simplified method for calculating DTL using parameters from the water retention curve based on the van Genuchten (1980) retention equation:

$$h_{DTL} \approx \frac{2}{\alpha} \left[\frac{1}{m} \right]^{\frac{1}{n}} n^{1.1} \qquad (3)$$

where h is the applied water potential or suction and α is a scaling factor for the water potential and n is a parameter governing the shape of the curve. The water content at dry tillage limit (θ_{DTL}) can be obtained by replacing the value of h in the van Genuchten (1980) equation for water content (Dexter *et al.*, 2005). However, this method does not provide the physical implication of soil strength on soil fragmentation during tillage.

Hoogmoed *et al.* (2003) applied the drop-shatter test to determine the dry tillage limits for tropical soils in Mexico. They reported that DTL was around pF 3.1 for the loam soil and pF3.5 for the clay soil (Table 1). Application of the definition used by Dexter and Bird (2001) implies that the soil strength at this water content (pF 3.1 and pF 3.5) will be twice the strength at water contents below WTL (θ_{OPT}) as evaluated by the air permeability test and MPV diagram interpretation discussed under Wet tillage limit. Beyond θ_{DTL}, soils generally have higher strength and more energy is required for tillage operations. It must be emphasized that, in general, there is limited research on dry limit for soil workability and the use of the drop-shatter test presents a great potential for evaluating θ_{DTL} for a range of soils. Soil workability is most likely to be limited by excessive moisture rather than dryness in temperate regions like Europe (Müller *et al.*, 2011), which could explain the lack of studies on the dry workability limit in these regions.

The range of water content for tillage. The range of water content for tillage ($\Delta\theta_{RANGE}$), also called the window of opportunity for tillage operations (Edwards *et al.*, 2016), is the difference between the wet and dry limits over which tillage can be executed to produce the desired seedbeds for crop growth without causing structural deformation to the soil (Dexter & Bird, 2001). The range of water content for tillage can be very narrow for most soils (Braunack & Dexter, 1989b). Cadena-Zapata *et al.* (2002) reported that $\Delta\theta_{RANGE}$ for tropical loam and clay soils in Mexico were pF1.9–3.1 and pF2.1–3.4, respectively. The upper and lower soil moisture limits for cultivation were 40 and 33 kg/kg respectively for soils in Turkey (clay content of soil is 72–79%) (Gülser *et al.*, 2009). Sitkei (1967) cited in Dexter and Birkas (2004), reported that water content of 18–24 kg/kg was the range of water content suitable for tillage for medium-textured Hungarian soils (Table 1). A combination of existing methods for determining soil workability and friability could be used to study the range of water content for soil workability for different textured soils to provide detailed knowledge for this topic.

Factors affecting soil workability

Soil workability varies for different soils, tillage implement used and for different farm operations. These variations depend on soil moisture content (discussed above) as well as other intrinsic soil properties (Ojeniyi & Dexter, 1979). Here, we discuss soil properties: texture, bulk density and SOM; and management factors: tillage systems that influence soil workability limits (Figure 1).

Soil texture. Soil texture is defined as the particle size distribution of the primary mineral particles (sand, silt and clay). Soil texture affects soil properties including porosity, air permeability, water-holding capacity (water retention), erodibility and infiltration.

Müller *et al.* (2011) reported that sandy soils are workable at any water content as long as there is free drainage, which corresponds to moisture content at field capacity. They noted that for the more fine textured soils, too wet or too dry conditions limits soil workability. Dexter and Bird (2001) studied the effect of clay content on tillage limits using a pedotransfer function. The authors assumed equal silt and sand contents, 0.03 kg/kg SOM and a constant soil bulk density of 1.5 Mg/m³. Their prediction showed that DTL, θ_{OPT} and WTL increased with increasing soil clay content. However, $\Delta\theta_{RANGE}$ generally decreased with increasing clay content. The increase in water content for soil workability limits with increasing clay content can be ascribed to the volume of intra-aggregate pores. The decrease in $\Delta\theta_{RANGE}$ can be related to a decrease in the volume of inter-aggregate pores, i.e. air-filled inter-aggregate pores play a crucial role in fragmentation by tillage as discussed in Introduction.

Organic matter content. Soil organic matter is an important component of soil that affects water content for soil workability. SOM enhances soil workability through improving the stability of soil because of its binding capacity, which affects soil strength and inter-aggregate or structural porosity. Soils with little SOM have higher risk of dispersibility of clay which reduces structural porosity and increases soil strength as a result of crusting and cementation. SOM has high absorptive capacity for water and increases θ_{OPT}, WTL, DTL and $\Delta\theta_{RANGE}$ through improving water-holding capacity of soil (Mosaddeghi *et al.*, 2009). Kirchhof (2006) explained the influence of SOM on the plastic behaviour of soil by shifting the plastic limit to greater water content. The author argued that SOM prevents the formation of water films until dehydration is completed.

Water films act as a lubricant between particles which allow soil structural elements to change shape without fragmentation under mechanical stress resulting in a plastic deformation.

Dexter and Bird (2001) predicted the tillage limit for silt loam soils in the Highfield long-term experiment that had different SOM contents. They found that soils with large SOM content (0.054 kg/kg) had wider $\Delta\theta_{RANGE}$ (0.078 kg/kg) compared to those with small SOM (0.019 kg/kg) which had $\Delta\theta_{RANGE}$ of 0.034 kg/kg. Experiments carried out by Czyż and Dexter (2010) on the same silt loam soils on Highfield showed that a large content of SOM reduced the proportion of large soil fragments (> 50 mm diameter), but increased the proportion of smaller soil fragments (< 5 mm diameter) after tillage. Soils with a large SOM (0.025 kg/kg) had stronger aggregates under wet conditions, and weaker aggregates under dry conditions than soils with little SOM (0.017 kg/kg) (Munkholm *et al.*, 2002). Keller and Dexter (2012) reported a positive correlation between SOM and plastic limits. These authors predicted that soils with clay content < 10% can be plastic because of the presence of SOM. However, the soil samples used in their study were randomly selected from nine different locations. The authors noted that the effects of SOM on plastic limits could be more evident from analysing soils with similar texture and SOM gradient.

In addition to the quantity of SOM (i.e. whether small or large), the type and quality of SOM also influence plastic limits and stability of soils, which can affect soil workability. Soil organic matter composed of large amounts of organic compounds such as polysaccharides, *n*-fatty acids and aliphatic polymers enhance soil stability (Hempfling *et al.*, 1990), which in turns plays a role in soil friability and fragmentation during tillage as discussed already. Leinweber *et al.* (1991) reported that soil with a large content of organic compounds, namely long-chained lipids (e.g. alkenes and fatty acids), N-compounds and lignin dimers had a large water content at the plastic limits. Some of these organic compounds act as coating in soils, resulting in soil water repellence (hydrophobicity) which reduces soil wettability (Doerr *et al.*, 2000).

The effects of clay and SOM on soil workability could be considered indirect (through their effects on soil bulk density) than being direct effects (Dexter *et al.*, 2005) as discussed above. In general, it is unclear by what magnitude workability alters with changes in soil properties, particularly clay and SOM (quantity and quality), and what is the threshold of these properties for workability. These questions need to be addressed in future studies on soil workability and fragmentation in tillage.

Bulk density. Soil bulk density (ρ_d) (the state of compaction or consolidation) is the change in soil volume at constant solid content. In agricultural soils, compaction is often because of the direct impact of heavy machinery, animal trampling and unstable soil structure because of small SOM contents. Increasing ρ_d reduces the amount of structural pores (Dexter & Richard, 2009a), which can increase soil strength (particularly when dry) and decrease soil friability.

Dexter (2004a) reported that the slope of SWRC and the water content at inflection point were less for the compacted sandy clay than for the non-compacted soil. In another study, Dexter and Bird (2001) predicted the effects of ρ_d on soil workability based on assumed constant clay content of 0.25 kg/kg and soil organic matter content of 0.03 kg/kg. They concluded that increasing ρ_d decreases θ_{OPT}, WTL, DTL and $\Delta\theta_{RANGE}$. An explanation of this inverse relationship is that increasing ρd reduces structural porosity, which implies that soils should be dried (drained) further for them to be workable (Mosaddeghi *et al.*, 2009). It must, however, be pointed out that the effects of compaction on soil workability has not been extensively studied in the literature. Consequently, there is currently poor knowledge about predicting workability for structurally degraded soils. Further research on different compaction levels and compaction followed by soil loosening will be useful to understand the relationships between soil bulk density and workability in tillage.

Tillage systems. Different tillage implements are used in soil tillage depending on the objective. In conventional tillage, ploughing (deep or shallow) may be done followed by harrowing, e.g. during seedbed preparation. Soil workability is influenced by the tillage system through soil-tillage implement interaction and tillage depth, which in turn largely depend on SOM, soil texture and water content. SOM increases structural porosity and the water content for soil workability (as explained under Soil organic matter). Elongation of air-filled micro-cracks under mechanical stress results in fragmentation in tillage. Soils are friable, and less energy is required to fragment soil when harrowing was done within $\Delta\theta_{RANGE}$ of pF 1.9–3.1 for loam soil, and pF 2.1–3.4 for clay soil (Cadena-Zapata *et al.*, 2002).

The largest proportion of small fragments (< 5 mm) and the smallest proportion of clods (> 25 mm) for silty clay loam soils in Iran were obtained when mouldboard ploughing followed by disc harrowing (MD), and disc ploughing followed by disc harrowing (DD) were executed at 0.8 θPL. But for the offset disking followed by disc harrowing (OD), the greatest amount of small fragments and fewest clods were obtained at 0.7 θPL. At these water contents, the proportion of fragments < 5 mm were 42–47% for MD, 33–35% for DD, and 22–45% for OD treatments (Barzegar *et al.*, 2004). Likewise, the greatest proportion of small fragments and smallest percentage of clods for a loam soil were obtained at 0.7 θPL for the MD and DD, and at

0.8 θPL for OD treatments. The percentage of fragments < 5 mm at these water contents were 40–49% for MD, 22–47% for DD, and 37–51% for OD treatments (Barzegar *et al.*, 2004). It should be stressed that the effects of a tillage system on soil workability are, in general, insufficiently understood. Also, in modern agricultural practices, many different tillage implements are used, which implies that it is difficult to have a general conclusion on the effects of tillage system on soil workability. It would be worth examining how different management options such as field traffic (compaction) and SOM inputs affect soil friability and fragmentation for different tillage systems to give detailed knowledge on workability under field conditions. This can be done by, for example, using finite element modelling to study soil cutting processes and soil–tool interaction to determine tillage and soil failure patterns. It is important to emphasize that the cutting edge geometry of tillage implements with the soil is essential and needs to be taken into account (Fielke, 1999).

Identification of research needs and future perspectives

In practice, conditions and guidelines for tillage activities have been assessed by farmers based on experience. Results from such evaluations may be subjective and can result in undesirable seedbeds for crop establishment and growth, tillage-induced soil structural degradation and large requirements for tractive energy. It is recognized that quantitative information on soil workability can be used to predict the 'go and no-go' days on a field (Simalenga & Have, 1992) and the production of suitable seedbeds during tillage. Moreover, the quantification of the available operation time for tillage can provide the basis for optimizing the machinery size and capacity on the farm (Søgaard & Sørensen, 2004) as well as estimating overall resource inputs (Sørensen *et al.*, 2014).

Despite the extensive literature on θo$_{PT}$ and WTL, the DTL and $\Delta\theta_{RANGE}$ for different soils are insufficiently understood. Knowledge on soil workability (θo$_{PT}$, WTL, DTL and $\Delta\theta_{RANGE}$) is useful in seedbed preparation as discussed previously. It can be used to determine the water content at which more soil failure will occur under mechanical stress to prevent the risk of tillage-induced soil structural damage because of tillage at unsuitable moisture conditions. That is to say, knowledge of soil workability limits can provide valuable information that can serve as basis for supporting decision on tillage planning and operations so as to sustain soil and environmental quality (Figure 2).

A range of methods exist for evaluating θo$_{PT}$, whereas few methods have been proposed for determining WTL and DTL. The strengths and drawbacks of the methods have been outlined. A major limitation of using PL for determining θo$_{PT}$ is its reliance on remoulded soils, because remoulding destroys the soil structure. The soil water retention curve based on the van Genuchten (1980) equation has been also used to estimate θo$_{PT}$, WTL, DTL and $\Delta\theta_{RANGE}$. Its application is not without limitations. We emphasized that the characteristics of the curve at inflection provide little information on the physical basis for soil behaviour during tillage. How water content affects soil strength and friability is still an open question for research. Hoogmoed *et al.* (2003) applied the drop-shatter test (Hadas & Wolf, 1984) to determine DTL of tropical soils in Mexico. It is a semi-quantitative method used to estimate soil friability and to quantify how soil fractionates after applying stress. The fragment size distributions are expressed as mean weight diameter or geometric mean diameter (mm) (Munkholm, 2011). Hoogmoed *et al.* (2003) showed that the drop-shatter test was useful for determining DTL by doing the test at different water content and evaluating the fragment size distributions. It is important that the method be applied to soils in other regions (e.g. temperate soils) to provide further insights into its general applicability.

We also propose that existing methods for evaluating soil workability are combined with quantitative methods for assessing soil friability, particularly tensile strength and rupture energy (calculated from mean force and deformation) of soil cores and aggregates to address the gaps in soil workability research raised in this paper. Tensile strength may be defined as the maximum stress a material can withstand before failure. It can be calculated from the force needed to crush individual soil aggregates between two parallel plates (Rogowski, 1964; Dexter & Kroesbergen, 1985). Combining the methods would help to capitalise on the strengths of each. For instance, the tensile strength or rupture energy of undistorted soil cores and aggregates may be measured at different water contents. The measured tensile strength or rupture energy at the different points on the water retention curve can be used to deduce soil workability based on where soils have little strength or small rupture energy and large friability. For example, SWRC together with the drop-shatter test, tensile strength or rupture energy can be used to evaluate soil workability for different textured soils and how soil management options affect the water content for soil workability.

We suggest combining these methods to further investigate the following issues: (i) to quantify the effects of soil compaction on workability and fragmentation in tillage, (ii) to quantify the effects of clay and SOM on soil workability and (iii) to quantify the interactions between SOM and compaction on soil workability. Finally, we propose that the workability limits from these laboratory-based studies are compared to water content for soil workability in actual field conditions. Results from such studies will be useful to reduce the energy requirement for seedbed preparation. It will also serve as the basis for improving the knowledge needed to develop decision support

for tillage planning and operations, and for incorporating workability predicting capabilities in comprehensive farm management information systems (Sørensen *et al*., 2010).

Conclusion

This paper reviews soil workability and soil fragmentation based on a discussion of different methods namely plastic limit, soil water retention curve (SWRC), standard Proctor procedure, field assessment, air permeability, interpretation of moisture-pressure-volume diagram and drop-shatter tests that have been used to determine workability limits. The strengths and limitations of these methods were evaluated. The effects of soil properties (texture, bulk density and soil organic matter), and tillage systems on soil workability were also highlighted. The review revealed that the wet limit and the optimum water content for tillage have been extensively studied although typically estimated from remoulded soil. On the other hand, there is paucity of information about the dry tillage limits and the range of water content for tillage for different soils as these have not been well defined in the literature. The paper identified the need for further research to evaluate soil workability from structurally intact soils using for instance, a combination of SWRC, and the drop-shatter test and tensile strength measurements to determine soil fragmentation and friability, which can be used to assess soil workability. The purpose of using SWRC together with these methods is to overcome the weaknesses of the SWRC, some of which are discussed in the review. A combination of these methods will be useful to quantify the effects of soil texture, soil organic matter and compaction (bulk density) on soil workability and to compare soil water content for field workability to theoretical soil workability in order to improve predicting of soil workability as part of scheduling tillage operation systems.

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Conflict of interest

The authors declare that they have no conflict of interest.

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Paper 2

Soil organic matter widens the range of water contents for tillage

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Soil organic matter widens the range of water contents for tillage

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ABSTRACT

The effects of soil organic matter on the water contents for tillage were investigated by sampling soils with a uniform texture, but a range of soil organic carbon (SOC) from two long-term field experiments at Highfield in Rothamsted Research, UK and Askov Experimental Station, Denmark. The treatments studied in Highfield were Bare fallow (BF), Continuous arable rotation (A), Ley-arable (LA) and Grass (G); and in Askov: unfertilized (UNF), ½ mineral fertilizer (½ NPK), 1 mineral fertilizer (1NPK), and 1½ animal manure (1½AM). Minimally disturbed soil cores ($100 \, cm^3$) were sampled per plot in both locations from 6 to 10 cm depth to generate water retention data. Soil blocks were also sampled at 6–15 cm depth to determine basic soil properties and to measure soil aggregate strength parameters. The range of soil water contents appropriate for tillage were determined using the water retention and the consistency approaches. SOC content in Highfield was in the order: G > LA = A > BF, and in Askov: 1½ AM > 1NPK = ½NPK > UNF. Results showed that different long-term management of the silt loam Highfield soil, and fertilization of the sandy loam Askov soil affected the mechanical properties of the soils— for Highfield soil, aggregates from the G treatment were stronger in terms of rupture energy when wet (−100 hPa matric potential) than the BF treatment. As the soil dried (−300 and −1000 hPa matric potentials), soil aggregates from the G treatment were relatively weaker and more elastic than the BF soil. Our study showed, for both Highfield and Askov soils, a strong positive linear increase in the range of water contents for tillage with increasing contents of SOC. This suggests that management practices leading to increased SOC can improve soil workability by increasing the range of water contents for tillage. We recommended using the consistency approach over the water retention approach for determining the range of water contents for tillage because it seems to give realistic estimates of the water contents for tillage.

1. Introduction

Tillage plays an important role in arable farming. One of the primary purposes of tillage is for seedbed preparation, where operations are designed to alter soil bulk density, aggregate size distribution and other soil physical characteristics to create soil conditions and environment favoring crop establishment, germination and growth (Johnsen and Buchle, 1969).

Tillage can be performed over a range of water content ($\Delta\theta_{RANGE}$) where soil is workable. In this study, soil workability is defined as the ease of working with a well-drained soil to produce desirable seedbeds (Dexter, 1988), i.e. not consisting of fragments that are either too fine or too coarse for crop establishment. $\Delta\theta_{RANGE}$ is the difference between the wet tillage limit (θ_{WTL}) and the dry tillage limit (θ_{DTL}). θ_{WTL} and θ_{DTL} are the upper and lower water contents for tillage, respectively.

Optimum water content for tillage (θ_{OPT}) is the water content where tillage produces maximum number of smaller fragments and minimum number of large fragments (clods) (Dexter and Bird, 2001). Russell (1961) suggests that small soil fragments that create ideal seedbeds as those consisting 1–5 mm in size. The water contents for tillage have been estimated using the water retention approach (e.g., Dexter and Bird, 2001) and the consistency approach (e.g., Munkholm et al., 2002).

Performing tillage when soil is too wet can lead to structural damage due to remolding and puddling (Dexter and Bird, 2001). Likewise, executing tillage when soil is too dry requires high specific energy because soil is strong (Hadas and Wolf, 1983). Therefore, knowledge of θ_{WTL} and θ_{DTL} and the effects of soil physical properties on these limits are crucial. Such knowledge can provide practical information on the satisfactory $\Delta\theta_{RANGE}$ over which tillage operations produce desirable soil structures for crop establishment and growth (Obour et al., 2017).

Further, knowledge of the suitable water contents for tillage can be used in a decision support system to reduce the risk of structural damage, and the use of excessive energy during tillage (Sørensen et al., 2014).

Soil organic carbon content (SOC) is a critical soil property that affects many other soil physical properties and functions. Organic binding agents such as roots and fungal hyphae play an important role in soil aggregation and stabilization (Tisdall and Oades, 1982), and improves soil resistance and resilience to external stresses (Gregory et al., 2009). SOC also affects soil mechanical properties such as soil strength, bulk density, inter-aggregate or structural porosity, and enhances better soil fragmentation during tillage (Abdollahi et al., 2014). It also influences infiltration, drainage and water storage — it improves water retention due to high absorptive capacity for water (Murphy, 2015), and increases soil strength in wet conditions, which increases θ_{WTL}. In soils with small content of SOC, clay dispersion is higher (Watts and Dexter, 1997; Jensen et al., 2017), which may increase soil strength due to crusting and cementation on drying, consequently affecting the θ_{DTL}. There are few studies that have investigated the effect of SOC on the water contents for tillage. Although Dexter and Bird (2001) investigated the water contents for tillage for a silt loam in Highfield using the water retention approach, and Munkholm et al. (2002) a sandy loam soil in Askov using the consistency approach, they did not evaluate this effect statistically. There remains a need for more quantitative information on the SOC/water content relationship and its influence on tillage (Obour et al., 2017). Such information will help improve knowledge on how the physical condition of soil for tillage changes with changing SOC. In the present study, we investigated the effect of SOC on the water contents for tillage using both the water retention and consistency approaches to expand the findings of the previous studies. Our study focuses on water contents for secondary tillage used for seedbed preparation. It relates to unconfined fragmentation of soil aggregates rather than shearing of bulk soil.

The objectives of this study were to: (i) quantify the effect of SOC on the mechanical behavior of soil aggregates and the water contents for tillage, and (ii) evaluate the water retention and consistency approaches for determining the range of water contents for tillage. We hypothesized that the range of water contents for tillage increases with increasing SOC content.

2. Materials and methods

2.1. The experiments

Soil samples were taken from two long-term field experiments; the Highfield long-term, ley/arable experiment at Rothamsted Research, UK (51°80′N, 00°36′W) and from the Askov long-term experiment on animal manure and mineral fertilizers at Askov Experimental Station, Denmark (55° 28′ N, 09°07′E). These soils had uniform textures, but a range of SOC.

The soil from Highfield is a silt loam classified as Chromic Luvisol according to the World Reference Base (WRB) soil classification system (Watts and Dexter, 1997). The experimental site was originally established with grass, but for ~56 years prior to sampling, each of the plots has an unbroken history under its present management. As a consequence, the soil has a wide SOC gradient in the topsoil along the Bare fallow (BF), Continuous arable rotation (A), Ley-arable (LA) and Grass (G) treatments in the order: G > LA = A > BF (Table 1). The G treatment has been known as Reseeded grass, but throughout this paper, it will be called 'Grass (G)' treatment. The A, LA and G treatments were included in a randomized block design with four field replicates, whereas the four BF replicates were not part of the original design and were located at one end of the experimental site.

The soil from the Askov experimental site is a sandy loam classified as an Aric Haplic Luvisol according to the WRB classification system (IUSS Working Group WRB, 2015). The experiment includes the

following four nutrient treatments: Unfertilized plots (UNF), and plots that have received ½ mineral fertilizer (½NPK), 1 mineral fertilizer (1NPK), and 1½ animal manure (1½AM). The nutrient treatments represent ½, 1 and 1½ times the standard rate of a given crop for total nitrogen (N), phosphorus (P), and potassium (K) in AM or NPK fertilizer (Christensen et al., 2017). The experiment utilizes a randomized block design with three field replicates. The different levels of nutrients applied results in a SOC gradient among the treatments in the order: 1½AM > 1NPK = ½NPK > UNF plots (Table 1). Crop management has been a four-course rotation of winter wheat (*Triticum aestivum* L.), silage maize (*Zea mays* L.), spring barley (*Hordeum vulgare* L.), and a grass-clover mixture (*Trifolium hybridum* L*., Medicago sativa* L*., Lotus corniculatus* L*., Lolium perenne* L*., Festuca pratensis* Huds and *Phleum pratense* L.) used for cutting in the following year (Jensen et al., 2017).

Table 1 shows the basic characteristics of the studied soils. For a more detailed description of the experiment and treatments in Askov and in Highfield reference is made to Jensen et al. (2017) and Jensen et al. (2018), respectively. From here on the soils are referred to with the treatment labels explained above.

2.2. Sampling

At Askov, sampling took place in September 2014 following a winter wheat crop. At Highfield, sampling was done in March 2015. At both Askov and Highfield, soil cores (6.1 cm diameter, 3.4 cm high, 100 cm³) were taken from 6 to 10 cm depth by inserting steel cylinders gently into the soil. Six soil cores were sampled per plot at both locations. In addition, soil blocks were sampled at 6–15 cm depth: Two soil blocks (4000 cm³) per plot in Askov, and three blocks (2750 cm³) per plot in Highfield. The soil cores were stored in a field moist condition in a 2 °C room until analysis. Portions of the soil blocks per plot were spread out on a table and carefully fragmented by hand along natural planes of weakness and left to dry in a ventilated room ~20 °C.

2.3. Basic chemical and physical analysis

Air-dry soil samples from each plot was crushed to < 2 mm and SOC was determined by dry combustion using Flash 2000 NC Soil Analyzer (Thermo Fisher Scientific, Waltham, MA, USA). Soil texture was determined on portions of the < 2 mm samples using a combined hydrometer/sieving method after removal of soil organic matter by hydrogen peroxide (Gee and Or, 2002).

2.4. Soil water retention

To obtain water retention curves, water content was measured from the six soil cores per plot from Askov at −10, −30, −100 and −300 hPa matric potentials; and at −10, −30, −100, −300 and −1000 hPa matric potentials for Highfield soil on tension tables, vacuum pots and pressure plates (Dane and Hopmans et al., 2002). Water content at −15,000 hPa matric potential was determined from air-dry < 2 mm samples using WP4-T Dewpoint Potentiometer (Scanlon et al., 2002). Following equilibrium at each water potential the soil cores were oven dried at 105 °C for 24 h. Soil bulk density of each soil core was calculated from the mass of the oven-dried soil divided by the total soil volume. Bulk density was corrected for stone weight and volume for Highfield soil samples because they contained a significant amount of stones. Porosity was estimated from bulk density and particle density, where particle density was measured on one plot from each treatment using the pycnometer method (Flint and Flint, 2002). For the remaining plots, the particle density was predicted from SOC by a linear regression model. The pore size distributions of the soils were estimated from the water retention measurements, assuming the approximate relation:

$$d = -3000/\Psi \tag{1}$$

Table 1
Basic soil properties and water retention characteristics of the two soils investigated.

	Highfield soil[a]		Askov soil[b]					
	BF	A	LA	G	UNF	½NPK	1NPK	1½AM
SOC (g 100 g^{-1} minerals)	0.90	1.73a*	2.16a*	3.29b*	0.95a	1.07b	1.13b	1.33c
Clay < 2 µm (g 100 g^{-1} minerals)	27	26	26	26	9	10	10	10
Fine silt 2–20 µm (g 100 g^{-1} minerals)	25	26	26	27	9	10	9	10
Coarse silt 20–63 µm (g 100 g^{-1} minerals)	33	32	32	32	16	16	17	16
Sand 63–2000 µm (g 100 g^{-1} minerals)	15	16	16	15	65	64	64	65
Bulk density (g cm^{-3})	1.45	1.39b	1.21a*	1.13a*	1.54a	1.51a	1.41b	1.42b
Pores < 30 µm (m^3 m^{-3})	0.31	0.39a	0.39a	0.46b	0.21	0.23	0.22	0.25
Pores > 30 µm (m^3 m^{-3})	0.15	0.09a	0.15b	0.10a	0.19a	0.19a	0.24b	0.21ab
θ_{PL} (kg kg^{-1} oven dried soil)[c]	0.19	0.24a*	0.25a*	0.34b*	0.15	0.17	0.17	0.18

Treatments labelled with different letters in a given row for each soil are significantly different. Pairwise comparison for differences between Arable (A), Ley-arable (LA) and Grass (G) treatments at Highfield and between unfertilized (UNF), ½ mineral fertilizer (½NPK), 1 mineral fertilizer (1NPK), and 1½ animal manure (1½AM) treatments at Askov. Paired t-test for differences between Bare fallow (BF) and A, LA and G at $p < 0.05$. Values of A, LA and G with an asterisk (*) indicate it is significantly different from BF treatment based on the paired t-test.

θ_{PL}: water content at plastic limit.

[a] Data from Jensen et al. (2018).
[b] Data from Jensen et al. (2017).
[c] Data not reported in Jensen et al. (2017) and Jensen et al. (2018).

where d is equivalent cylindrical pore diameter (µm) and ψ is the soil matric potential (hPa).

2.5. Plastic limit

Plastic limit (PL) was determined using the standard ASTM (Casagrande) test procedure (McBride, 2007). In brief, for each plot, about 15 g of air-dry soil was sieved to < 1 mm and then mixed with water until it became plastic and easily molded into a ball. About 8 g of the soil was rolled between the fingers and a smooth glass plate. PL was determined as the gravimetric water content where the soil began to crumble when rolled into a thread of approximately 3.2 mm in diameter (McBride, 2007).

2.6. Calculations of water contents for tillage

The water contents for tillage were determined using two approaches: (i) water retention approach, and (ii) consistency approach.

2.6.1. Water retention approach

Dexter and Bird (2001) and Dexter et al. (2005) suggested that the water contents for tillage can be estimated from the parameters of the soil water retention curve using the van Genuchten (1980) water retention equation.

The gravimetric water content (θ, kg kg^{-1}) corresponding to each matric potential (hPa) was calculated by fitting the van Genuchten equation with the Mualem (1976) restriction of $m = 1-1/n$ to each set of water retention data obtained from each plot at Askov and Highfield:

$$\theta = (\theta_{SAT} - \theta_{RES})[1 + (\alpha h)^n]^{1-(1/n)} + \theta_{RES} \qquad (2)$$

where θ_{SAT} and θ_{RES} are the water contents at saturation, i.e. at h = 0, and the residual water contents, h = ∞, respectively, α is a scaling factor for h; and n is a fitted parameter that controls the shape of the curve. θ_{RES} was set equal to zero. Values of n were obtained using the curve-fitting program, RETC (van Genuchten et al., 1991).

The wet tillage limit (θ_{WTL}) was estimated as follows:

$$\theta_{WTL} = \theta_{INFL} + 0.4(\theta_{SAT} - \theta_{INFL}) \qquad (3)$$

The optimum water content for tillage (θ_{OPT}) was estimated as water content at the inflection point of the soil water retention curve (θ_{INFL}):

$$\theta_{INFL} = \theta_{SAT}\left[1 + \frac{1}{1-(1/n)}\right]^{1-(1/n)} \qquad (4)$$

The matric potential at the dry tillage limit (h$_{DTL}$) was estimated as proposed by Dexter et al. (2005):

$$h_{DTL} \approx \frac{2}{\alpha}\left[\frac{1}{1-(1/n)}\right]^{1/n} n^{1.1} \qquad (5)$$

The corresponding water content at the dry tillage limit (θ_{DTL}) was calculated by putting the value of h$_{DTL}$ from Eq. (5) into (2) yielding:

$$\theta_{DTL} = \theta_{SAT}[1 + (\alpha h_{DTL})^n]^{1-(1/n)} \qquad (6)$$

The range of water contents for tillage using the water retention approach ($\Delta\theta_{RANGE}$ (water retention)) was calculated as:

$$\Delta\theta_{RANGE} \text{ (water retention)} = \theta_{WTL} - \theta_{DTL} \qquad (7)$$

2.6.2. Consistency approach

The water contents for tillage based on the consistency approach were determined as follows:

θ_{WTL} and θ_{OPT} were determined according to Dexter and Bird (2001):

$$\theta_{WTL} = \theta_{PL} \qquad (8)$$

$$\theta_{OPT} = 0.9 \, \theta_{PL} \qquad (9)$$

θ_{DTL} was graphically determined for each plot as water content at twice the strength at θ_{OPT} from the relation between natural logarithm of tensile strength (Y) of 8–16 mm soil aggregates and gravimetric water content measured at different matric potentials (Munkholm et al., 2002). Examples of how it was determined are shown in Section 3.5.

The range of water contents for tillage using the consistency approach ($\Delta\theta_{RANGE}$ (consistency)) was calculated as described by Munkholm et al. (2002):

$$\Delta\theta_{RANGE} \text{ (consistency)} = \theta_{WTL} - \theta_{DTL} \qquad (10)$$

2.7. Aggregate tensile strength

2.7.1. Highfield soil

We crushed portions of the air-dry soil using the rolling method suggested by Hartge (1971). The crushed soil was passed through a nest of sieves with 8–16, 4–8, 2–4 and 1–2 mm of apertures to obtain four different aggregate size fractions. Some of the 8–16 mm air-dry aggregates were selected randomly from each sampling plot, saturated by capillarity and then drained to −100, −300 and −1000 hPa matric potentials using tension tables, vacuum pots and pressure plates,

respectively. Fifteen aggregates were selected at random from each size fraction of the air-dry aggregates (8–16, 4–8, 2–4 and 1–2 mm), and the 8–16 mm aggregates equilibrated at the three matric potentials. These aggregates were used to measure Y using the indirect tension test (Rogowski, 1964). This test assumes brittle fracture theory and we checked we did not exceed the 20% maximum strain limit for onset of plastic deformation (Kuhn and Medlin, 2000); particularly when aggregates were tested at a wetter state (-100 hPa matric potential). Each of the aggregates was weighed individually and subjected to indirect tension testing by crushing the individual aggregates between two parallel plates (Rogowski, 1964) using an automatically operated mechanical press (Instron Model 5969, Instron, MA,USA). The point of failure for each aggregate was automatically detected when a continuous crack or sudden drop in force (40% of the maximum load) was read. The maximum force at failure was automatically recorded by a computer program. After the test, the crushed aggregates were oven-dried at 105 °C for 24 h to determine their gravimetric water content.

2.7.2. Askov soil

Portions of the field-moist soil was fragmented by hand and sieved to obtain 8–16 mm aggregates. These aggregates were divided into three groups based on their moisture status: air-dry, air-dry rewetted to field capacity (-100 hPa matric potential (Munkholm and Kay, 2002)) and field moist aggregates. Aggregate tensile strength for Askov soil was measured as described in Jensen et al. (2017).

For both Highfield and Askov soils, Y was calculated from the equation suggested by Dexter and Kroesbergen (1985):

$$Y = 0.567F/d^2 \tag{11}$$

where 0.576 is the proportionality constant resulting from the relation between the compressive load applied and the tensile stress exerted on the aggregate. F is the maximum force (N) at failure and d is the effective diameter of the spherical aggregate (m); it was obtained by adjusting the aggregate diameter according to the individual masses (Dexter and Kroesbergen, 1985):

$$d = d_1(m_0/m_1)^{1/3} \tag{12}$$

where $d_1 =$ is the diameter of aggregates defined by the average sieve sizes (e.g., 0.012 m for 8–16 mm aggregates), m_0 is the mass (g) of the individual aggregate and m_1 is the mean mass of a batch of aggregates of the same size class (in this case 15 aggregates for each size fractions).

Rupture energy (E_r) was calculated from the area under the stress-strain curve up the point of tensile failure (Vomocil and Chancellor, 1969):

$$E_r \approx \Sigma_i \, F(s_i)\Delta s_i \tag{13}$$

where $F(s_i)$ denotes the mean force at the ith subinterval and Δs_i s_i the displacement length of the ith subinterval. The mass specific rupture energy (E_{sp}) was defined on gravimetric basis from the equation:

$$E_{sp} = E_r/m \tag{14}$$

where m is the mass of the individual aggregates.

Young's modulus (E) was determined to obtain a quantitative measure of stiffness (elasticity) of the aggregates (determined only for the Highfield samples). It was estimated from the gradient of the stress-strain curve to the elastic limit, assuming linearity up to that point, which was determined using a macro program:

$$E = \sigma / \varepsilon \tag{15}$$

where σ is stress (Pa) and ε is strain.

2.8. Statistical analysis

All statistical analyses were carried out in R software package (R Core Team, 2017). The Y, E_{sp} and E data were log-transformed (ln) to

yield normal distribution. The Highfield data were fitted to a linear mixed effect model, which comprised treatment as fixed and block as random factors. The Kenward-Roger method was used to calculate degrees of freedom. For the Askov data, treatment effects were analyzed using a linear model which comprised block as a fixed effect. We used $p < 0.05$ as a criterion for statistical significance of treatment effects. Where effect of treatment was found to be significant, further analyses were made to identify which treatment means were different (pairwise comparison) using the general linear hypotheses (*glht*) function implemented in R multcomp package. For the four BF replicates which were not included in the original randomized block design, a paired *t*-test was used to investigate if the treatment significantly differed from the A, LA and G treatments. We acknowledged that the paired *t*-test statistics performed to compare statistical significance difference between the BF treatment and the A, LA and G treatment was a less robust test. Throughout the presentation of Results (Section 3), statistical significant differences between the A, LA and G treatments based on the pairwise comparison are labeled with different letters, whereas statistical significant differences between the BF treatment compared to the A, LA and G treatments based on the paired *t*-test are shown by an asterisk (*) symbol against the A, LA or G treatment.

3. Results

3.1. Basic properties of the investigated soils

Soil bulk density was significantly greater for the BF and A soils than the LA and G treatments, and for the UNF and ½NPK compared to the 1NPK and 1½AM treatments (Table 1). There were more large pores > 30 μm in the LA treatment compared to the G and A treatments from Highfield, and for the 1NPK than the UNF and ½NPK soils. Pores < 30 μm, generally, increased with SOC. θ_{PL} was lower for the BF treatment than the other treatments at Highfield (Table 1). θ_{PL} increased with an increase in SOC at Highfield ($R^2 = 0.82$, $p < 0.001$). The same was also seen at Askov, although not significant ($R^2 = 0.15$, $p = 0.21$).

3.2. Tensile strength parameters of air-dry aggregates

In this section and in Sections 3.3 and 3.4, only results from Highfield are presented. Tensile strength parameters of the Askov soil have previously been reported in another study by Jensen et al. (2017). Y and E_{sp} values for all the aggregate size fractions measured did not differ between the treatments (Table 2). Geometric mean of E_{sp} value of all size fractions was greater for the G treatment (19.1 J kg^{-1}) compared to the A and BF treatments (15.4 and 14.9 J kg^{-1}, respectively). Aggregates for the size fraction 2–4 mm were more elastic for the G treatment than the A and LA treatments, whereas for 4–8 mm size fraction, the LA treatment was more elastic compared to both the A and G treatments. Geometric mean values of all size fractions showed that the G and LA treatments had lower E (high elasticity) compared to the BF treatment (Table 2).

3.3. Tensile strength parameters of rewetted aggregates

As expected, for all treatments, Y, E_{sp} and E all increased as the soil dries: the soils become stronger and stiffer. At wet and wet–moist state (-100 and -300 hPa matric potentials), Y values did not differ significantly between treatments, whereas at moist–dry state (-1000 hPa matric potential), aggregates for the LA and G soils had lower Y compared to the A treatment (Table 3). Conversely, the G soil with large SOC had higher E_{sp} at -100 hPa matric potential than the other treatments. On the other hand E_{sp} was not significantly different between treatments when aggregates were tested at -300 and -1000 hPa matric potentials (Table 3). Similar to the air-dry aggregates, lower E was observed for the G aggregates at -300 and

Table 2
Geometric means of tensile strength (Y), mass specific rupture energy (E_{sp}) and estimated Young's modulus (E) of air-dry soil aggregates.

Soil attribute	Aggregate size	BF	A	LA	G
Y (kPa)	1–2 mm	617	544	637	526
	2–4 mm	534	570	530	492
	4–8 mm	394	365	361	307
	8–16 mm	419	400	363	279
	Mean	483	462	459	386
E_{sp} (J kg^{-1})	1–2 mm	15.4	19.8	23.5	24.1
	2–4 mm	16.3	21.8	18.8	24.6
	4–8 mm	18.5	12	16.8	17.1
	8–16 mm	9.4	10.8	11.7	13.2
	Mean	14.9	15.4a	17.1ab	19.1b*
E (MPa)	1–2 mm	15.9	14.4	13.8	15.4
	2–4 mm	34.3	32.9b	32.6b	25.9a
	4–8 mm	36.1	44.5c	24.7a	34.7b
	8–16 mm	31.9	23.2	22.8	14.8
	Mean	28.2	26.4	22.4*	21.2*

Geometric means of all size fraction for Y, E_{sp} and E are shown. Treatments labelled with different letters in a given row are significantly different. Pairwise comparison for differences between Arable (A), Ley-arable (LA) and Grass (G), and paired t-test for differences between Bare fallow (BF) and A, LA and G at $p < 0.05$. Values of A, LA and G with an asterisk (*) indicate it is significantly different from BF treatment based on the paired t-test.

Table 3
Geometric mean of tensile strength (Y), mass specific rupture energy (E_{sp}) and estimated Young's modulus (E) of 8–16 mm soil aggregates adjusted at −100, −300 and −1000 hPa matric potentials.

Matric potential	Soil attribute	BF	A	LA	G
−100 hPa	Y (kPa)	14.6	15.3	15.2	15.8
	E_{sp} (J kg^{-1})	0.55	0.62a	0.86a	1.64b*
	E (MPa)	0.83	0.83b	0.73a	0.68a
−300 hPa	Y (kPa)	23.0	27.3	23.5	20.1
	E_{sp} (J kg^{-1})	1.04	1.36	1.31	1.68
	E (MPa)	1.20	1.00	0.87*	0.82*
−1000 hPa	Y (kPa)	38.5	45.1b	30.7a	25.9a*
	E_{sp} (J kg^{-1})	1.49	2.05	1.50	2.15
	E (MPa)	2.43	1.81c	1.42b*	1.09a*

Treatments labelled with different letters in a given row are significantly different. Pairwise comparison for differences between Arable (A), Ley-arable (LA) and Grass (G), and paired t-test for differences between Bare fallow (BF) and A, LA and G at $p < 0.05$. Values of A, LA, and G with an asterisk (*) indicate it is significantly different from BF treatment based on the paired t-test.

−1000 hPa matric potentials compared to the BF treatment (Table 3).

3.4. Relationship between strength parameters of air-dry aggregates and soil organic carbon

Geometric mean of Y, E_{sp} and E across the four aggregate size fractions (8–16, 4–8, 2–4 and 1–2 mm) were related to SOC content. There was a negative linear decrease in Y with increasing SOC content ($p < 0.05$). A stronger negative linear relationship was found between SOC and E ($p < 0.001$). In contrast, there was a positive linear increase in E_{sp} with increasing SOC content, although not significant ($p = 0.07$) (Fig. 1a–c). Overall, 29%, 22% and 61% of the variation in Y, E_{sp}, and E, respectively of aggregates could be explained by SOC (Fig. 1a–c).

3.5. Water contents for tillage

Water content at dry tillage limit (θ_{DTL}) for each plot was graphically determined from the relationship between Y of aggregates in the 8–16 mm size range and the gravimetric water content at −100, −300, −1000 hPa matric potentials and at air-dry state. Examples of how we

determined water content at twice the strength at θ_{OPT} for the BF and G soils from Highfield, and the UNF and 1½AM soils from Askov are presented in Fig. 2a– d. For these examples, water content at θ_{DTL} for the BF soil was 0.16 kg kg^{-1} and 0.22 kg kg^{-1} for the G soil. θ_{DTL} for the UNF and 1½AM soil were 0.09 and 0.10 kg kg^{-1}, respectively.

The $\Delta\theta_{RANGE}$ (water retention) and $\Delta\theta_{RANGE}$ (consistency) are presented in Fig. 3a and b for Highfield soil, and Fig. 3c and d for Askov soil. θ_{DTL}, θ_{OPT}, θ_{WTL} at treatment levels are also shown for the two approaches. The G treatment with high SOC content had wider $\Delta\theta_{RANGE}$ compared to the BF treatment at Highfield; and for the 1½AM compared to the UNF at Askov. Based on the water retention approach, $\Delta\theta_{RANGE}$ for the G and BF treatments were 0.18 and 0.06 kg kg^{-1}, respectively (Fig. 3a), and 0.08 and 0.07 kg kg^{-1} for the 1½AM and UNF treatments (Fig. 3c). Similar trends were seen for the consistency approach indicating that $\Delta\theta_{RANGE}$ (consistency) for the G treatment was 0.11 kg kg^{-1} compared to 0.03 kg kg^{-1} for the BF treatment, and 0.06 kg kg^{-1} for the ½AM treatment compared to 0.05 kg kg^{-1} for the UNF treatment (Fig. 3b and d).

SOC content had a highly significant positive effect on $\Delta\theta_{RANGE}$ (Fig. 4a–d). The effect of SOC content on $\Delta\theta_{RANGE}$ (consistency) was more significant and more of the variation was explained (Fig. 4b and d) than with $\Delta\theta_{RANGE}$ (water retention) (Fig. 4a and c).

4. Discussion

### 4.1. Effect of soil organic carbon content on aggregate strength parameters

The indirect tension test causes soil aggregates (or cores) to fail along pre-existing failure zones, and planes of weakness making Y a potentially sensitive measure of soil structural condition. Results showed that SOC had a negatively and a significant effect on geometric mean of Y across the four aggregate size classes when air-dry (Fig. 1a). This can be interpreted as Y reflects the degree of aggregation in a soil; it is influenced by aggregate porosity and bonds, failure planes within the aggregates and abundance of internal micro-cracks within the aggregates, which in turn are influenced by SOC (Watts and Dexter, 1998; Blanco-Canqui and Lal et al., 2006). Studies investigating the effect of SOC on aggregate strength show that for soil with less SOC, Y decreases with increasing soil moisture content whereas for soil with large SOC, aggregates are relatively stronger when wet and weaker when dry. For examples, Causarano (1993) and Munkholm et al. (2002) found that for clay and sandy loam soils, respectively with large SOC content, aggregates were stronger at water content at field capacity and weaker when air-dry. This may imply that wet soils do not slump under their own weight when wet during the winter and are relatively weak when dry; leading to easier root penetration and tillage. For the silt loam soil investigated here, Y did not significantly differ between the treatments at −100 and −300 hPa matric potentials (Table 3). However, when tested at −1000 hPa, Y was lower for the G treatment, 25.9 kPa compared to the BF and A treatments, 38.5 and 45.1 kPa, respectively (Table 3). Our results are consistent with Jensen et al. (2017) who found no significant difference in Y between the 1½ AM with large SOC content and the UNF treatment with small SOC content for aggregates at field capacity (−100 hPa matric potential) for the sandy loam soil at Askov. Results here suggest that the range of water content for measurement of Y is important to study the effect of SOC on soil aggregate strength.

Perfect and Kay (1994) suggested using rupture energy for the statistical characterisation of aggregates in tillage studies. They argued that, unlike Y, E_{sp} does not involve any assumption of the mode of failure, making it more appropriate for estimating the strength of dry aggregates. Munkholm and Kay (2002) highlighted that E_{sp} is also appropriate for estimating the strength and fragmentation of wet aggregates. We observed that at −100 hPa matric potential, E_{sp} was significantly greater for the G compared to the other treatments at Highfield. This could be ascribed to the influence of SOC including
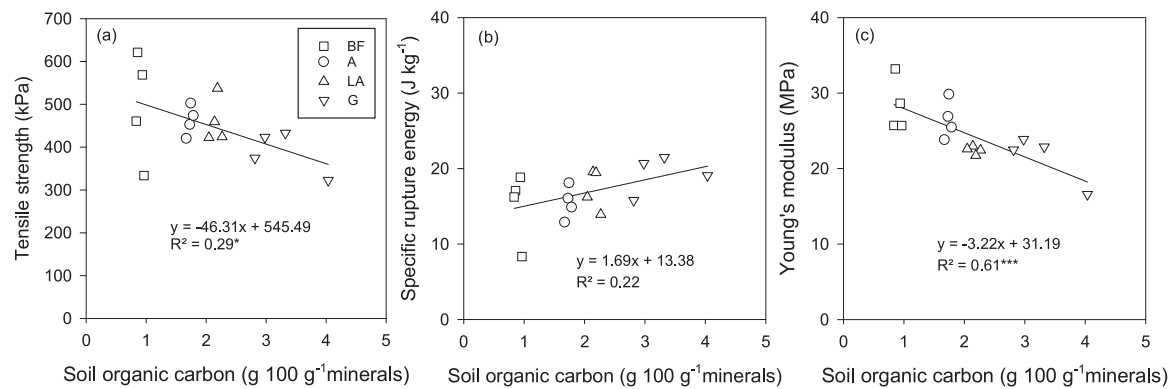
Fig. 1. (a) Tensile strength, (b) Mass specific rupture energy and (c) Young's modulus of air-dry aggregates calculated as geometric means across the four aggregate classes (8–16, 4–8, 2–4 and 1–2 mm) for each plot as a function of soil organic carbon. Bare fallow (BF), Arable (A), Ley-arable (LA) and Grass (G) treatments, and Unfertilized (UNF), ½ mineral fertilizer (½NPK), 1 mineral fertilizer (1NPK), and 1½ animal manure (1½AM) treatments. *p < 0.05 and ***p < 0.001.
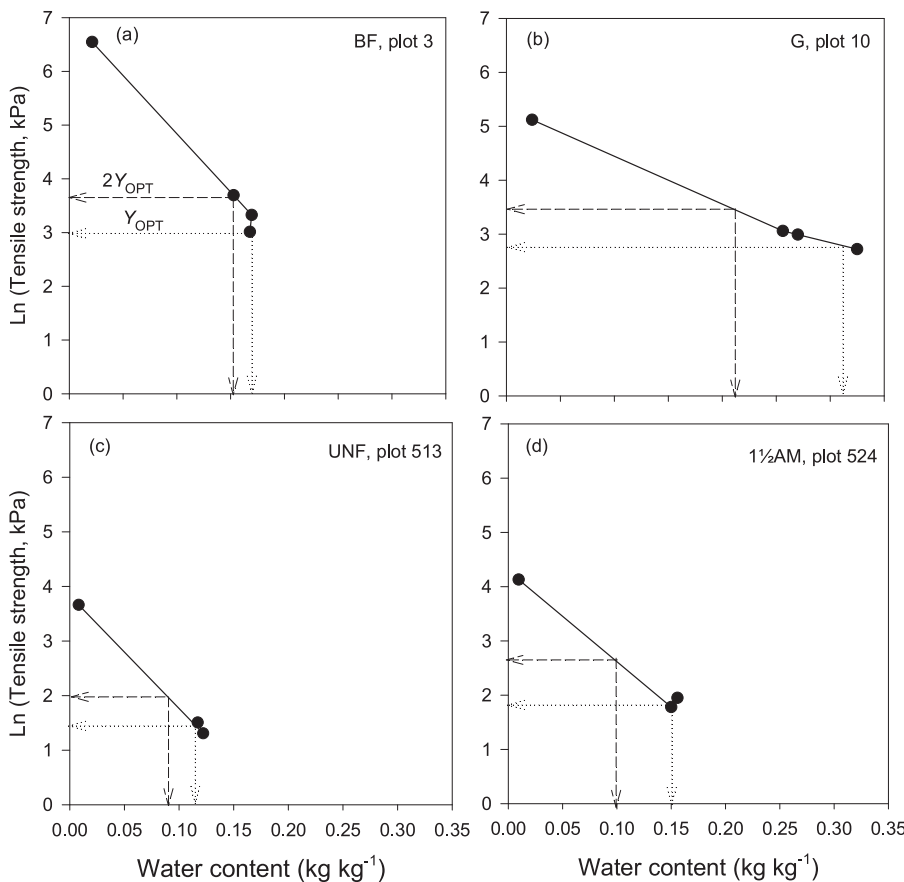
Fig. 2. Graphical approach for determining θ_{DTL}: For Highfield, from natural logarithm of tensile strength of 8–16 mm soil aggregates related to gravimetric water content determined on the aggregates at −100, −300, −1000 hPa matric potentials and at air-dry state for (a) Bare fallow (BF) soil and (b) Grass (G) soil. For Askov, from natural logarithm of tensile strength of 8–16 mm aggregates related to gravimetric water content determined on the aggregates at field capacity, field moist and air-dry state for (c) Unfertilized (UNF) soil and (d) 1½ animal manure (1½AM) soil (n = 4 for Highfield, n = 3 for Askov).

organic binding and bonding materials such as polysaccharides fungal hyphaes and roots (Tisdall and Oades, 1982). Previous study of the BF, A and G treatments showed more diverse and active root biomass in the G treatment compared to the A soil (Hirsch et al., 2009). The results from the Highfield contrast with Jensen et al. (2017) who found that for the sandy loam soil at Askov, E_{sp} of aggregates did not significantly differ between the UNF, ½ NPK, 1NPK and 1½AM treatments at field capacity (−100 hPa matric potential). Our results showed that geometric mean of E_{sp} across the four aggregate size classes in air-dry state increased with increasing SOC content, although the relatioship was weak (Fig. 1b). In the wet state (−100 hPa matric potential), aggregates from the G treatment were stronger based on E_{sp} than aggregates from the BF, A and LA treatments. Although E_{sp} may include some plastic strain energy, the larger E_{sp} for G implies that it is less

susceptible to plastic deformation than the other treatments in a wet condition. Lower E was observed for the G aggregates at -300 and −1000 hPa matric potentials compared to the BF treatment. This can be interpreted as the G soil aggregates were more elastic than the BF soil. The influence of SOC on aggregate elasticity is further illustrated in Fig. 1c showing a strong negative linear decrease in E with increasing SOC content. Gregory et al. (2009) reported that compressed remolded soil cores from the G treatment were more elastic than the A treatment. Further, the authors found that the initial recovery of void ratio, used as an index of resilience after compression was greater in the G treatment (0.28–0.80) than the A treatment (0.16–0.58). This is an indication that the G soil cores were more elastic and rebounded more than the A soil cores following the removal of the compression stress.
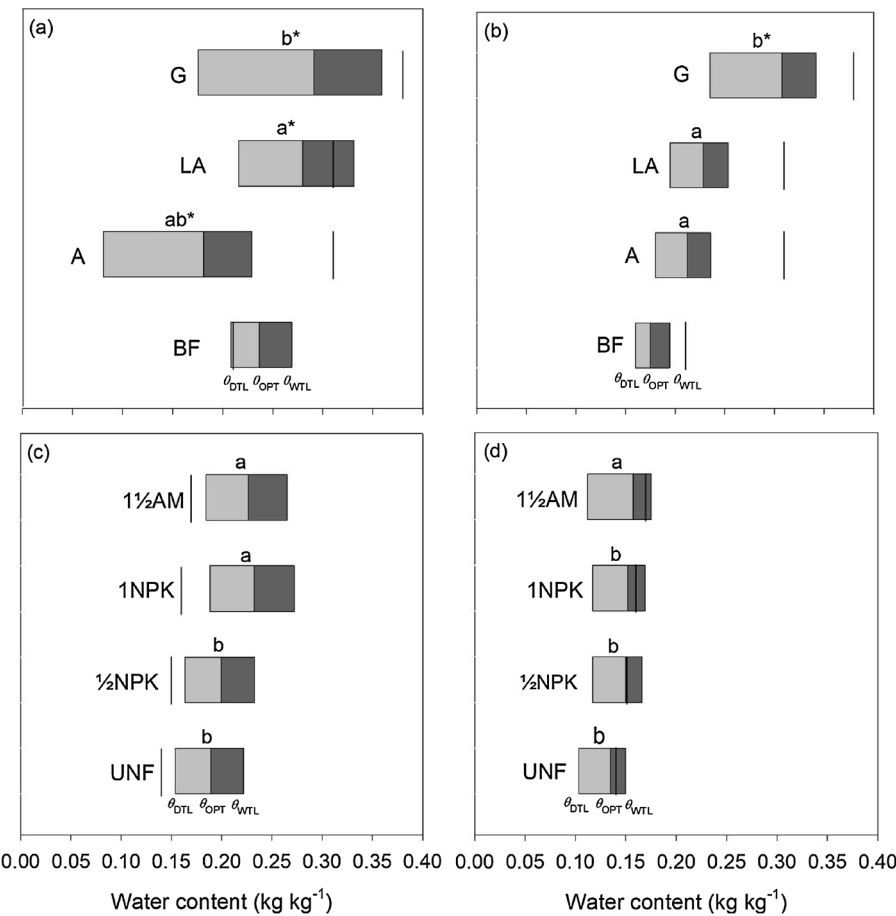
Fig. 3. Water contents for tillage based on the water retention approach (a and c), and the consistency approach (b and d) for Highfield and Askov soils. θ_{DTL} (dry tillage limit), θ_{OPT} (optimum water content for tillage) and θ_{WTL} (wet tillage limit). Solid short vertical lines show water content at -100 hPa matric potential. For Highfield soils, treatments labelled with different letters are significantly different. Pairwise comparison for differences between Arable (A), Ley-arable (LA) and Grass (G), and paired t-test for differences between Bare fallow (BF) and A, LA and G at $p < 0.05$. Values of A, LA, and G with an asterisk (*) indicate it is significantly different from BF treatment based on the paired t-test. At Askov: Unfertilized (UNF), ½ mineral fertilizer (½NPK), 1 mineral fertilizer (1NPK), and 1½ animal manure (1½AM) treatments. Treatments with different letters are significantly different ($p < 0.05$).
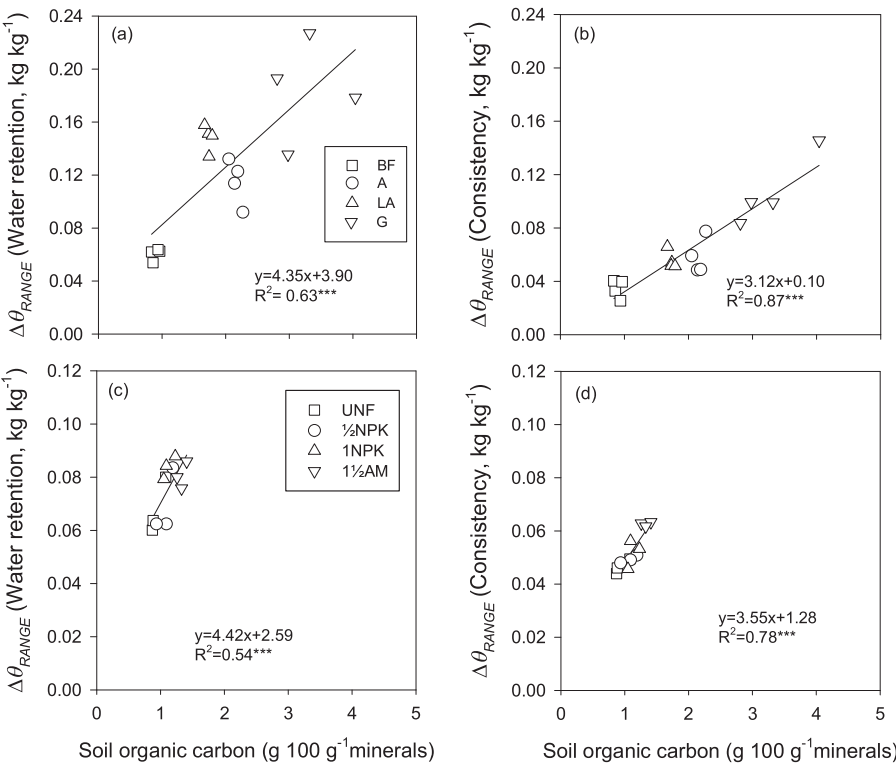
Fig. 4. $\Delta\theta_{RANGE}$ (water retention) and $\Delta\theta_{RANGE}$ (consistency) as a function of soil organic carbon content for the Highfield (4a and b) and the Askov (4c and d) soils. Bare fallow (BF), Arable (A), Ley-arable (LA) and Grass (G) treatments, and Unfertilized (UNF), ½ mineral fertilizer (½NPK), 1 mineral fertilizer (1NPK), and 1½ animal manure (1½AM) treatments. Lines indicate linear regression. ***$p < 0.001$.

4.2. Effect of soil organic carbon on water contents for tillage

The G and 1½AM soils with large SOC content had wider $\Delta\theta_{RANGE}$ compared to their counterpart BF and UNF soils, respectively that had small SOC contents (Fig. 3a and b, Highfield soil; and Fig. 3c and d, Askov soil). The results support our hypothesis that increased SOC widens the range of water contents for tillage. Our results agreed with Munkholm et al. (2002) who determined $\Delta\theta_{RANGE}$ using the consistency approach for soil from two of the experimental fields in Askov, which have the same sandy loam texture as the field investigated in the present study. The authors also reported that for both fields, $\Delta\theta_{RANGE}$ was wider for the animal manure (AM) soil (0.09 kg kg^{-1}) than the UNF soil (0.06 kg kg^{-1}).The wider $\Delta\theta_{RANGE}$ (consistency) for the G soil at Highfield (0.11 kg kg^{-1}) compared to what was reported by Munkholm et al. (2002) can be explained by the differences in soil type, i.e., the silt loam soil at Highfield compared to sandy loam soil at Askov, as well as the wider range of SOC content for the Highfield soil compared to the Askov soil. The positive linear relation between SOC and $\Delta\theta_{RANGE}$ showed that an increase in SOC content could potentially improves the window of opportunity for tillage operations by increasing $\Delta\theta_{RANGE}$ over which tillage can be satisfactorily executed. Mosaddeghi et al. (2009) reported that SOC has greater absorptive capacity for water and improves water-holding capacity of soil thereby increasing θ_{WTL}, θ_{OPT}, θ_{DTL} and $\Delta\theta_{RANGE}$. Moreover, SOC influences the plastic behavior of soil by shifting the plastic limit to greater water content (Kirchhof, 2006).

We observed that using the water retention approach, the θ_{DTL} was very dry, especially for the A treatment (0.08 kg kg^{-1}), whereas it was very wet (wetter than -100 hPa matric potential) for the BF soil (Fig. 3a); which seems unrealistic. Similarly, we observed that θ_{DTL} estimated from the water retention approach was wetter than -100 hPa matric potential for all the treatments studied in Askov (Fig. 3c). Mueller et al. (2003) reported that θ_{OPT} estimated using the water retention approach was, generally, wetter than other approaches such as the consistency approach evaluated for 80 soils with differences in terms of geographical origin, parent material, texture, bulk density and SOC content. They found that θ_{OPT} was outside the suitable range of soil workability in the field. It must however, be emphasized that Mueller et al. (2003) only estimated θ_{OPT} using different approaches, but did not investigate θ_{WTL}, θ_{DTL}, and $\Delta\theta_{RANGE}$ as done in this study. Dexter et al. (2005) and Dexter et al. (2008) suggested that although the water retention approach works for many soils, it does not work well for soils with bi-modal pore size distribution. This is because the van Genuchten equation assumes that soils have uni-modal pore size distribution. The pore size distribution calculated by numerical differentiation of the raw water retention data for the G treatment at Highfield, and the 1½AM treatment at Askov showed that the pore size distribution of the soils studied are better expressed with bi-modal water retention model, e.g., Double-exponential water retention equation (Dexter and Richard, 2009) than with uni-modal model such as the van Genuchten equation (data not shown). This helps explain the limitation of the water retention approach for estimating the water contents for tillage discussed previously. We suggest that the water retention approach is modified to take into account soils that cannot be fitted well with the van Genuchten equation.

The consistency approach, unlike the water retention approach seems to give a more reliable estimate of the water contents for tillage for the soils studied here by indicating when the soils were either too wet at θ_{WTL} or too dry at θ_{DTL}. As for the consistency approach, θ_{WTL} was estimated from remolded soil (where air-dry soil sieved to 1 mm was remolded) destroying the soil structure and therefore, does not represent soils with intact structure. Moreover, plastic limit (PL) does not take into consideration pre-existing cracks which are important in soil fragmentation (Keller et al., 2007). There is a potential of using pedo-transfer functions to estimate PL of soils. For example, Keller and Dexter (2012) proposed estimating PL from soil texture and clay content.

With respect to the determination of θ_{DTL}, even though Dexter et al.

(2005) provided a reasoning for defining θ_{DTL} as water content at which soil strength is twice its value at the θ_{OPT} as done in this study, they acknowledged that the approach provides an arbitrary way of determining θ_{DTL}. We propose that a fixed value is defined for θ_{DTL}. There is also a potential of using pedotransfer functions to estimate soil strength increases with decreasing water content to help reduce arbitrariness associated with the consistency approach.

4.3. Utilization of water contents for tillage and SOC information in farm management

Knowledge of the water contents (wet and dry limits) for tillage is useful for determining the range of water contents over which soil is workable, i.e., tillage can be performed satisfactorily. In temperate regions like Northern Europe, where soil workability is likely to be limited by excessive moisture, information on θ_{WTL} is of utmost importance to: (1) avoid producing soil seedbed dominated by large smeared fragments during tillage, which are of less agronomic value in terms of crop establishment (Dexter and Birkas, 2004); and (2) reduce the risk of soil puddling and remolding leading to excessive soil deformation and damage to the soil microstructure.

Knowledge of θ_{DTL} is also useful to: (1) avoid soil pulverization during tillage because seedbeds become dominated by both large intractable clods and very fine particles (dust) leading to poor aeration, vulnerability to crusting and greater erodibility (Braunack and Dexter, 1989); and (2) prevent the use of excessive tillage energy because soil is too strong. In these circumstances where clods are difficult to break down, considerable energy is expended to little or no effect. In a nutshell, quantitative information on the water contents for tillage can be used by farmers and environmental managers to improve their decision support system (DSS) for planning and optimizing tillage operations (Edwards et al., 2016).

Mullins et al. (1988) reported that in practice, farmers can be faced with a narrow window of opportunity to perform tillage operations, especially for hard-setting soils. Our results suggest that for the same soil type, increase in SOC increased the $\Delta\theta_{RANGE}$. This information can provide practical evidence to farmers to engage in farm management practices that improve SOC as a way of widening the window of opportunity over which tillage can be performed satisfactorily.

It should be emphasized that for practical purposes before the application of our results in a DSS, it is important that the more promising consistency approach for determining the range of water contents for tillage, is validated under field conditions. Also, more knowledge is needed on the effect of SOC on different soil types and at different scales. It should also be pointed out that the high values of SOC associated with the G treatment may be due in part to the fact that it has not been cultivated. Cultivating it would lead to a sharp drop in SOC over time. However, the scope of this study could be expanded to identify appropriate conditions for grazing without risk of damage (poaching) to the underlying soil structure.

5. Conclusions

This study showed that the different long-term management practices on two contrasting soils lead to differences in soil organic carbon (SOC). This in turn led to major differences in soil mechanical properties (aggregate tensile strength, rupture energy and Young's modulus and elastic range) which are useful in identifying appropriate soil moisture conditions for tillage. Two approaches were used to identify the range of soil water contents for tillage: (i) Based on fixed points (water contents) generated from modeled water retention characteristics and (ii) based on a combination of soil consistency relationships (plastic limit) and an estimate of tensile strength of aggregates in the 8–16 mm size class. The evidence here suggests:

- The aggregates from the Grass (G) treatment with large SOC content

were stronger based on the mass specific rupture energy when soil was wet than the Bare fallow (BF) soil with small SOC content.

- Aggregate tensile strength for the G treatment was significantly lower than the Arable (A) and BF, and more elastic than the BF, A and Ley-arable (LA) treatments when soil was moist.
- The soil consistency approach provided more reliable estimates of tillage limits (upper, optimum and lower soil water contents) than the water retention approach.
- Management practices leading to increased SOC content can improve soil workability by increasing the range of soil water contents suitable for tillage ($\Delta\theta_{RANGE}$) —SOC explains 78 and 87% of the variation in $\Delta\theta_{RANGE}$ for the studied soils.

Conflicts of interest

None.

Acknowledgements

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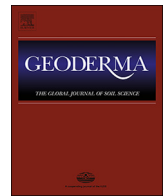
Paper 3

Pore structure characteristics and soil workability along a clay gradient

Peter Bilson Obour, Thomas Keller, Mathieu Lamandé, and Lars J. Munkholm

Pore structure characteristics and soil workability along a clay gradient

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ABSTRACT

Clay is a basic soil constituent that governs many soil properties including pore characteristics, which in turn control a range of crucial soil properties and functions. This study explored the relationships between aggregate strength and soil pore structure characteristics for a range of clay contents along a natural gradient, and investigated the influence of clay content and matric potential on soil workability. Soil samples ($100 \, cm^3$ soil cores and bulk soil) were sampled from the 5–15 cm depth in four locations in an arable field near Lerbjerg, Denmark, which ranged in clay content from 0.119 to $0.446 \, kg \, kg^{-1}$. The soil cores were drained to five matric potentials in the range -10 to $-1000 \, hPa$ to obtain volumetric water content and air-filled porosity (ε_a). We measured air permeability and gas diffusivity and calculated tortuosity (τ) and pore organization at $-100 \, hPa$. Soil aggregates were obtained from the bulk soil and their tensile strength (Y) and specific rupture energy (E_{sp}) were determined at -100, -300, $-1000 \, hPa$ and at air-dry state. Y and E_{sp} increased with decreasing matric potential and with increasing clay content, which consequently affected soil workability. ε_a at $-100 \, hPa$ or air-filled macroporosity were negatively related to Y and E_{sp}, and positively to the range of water contents for tillage ($\Delta\theta_{RANGE}$). This indicates the importance of air-filled macroporosity for soil crumbling during tillage. The findings of the study suggest that management practices that increase soil macroporosity can potentially decrease aggregate strength and increase $\Delta\theta_{RANGE}$ and hence improve soil workability. We suggest that in fields with highly variable soils operations should be scheduled at periods when the range of water contents for tillage are suitable for the whole field to reduce the risk of soil structural damage induced by tillage.

1. Introduction

Soil workability is the ease with which a well-drained soil can be tilled to produce a desirable seedbed (Dexter, 1988). An optimal seedbed for crop establishment has been defined as a seedbed with fragments that are neither too coarse nor too fine (Braunack and Dexter, 1989). Soil workability is influenced by water content and soil strength. When performed under unsuitable soil water contents tillage can lead to undesirable results. When the soil is too wet, it will not crumble during tillage, but deforms instead (Watts and Dexter, 1998). Consequently, tillage can damage soil structure and create seedbeds consisting of large soil fragments, which become hard upon drying. When the soil is too dry, tillage requires a high energy input and can create a seedbed composed of finer fragments, which are susceptible to crusting and wind and water erosion (Braunack and Dexter, 1989). Soil workability can be assessed from tensile strength (Y) and soil friability, i.e. the tendency of a mass of unconfined soil to disintegrate and crumble under

applied stress into a particular range of smaller soil fragments (Utomo and Dexter, 1981). Friability of a soil is a key factor in determining soil response to tillage. It provides information on the ease of producing an optimal seedbed that favors soil-seed contact during tillage. Friability also yields valuable information on the ability of soil to minimize the energy requirement for tillage (Munkholm, 2011). Y and friability are related to brittle failure of soil; it involves crack propagation and opening of the weakest flaws (Braunack et al., 1979). Under applied stress, the cracks expand, elongate and coalesce, resulting in fragmentation of the soil (Snyder and Miller, 1989). The progressive development and opening of cracks depend on factors such as air-filled porosity and inter-particle bonding at the crack tips (Hatibu and Hettiaratchi, 1993). This suggests that there is a strong link between soil strength properties and the pore system. However, there is limited understanding of the influence of soil pore structure characteristics on soil strength properties. Such information can be useful for improving the prediction of soil mechanical conditions in tillage.

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Clay is a basic soil constituent and governs soil physical, chemical and biological properties and processes. The degree of packing of clay mineral particles influences soil structure and inter-particle bonding, which in turn affects pore structure characteristics and mechanical properties such as tensile strength. Clay content also influences soil water-holding capacity and plastic limits, which affect soil workability. Dexter and Bird (2001) predicted that the water content at the wet (upper) tillage limit, θ_{WTL}, the optimum water content for tillage (θ_{OPT}) and the water content at the dry (lower) tillage limit (θ_{DTL}) increase with increasing clay content, whereas the range of water contents for tillage ($\Delta\theta_{RANGE}$) decreases with increasing clay content. Until now, these findings by Dexter and Bird (2001) have not been validated against measured data. Quantitative knowledge of the impact of clay content on soil workability can be relevant for addressing cultivation problems in agricultural soils with clay variability.

This study investigated a soil in an arable field with a naturally occurring clay gradient. The objectives were to: (i) explore the relationships between soil tensile strength and pore structure characteristics, and (ii) examine the influence of clay and matric potential on soil workability. Soil workability was assessed by relating it to the quantitative information on aggregates tensile strength properties, soil friability and the estimated range of water contents for tillage.

2. Materials and methods

2.1. Soil sampling

Soil samples were retrieved from 5 to 15 cm depth on September 29, 2016 at four locations along a naturally occurring texture gradient from an arable field near Lerbjerg, Denmark (56°22′N, 9°59′E) Fig. 1. Soil in the field was developed on Weichselian morainic deposits. The mineralogy of soil along the clay gradient is similar; the clay fraction (< 2 μm) is dominated by illite, smectite (predominantly

montmorillonite), and vermiculite with smaller proportions of kaolinite (Schjønning et al., 1999). For many years, the field has been cropped with mainly winter cereals and dressed with pig slurry and mineral fertilizers (Kristiansen et al., 2006). At sampling, the field was established with winter barley (*Hordeum vulgare* L.) with an undersown grass. A reduced-tillage system has been employed for about 15 years (2000–2015). Since 2015, a conventional chisel plowing to ~15 cm depth has been employed.

Soil cores measuring 100 cm³ (6.1 cm diameter, 3.4 cm high) were sampled from four locations with clay contents of 0.119, 0.220, 0.289 and 0.446 kg kg⁻¹. The locations have previously been called, respectively, L1, L3, L4 and L6 (e.g., Schjønning et al., 2003), but throughout this paper will be referred to as L12, L22, L29 and L45 to indicate the clay content. The relative positions of the sampling locations in the field are shown in Fig. 1. The soil cores were sampled from an area of about 1 m² using metal cylinders. Eighteen soil cores were sampled per location. Three soil blocks (~2750 cm³) were taken from each sampling location and at the same depth as the soil cores and were placed in plastic boxes and covered with tight lids. All soil samples were stored in a 2 °C room until laboratory analyses.

2.2. Soil preparation and laboratory measurements

The three soil blocks from each location were gently fragmented by hand along natural planes of weakness. The fragmented soil was spread out on a table at room temperature to air-dry.

2.2.1. Basic chemical and physical analyses

A portion of the air-dry soil samples from each location was crushed to < 2 mm using a soil crushing machine. The crushed samples were used to determine soil organic carbon (SOC) and soil texture (Table 1). SOC was determined by measuring the carbon dioxide evolved by high temperature (1650 °C) dry combustion with a Thermo Flash 2000 NC
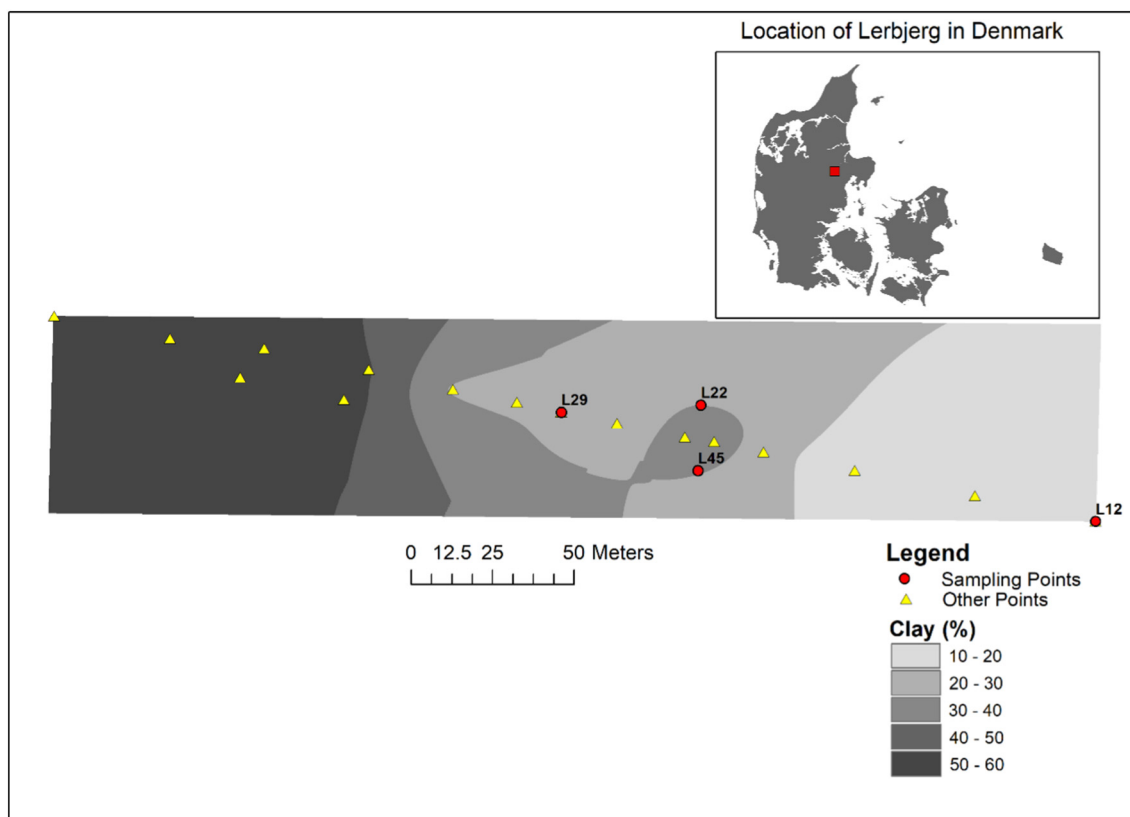

Fig. 1. Map of the sampling field at Lerbjerg, Denmark with contours of soil clay content. The designations L12, L22, L29 and L45 refer to sampling locations.

Table 1
Basic soil characteristics along the clay gradient.

	Soil			
	L12	L22	L29	L45
Texture (USDA)	Loamy sand	Sandy clay loam	Sandy clay loam	Clay
SOC (kg kg^{-1})	0.014	0.014	0.014	0.016
Clay < 2 μm (kg kg^{-1})	0.119	0.220	0.289	0.446
Silt 2–20 μm (kg kg^{-1})	0.044	0.070	0.088	0.122
Fine sand 20–200 μm (kg kg^{-1})	0.334	0.271	0.225	0.157
Coarse sand 200–2000 μm (kg kg^{-1})	0.503	0.439	0.398	0.275

Soil Analyzer (Thermo Fisher Scientific, Waltham, MA, USA). Soil texture was determined by the sieving and sedimentation method (Gee and Or, 2002). The texture of the soil ranged from loamy sand for L12 to clay for L45. The four locations had similar SOC contents.

2.2.2. Soil water retention and bulk density

To obtain water retention data, the soil cores were capillary wetted to saturation and drained progressively to −10, −30, −100, −300 and −1000 hPa matric potentials using tension tables, vacuum pots and pressure plates (Dane and Hopmans, 2002). Water content at −15,000 hPa (permanent wilting point) was determined from air-dry < 2 mm samples for each location using a WP4-T Dewpoint Potentiometer (METER Group Inc., Pullman, WA, USA). After successive equilibration, bulk density (ρb) was determined by oven-drying the soil cores at 105 °C for 24 h. Total porosity (Φ) was calculated from ρb and particle density (ρd) as $\Phi = 1 - \rho b / \rho d$. ρd values of 2.64, 2.64, 2.65 and 2.69 were used for L12, L22, L29 and L45, respectively (Schjønning et al., 1999). The volumetric water content (θ, m^3 m^{-3}) at each matric potential was calculated by multiplying ρb and gravimetric water content at the given matric potential. Air-filled porosity (ε_a) at each matric potential was calculated by subtracting θ at each matric potential from Φ.

2.2.3. Air permeability, gas diffusivity and pore characteristics

Air permeability (k_a) was measured on the soil cores at −100 hPa using the Forchheimer approach described by Schjønning and Koppelgaard (2017). Gas diffusivity (Dp/Do) was also measured on the soil cores at the same matric potential using an apparatus developed by Schjønning (1985) for measuring gas diffusivity by a non-steady method described by Taylor (1949).

To obtain the pore size distribution and continuity of pores, pore contiuity or organization (PO_1) (Blackwell et al., 1990) was assessed. The PO_1 index gives an indication of the structural differences between soils. According to Groenevelt et al. (1984), soils with identical PO_1 have pore systems with similar size distributions and differing in the volume of ε_a. A high PO_1 value indicates a high capacity of the air-filled pore space to conduct air:

$$PO_1 = k_a / \varepsilon_a \tag{1}$$

Tortuosity (τ), which is the ratio of pore length to soil sample, was estimated according to the tube model of Ball (1981) assuming soil pores are cylindrical tubes. High τ values signify a large number of marginal pores lying peripheral to the arterial diffusion pathway (Arah and Ball, 1994), thus hindering the diffusion process in soil:

$$\tau = \left\{ \frac{\varepsilon_a}{Dp/Do} \right\}^{1/2} \tag{2}$$

2.2.4. Aggregate tensile strength

Portions of the air-dry soil samples for each location were crushed using the roller method (Hartge, 1971) and thereafter sieved through a set of sieves to obtain the following aggregate size fractions: 8–16, 4–8, 2–4 and 1–2 mm. Some of the 8–16, 4–8 and 2–4 mm aggregates were capillary-adjusted to −100, −300 and −1000 hPa using tension tables, vacuum pots and pressure plates (Dane and Hopmans, 2002). About 60 aggregates were drained for each soil, size fraction and at each matric potential. For both the air-dry aggregates and the aggregates equilibrated at the different matric potentials, a batch of 30 aggregates were randomly selected from each soil and size fraction to measure their tensile strength (Y) using the indirect tension test (Rogowski, 1964). Briefly, the mass of each aggregate was determined by weighing it and subsequently subjecting it to indirect tensile testing using a mechanical press as described by Obour et al. (2018) at a constant rate of displacement of 1 mm min^{-1}. The remaining crushed aggregates for each soil were collected and oven-dried at 105 °C for 24 h to determine their water content.

Tensile strength was calculated according to Dexter and Kroesbergen (1985):

$$Y = 0.567F/d^2 \tag{3}$$

where F is the maximum force (N) required to fracture the aggregate and d (m) is the effective diameter of the spherical aggregate obtained by adjusting the aggregate diameter according to the individual masses (Dexter and Kroesbergen, 1985):

$$d = d_1 (m_0/m_1)^{1/3} \tag{4}$$

where d_1 = is the diameter of aggregates (m) defined by the average sieve sizes, m_0 is the mass (g) of the individual aggregate and m_1 (g) is the mean mass of a batch of aggregates of the same size class.

Rupture energy (E_r) was calculated from the area under the stress-strain curve up the point of tensile failure (Vomocil and Chancellor, 1969):

$$E_r \approx \Sigma_i F(s_i) \Delta s_i \tag{5}$$

where $F(s_i)$ denotes the mean force at the ith subinterval and Δs_i the displacement length of the ith subinterval. The mass specific rupture energy (E_{sp}) was defined on gravimetric basis from the equation:

$$E_{sp} = E_r / m \tag{6}$$

where m is the mass of the individual aggregates.

Soil friability index (k_Y) was quantified as the slope of the plot of the natural logarithm (Ln) of Y for all size fractions and the natural logarithm of the aggregate volume (Utomo and Dexter, 1981):

$$Ln(Y) = -k \, Ln(V) + b \tag{7}$$

where k is an estimate of friability, b is the intercept of the regression and denotes the predicted Ln (Y) (kPa) of 1 m^3 of bulk soil, and V (m^3) is the estimated aggregate volume. For the friability of L12 to L45 the friability classification of Imhoff et al. (2002) was used where < 0.1 = not friable, 0.1–0.2 = slightly friable, 0.2–0.5 = friable, 0.5–0.8 = very friable and > 0.8 = mechanically unstable.

The effective stress (σ_e) at −100, −300, −1000 hPa, and at air-dry state was calculated according to Towner and Childs (1972). In the absence of an external mechanical stress, σ_e has two components matric suction (ψ) and surface tension (γ) (Towner and Childs, 1972). The contribution of γ to soil strength is important when the degrees of saturation (χ) is < 0.3. In our case χ ranged from 0.05 to 0.95 therefore, both ψ and γ were used:

$$\sigma e = \chi\psi + \frac{0.3}{\alpha} \left[\left(\frac{\psi_2 + \psi_1}{2} \right)(\chi_1 - \chi_2) \right] \tag{8}$$

χ was calculated according to Dexter et al. (2007):

$$\chi = \left(\frac{\theta - \theta_{RES}}{\theta_{SAT} - \theta_{RES}} \right) \tag{9}$$

where θ is the gravimetric water content at a given matric suction, θ_{RES} is the residual water content and θ_{SAT} is the water content at saturation.

$$\alpha = \left(\frac{\theta - \theta_{RES}}{\theta_{SAT}} \right) \tag{10}$$

2.2.5. Water contents for tillage

The water contents for tillage (wet tillage limit, θ_{WTL}; optimum water contents for tillage, θ_{OPT}; and dry tillage limit, θ_{DTL}) were determined using the consistency approach as described in Obour et al. (2018). In short, θ_{WTL} was estimated as the water content at plastic limit (θ_{PL}), θ_{OPT} as $0.9\theta_{PL}$ according to Dexter and Bird (2001), and θ_{DTL} was graphically determined as the water content at which soil strength is twice the strength at θ_{OPT}. θ_{PL} was determined using the standard ASTM (Casagrande) test procedure (McBride, 2007). Air-dry soil from L12, L22, L29 and L45 were separately crushed in a mortar and sieved to 425 μm. For each of the locations, about 15 g of the sieved sample was mixed with water until it became plastic and easily molded into a ball. Thereafter ~8 g of the soil was rolled between the fingers and a smooth glass plate. PL was determined as the gravimetric water content where the soil began to crumble when rolled into a thread of approximately 3.2 mm in diameter (McBride, 2007).

2.3. Data analysis

For non-normally distributed variables (k_a, PO_1, σ_e, Y and E_{sp}), data were log-transformed to yield normality. Results are reported as the geometric mean for the non-normally distributed variables, and as the arithmetic mean for the normally distributed variables (ρb, θ, ε_a, Dp/Do, τ and k_Y). The experimental design of the field with no true replicates prevented a statistical comparison to determine the effect of clay content. Thus, the analysis was based on observed trends obtained from relating soil mechanical properties to soil pore characteristics. Linear and non-linear regression analyses were carried out in MS Excel. Parallel line analysis was conducted using SigmaPlot (Systat Software, San Jose, CA) to test whether the k_Y differed significantly between matric potentials. We used $p \leq 0.05$ as a criterion for statistical significance.

3. Results

3.1. Soil bulk density, pore structure characteristics and gas transport properties

Bulk density (ρb) varied from 1.43 Mg m^{-3} for L22 to 1.22 Mg m^{-3} for L45. Volumetric water content (θ) at −100 hPa ranged between 0.27 for L12 and 0.49 m^3 m^{-3} for L45 (Table 2). This corresponds to gravimetric water contents of 0.19 and 0.41 kg kg^{-1}, respectively. Water content at plastic limit θ_{PL} ranged from 0.21 to 0.29 kg kg^{-1} for L12 to L45. Air-filled porosity (ε_a) decreased with increasing clay content at −100, −300 and −1000 hPa. Volumetric water and ε_a at −100 hPa represent the volume of pores with < 30 and > 30 μm tube-equivalent diameters, respectively (Hillel, 1982). The terminologies θ at −100 hPa or volume of pores < 30 μm, and ε_a at −100 hPa or volume of pores > 30 μm will be used interchangeably hereafter. Air-permeability (k_a) and relative gas diffusivity (Dp/Do) at −100 hPa both decreased with increasing clay content. Pore organization (PO_1) ranged from 85.7 to 438.6 μm^2 for the four locations, with the lowest for L45 and highest for L22, and tortuosity (τ) ranged from 5.2 to 21.7 m m^{-1} increasing in the order L12 to L45 (Table 2).

Table 2
Arithmetic mean of bulk density (ρb); volumetric water content (θ) at −100 hPa; water content at plastic limit (θ_{PL}); air-filled porosity (ε_a) at −100, −300 and −1000 hPa; relative gas diffusivity (Dp/Do), tortuosity (τ), geometric mean of air permeability (k_a) and pore organization ($PO_1 = k_a/\varepsilon_a$) at −100 hPa for L12, L22, L29 and L45.

	Soil			
	L12	L22	L29	L45
ρb (Mg m^{-3})	1.41 (0.02)	1.43 (0.01)	1.37 (0.01)	1.22 (0.02)
θ (m m^{-3}), −100 hPa	0.27 (0.00)	0.39 (0.01)	0.43 (0.00)	0.49 (0.01)
θ_{PL} (kg kg^{-1})	0.21 (0.004)	0.23 (0.004)	0.25 (0.003)	0.29 (0.007)
ε_a (m m^{-3}), −100 hPa	0.20 (0.01)	0.07 (0.01)	0.06 (0.01)	0.05 (0.00)
ε_a (m m^{-3}), −300 hPa	0.25 (0.01)	0.11 (0.01)	0.10 (0.01)	0.09 (0.00)
ε_a (m m^{-3}), −1000 hPa	0.28 (0.01)	0.14 (0.01)	0.13 (0.01)	0.14 (0.01)
Dp/Do, −100 hPa	0.021 (0.00)	0.006 (0.00)	0.004 (0.00)	0.002 (0.00)
k_a (μm^2), −100 hPa	55.4 [0.24]	30.5 [0.66]	14.5 [0.66]	4.3 [0.79]
PO_1 (μm^2), −100 hPa	282.7 [0.23]	438.6 [0.59]	259.2 [0.61]	85.7 [0.80]
τ (m m^{-1}), −100 hPa	5.2 (0.33)	9.6 (1.70)	14.2 (2.40)	21.7 (5.15)

Numbers in parentheses are standard errors.
Numbers in square brackets indicate standard errors for the log-transformed data.

3.2. Aggregate strength, specific rupture energy, effective stress vs. clay content

Tensile strength (Y) generally increased with decreasing matric potential and with increasing clay content. At −100 hPa, Y varied from 7.8 to 13.9 kPa from L12 to L45, and from 87 to 788 kPa at air-dry (Table 3). The relative change in Y from −100 hPa to air-dry was by a factor of 11 for L12, 20 for L22, 46 for L29 and 57 for L45. Specific rupture energy (E_{sp}) also generally increased with decreasing matric potential and with increasing clay content (Table 3).

3.3. Relationship between tensile strength and specific rupture energy, and effective stress

The relationship between on the one side geometric mean values of Y and E_{sp} across all aggregate size fractions at −100, −300, −1000 hPa and at air-dry and on the other effective stress (σ_e) is presented in Fig. 2a–b. Both Y and E_{sp} linearly and significantly increased with increasing σ_e ($p < 0.001$). Effective stress explained 89 and 56% of the variations in Y and E_{sp}, respectively. For the range of clay contents studied, Y and E_{sp} can be predicted from clay content and σ_e from the equation:

$$\text{Ln}\,(Y) = 1.019 + 2.81\,(\text{clay}) + 0.41\,(\sigma_e), \text{R}^2 = 0.95, p < 0.001 \tag{11}$$

and

$$\text{Ln}\,(E_{sp}) = -2.38 + 5.34\,(\text{clay}) + 0.31\,(\sigma_e), \text{R}^2 = 0.80, p < 0.001 \tag{12}$$

Parallel line analysis showed that the relationship between Y and σ_e was influenced by clay content, although only statistically significant between L12, L22 and L45 ($p < 0.05$), whereas we found no statistical significant influence of clay when E_{sp} was related to σ_e.

3.4. Soil friability

Soil friability (k_Y) measured at −100, −300, −1000 hPa and air-dry from the relationship between the natural logarithm of Y and aggregate volume varied from 0.23–0.44 for L12, 0.16–0.46 for L22, 0.14–0.46 for L29 and 0.14–0.54 for L45. For L12, k_Y tended to increase from −100 hPa to −300 hPa and then decreased from −1000 hPa to air-dry, whereas for L45, k_Y increased from −100 hPa to −1000 hPa and then decreased for air-dry. For both L22 and L29, k_Y increased from

Table 3

Geometric mean values of tensile strength (Y) and specific rupture energy (E_{sp}) for L12, L22, L29 and L45 at -100, -300, -1000 hPa and at air-dry. The geometric mean values of Y and E_{sp} for all aggregate size fractions are shown.

Soil attribute	Aggregate size	-100 hPa				-300 hPa				-1000 hPa			Air-dry				
		L12	L22	L29	L45	L12	L22	L29	L45	L12	L22	L29	L45	L12	L22	L29	L45
Y (kPa)	1–2 mm	nd[a]	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	223.8	401.8	790.8	1190.7
	2–4 mm	26.3	32.9	31.1	33.7	39.9	59.4	77.8	82.3	40.4	88.4	155.1	200.1	80.5	311.8	654.5	921.5
	4–8 mm	9.1	9.5	10.3	11.9	12.4	16.5	25.5	28.6	16.7	34.3	36.7	46.7	63.9	217.7	432.7	692.6
	8–16 mm	4.5	6.8	5.6	6.7	6.4	15.9	17.7	15.2	8.3	13.3	23.2	22.5	49.8	146.2	336.2	507.4
	Mean	7.8	12.7	11.5	13.9	14.7	24.9	32.8	33.0	17.8	34.3	51.0	59.4	87.0	251.3	523.8	788.0
E_{sp} (J kg^{-1})	1–2 mm	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	3.6	8.5	16.3	31.5
	2–4 mm	2.3	1.1	1.1	0.9	1.2	2.6	5.0	5.2	1.3	5.2	16.5	22.0	0.9	7.5	13.7	21.7
	4–8 mm	0.2	0.2	0.3	0.4	0.4	0.6	1.7	2.4	0.6	1.7	2.8	5.0	0.9	3.9	11.0	23.1
	8–16 mm	0.1	0.5	0.2	0.4	0.2	1.0	1.2	1.4	0.4	1.1	2.4	3.1	0.8	3.2	8.8	15.5
	Mean	0.2	0.5	0.4	0.5	0.4	1.2	2.2	2.6	0.7	2.2	4.8	7.0	1.3	5.3	12.1	22.2

[a] nd = not determined.
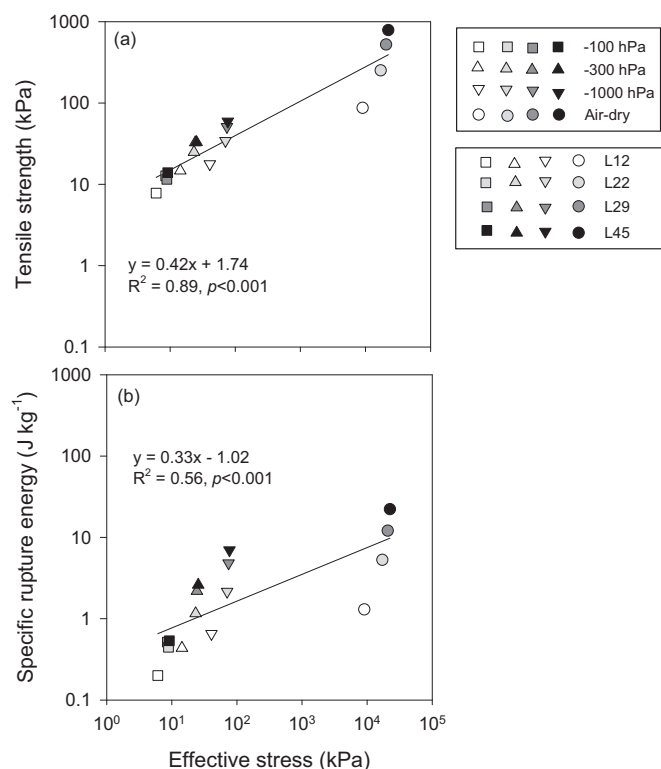
Fig. 2. Geometric mean values of (a) tensile strength and (b) specific rupture energy calculated as geometric means across all size fractions as a function of the geometric mean of effective stress. Symbols represent means of L12, L22, L29 and L45 at -100, -300, -1000 hPa and at air-dry.

-300 hPa to -1000 hPa and decreased at air-dry (Table 4). Results from the parallel lines analysis showed that for L12, k_Y at -100, -300 and -1000 hPa significantly differed from the air-dry state ($p < 0.05$), while for L22 and L45, k_Y differed significantly only between -1000 hPa and air-dry ($p < 0.001$ and $p = 0.05$, respectively). For L29, k_Y did not differ significantly between any of the matric potentials.

3.5. Relationship between aggregate strength and soil pore characteristics

At -100 hPa, Y linearly and significantly decreased with increasing volume of pores $> 30\,\mu m$ (Fig. 3a). A similar linear and negative relationship was found between Y and PO_1, but with a wide scatter (Fig. 3b). Although not significant, Y positively and linearly increased with increasing τ (Fig. 3c). Similar to Y, E_{sp} was linearly and negatively related to the volume of pores $> 30\,\mu m$ or PO_1 and linearly and

Table 4

Linear regression parameters for the relation between the natural logarithm of tensile strength and aggregate volume for L12, L22, L29 and L45 at -100, -300, -1000 hPa and air-dry where b is the intercept and n is the slope of the regression equation. Slope indicates soil friability and the p-value indicates the overall significance of the linear regression model.

Soil	Matric potential	b (kPa)	n (Friability index, k_Y)	R^2	p-value
L12	-100 hPa	-4.47	0.42	0.98	*0.08*
	-300 hPa	-4.38	0.44	0.98	*0.11*
	-1000 hPa	-3.31	0.39	1.00	*0.03*
	Air-dry	0.57	0.23	0.86	*0.07*
L22	-100 hPa	-3.58	0.38	0.90	*0.20*
	-300 hPa	-1.91	0.32	0.78	*0.31*
	-1000 hPa	-3.79	0.46	1.00	*0.001*
	Air-dry	2.75	0.16	0.99	*0.005*
L29	-100 hPa	-4.20	0.42	0.97	*0.10*
	-300 hPa	-2.29	0.36	0.92	*0.18*
	-1000 hPa	-3.46	0.46	0.92	*0.18*
	Air-dry	3.82	0.14	0.98	*0.009*
L45	-100 hPa	-3.65	0.39	0.97	*0.10*
	-300 hPa	-3.08	0.41	0.98	*0.09*
	-1000 hPa	-4.55	0.54	0.97	*0.12*
	Air-dry	4.34	0.14	1.00	*0.001*

positively to τ, albeit neither was statistically significant (Fig. 3d–f).

A simple linear regression analysis was also used to relate at -100 hPa Y and E_{sp} to ka and Dp/Do. It can be deduced from Fig. 4a–d that the strength of aggregate decreased with increasing ka or Dp/Do.

3.6. Water contents for tillage

The water content at the wet tillage limit (θ_{WTL}) ranged from 0.21 to 0.29 kg kg^{-1} while the dry tillage limit (θ_{DTL}) ranged from 0.09 to 0.24 kg kg^{-1} from L12 to L45 (Fig. 5). This corresponds to approximately -65 to -1800 hPa and -3600 to -4100 hPa on soil water retention curves for L12 to L45. The relationships between water contents for tillage and clay content or volume of pores $> 30\,\mu m$ are shown in Fig. 6a–f. In general, both θ_{WTL} and θ_{DTL} linearly and significantly increased with increasing clay content (Fig. 6a, c). The range of water contents for tillage ($\Delta\theta_{RANGE}$) rapidly decreased from L12 to L45 to a halving of the value (0.12 to 0.06 kg kg^{-1}) (Fig. 6e). For θ_{WTL} and θ_{DTL} there was a sharp decrease with decreasing volume of pores $> 30\,\mu m$ from L12 to L45 (Fig. 6b, d), whereas $\Delta\theta_{RANGE}$ was linearly and positively related with the volume of pores $> 30\,\mu m$ (Fig. 6f).
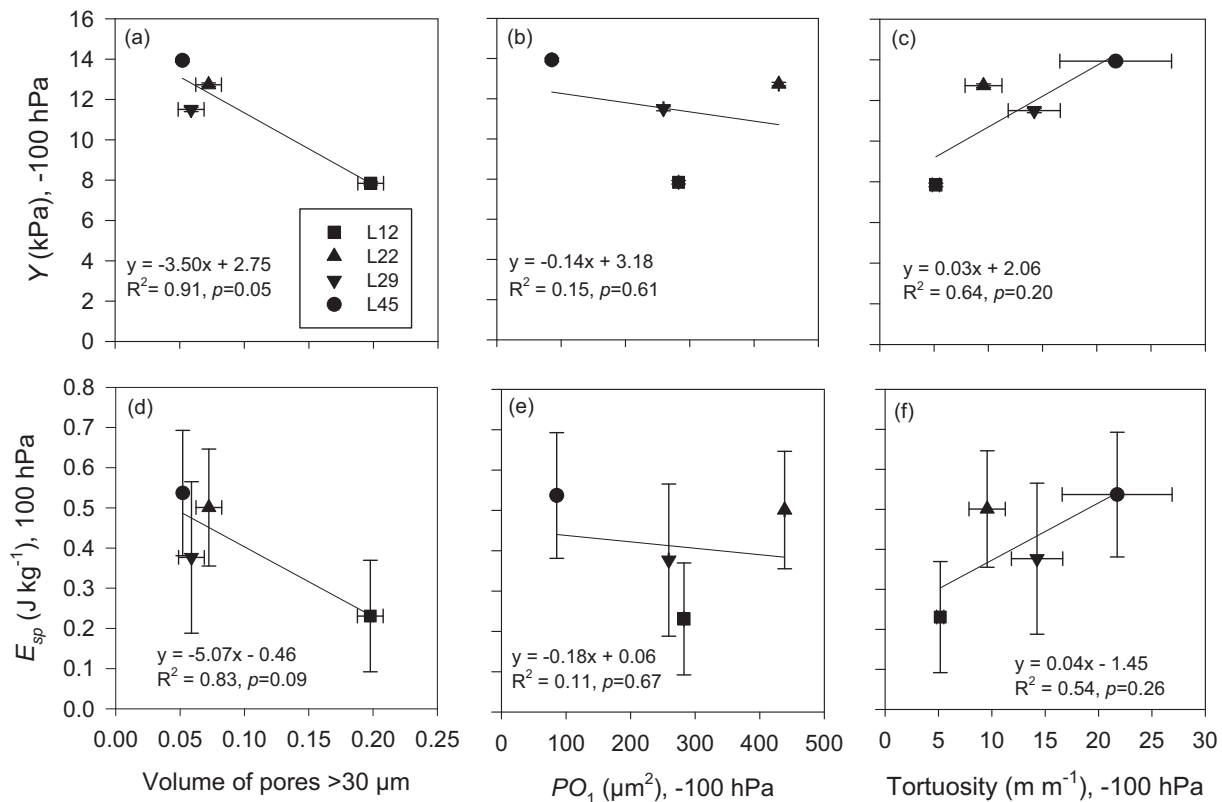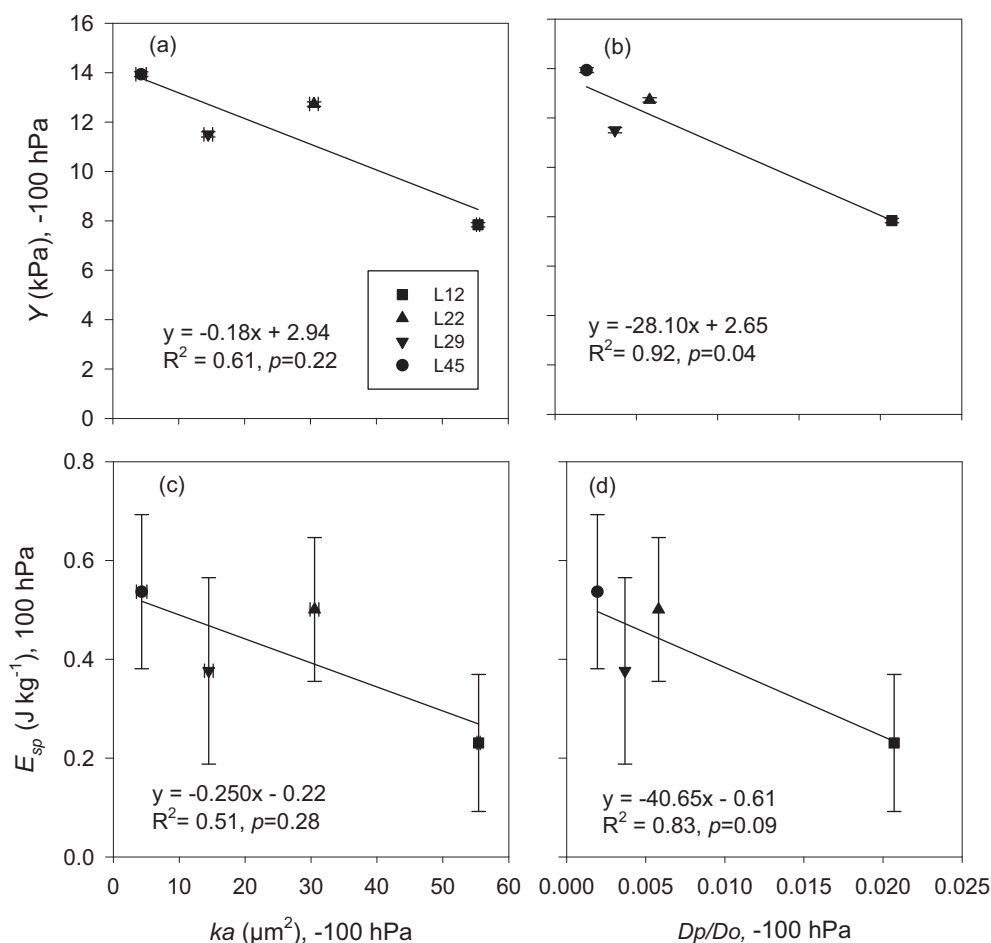
Fig. 3. Tensile strength (Y) and specific rupture energy (E_{sp}) calculated as the geometric mean of 2–4, 4–8 and 8–16 mm size fractions at -100 hPa as a function of (a and d) volume of pores > 30 µm, (b and e) pore organization ($PO_1 = k_a / \varepsilon_a$) and (c and f) tortuosity at -100 hPa. Error bars indicate the standard error.

4. Discussion

4.1. Soil workability as a function of clay content and matric potential

Soil workability is an indicator of the ease with which the soil can be tilled to produce the desired soil fragments for crop establishment (Dexter, 1988; Goense, 1987). The ease of tilling soil implies that soil should be friable, and should be neither too wet nor too dry in order to avoid the risk of soil structure damage in the former case and a high specific energy input for soil fragmentation during tillage in the latter. The conditions describing soil workability, namely ease of crumbling and a soil that is neither too weak nor too strong, are assessed from the quantitative measurements of tensile strength properties as a function of aggregate size and matric potential, and the estimated range of water contents suitable for tillage.

Soil workability is primarily governed by the mechanical state of soil (Earl, 1997). Results from the study showed that clay content and matric potential had considerable influence on tensile strength properties, friability and the water contents for tillage. Perfect and Kay (1994) proposed using E_{sp} for statistical characterization of aggregate strength in tillage studies. They found E_{sp} to be more appropriate for estimating the strength of dry aggregates than Y, because it involves no assumption on mode of failure. Munkholm and Kay (2002) found E_{sp} to be also useful for estimating the strength and fragmentation of wet aggregates.

For the matric potentials studied, both Y and E_{sp} generally increased with decreasing matric potential and with increasing clay content (Table 3). Increase in strength with increasing clay content can be explained as Y is largely dependent on the random distribution of flaw planes in a soil (Braunack et al., 1979). Increased clay content tends to increase the number of smaller pores (as evidenced by increasing volume of pores < 30 µm with increasing clay content (Table 2)). The smaller pores tend to have a more uniform pore size distribution and

therefore have fewer sites for the propagation of failure zones (Grant, 1989). Increase in strength with decreasing water content or matric potential can be ascribed to effective stresses (σ_e) from matric suction which pulls soil particles together (Terzaghi, 1923). Effective stress explained 89 and 56% of the variations in Y and E_{sp}, respectively (Fig. 2). High Y and E_{sp} values can in turn reduce soil workability because it is an indication of stronger soil fragments, and thus more mechanical stress or specific energy is required for soil crumbling. In terms of seedbed quality for crop establishment, it has been shown that seedbeds consisting of stronger aggregates can delay germination and hamper root growth and proliferation (Nasr and Selles, 1995), which can adversely affect crop growth and yield.

Both θ_{WTL} and θ_{DTL} increased with increasing clay content (Fig. 6a, c), whereas the range of water content for tillage ($\Delta\theta_{RANGE}$) decreased with increasing clay content (Fig. 6e) which is consistent with Dexter and Bird (2001). The positive relationship between θ_{WTL} or θ_{DTL} and clay content can be ascribed to an increase in the volume of intra-aggregate pores with increasing clay content, whereas the negative relationship between $\Delta\theta_{RANGE}$ and clay content can be attributed to a decrease in the volume of inter-aggregate pores (Obour et al., 2017). In fact, $\Delta\theta_{RANGE}$ was positively and strongly related to air-filled macroporosity (volume of pores > 30 µm) (Fig. 6f).

Water content at the wet tillage limit, which was estimated as the water content at the plastic limit (Dexter and Bird, 2001) corresponded to -65 hPa for L12, -479 hPa for L22, -1221 hPa for L29 and -1846 hPa for L45. This implies that a soil with a low clay content is workable at high matric potentials, whereas a soil with a high clay content has to drain to a more negative matric potential to be workable. The water content at θ_{DTL} corresponded approximately to -3600 hPa, for L12, -4700 hPa for L22, -3400 hPa for L29 and -4100 hPa for L45. Although when based on the friability classification of Imhoff et al. (2002) the L12 to L45 are classified as "friable" from -100 to -1000 hPa, and "slightly friable" at air-dry (Table 4), it was deduced

Fig. 4. Tensile strength (*Y*) and specific rupture energy (*E_sp*) calculated as geometric mean of 2–4, 4–8 and 8–16 mm size fractions at −100 hPa as a function of (a and c) geometric mean of air permeability (*ka*), (b and d) arithmetic mean of relative gas diffusivity (*Dp/Do*) at −100 hPa. Error bars indicate standard errors.
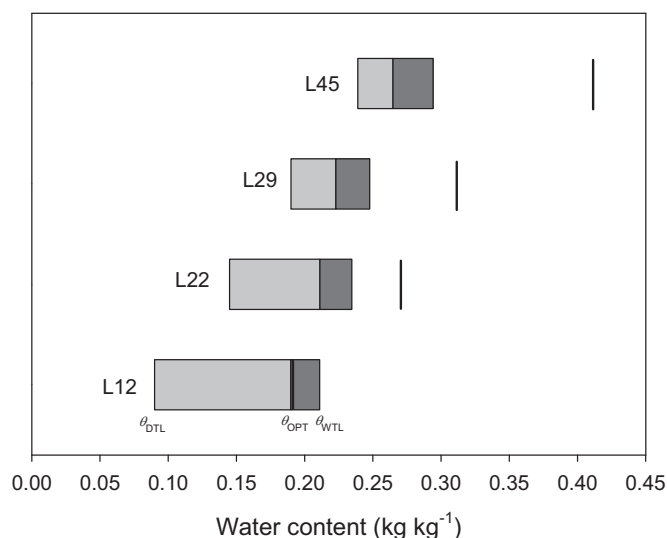

Fig. 5. Water contents for tillage for L12, L22, L29 and L45. θ_{DTL}: dry tillage limit, θ_{OPT}: optimum water content for tillage and θ_{WTL}: wet tillage limit. Solid short vertical lines show water contents at −100 hPa.

that at −1000 hPa the water content of L45 (0.34 kg kg⁻¹) was wetter than θ_{WTL} (0.29 kg kg⁻¹). This implies that the soil may fragment poorly when tillage is performed at that water content because the soil is in a plastic state. These results show the importance when determining the optimum water content for tillage of measuring k_Y at several points on the water retention curve and over a wide range of water contents or matric potentials because friability does reach a maximum. The results also highlight the importance of using a combination of criteria to quantitatively assess the conditions of optimum water for soil workability. It must be stressed that θ_{WTL} was estimated as the water content at the plastic limit, which is determined on a remolded soil, i.e. involving the destruction of the soil structure. Therefore, θ_{PL} does not take into account pre-existing micro-cracks and structural pores that are air-filled, and which play a key role in soil crumbling (Dexter and Bird, 2001).

4.2. Influence of pore structure characteristics on tensile strength and specific rupture energy

Aggregate strength was highly influenced by macroporosity. Both *Y* and *E_sp* linearly and strongly decreased with increasing volume of pores > 30 μm (Fig. 3a, d), but were weakly related to total porosity (data not shown). This implies that aggregate strength is not highly dependent on porosity per se, but, more importantly, on the air-filled macropore spaces. Tensile strength (*Y*) is largely influenced by air-filled micro-cracks and structural pores, which create sites for the propagation of flaw planes, i.e. failure zones. Under applied stress, the air-filled pores expand, elongate and join up, leading to soil failure (Dexter and Richard, 2009). At all the matric potentials studied, *Y* and *E_sp* increased in the order from L12 to L45. This can be ascribed to the arrangement of mineral particles of clay. An increase in clay content increases the area of contact, which strengthens the bonding between large particles
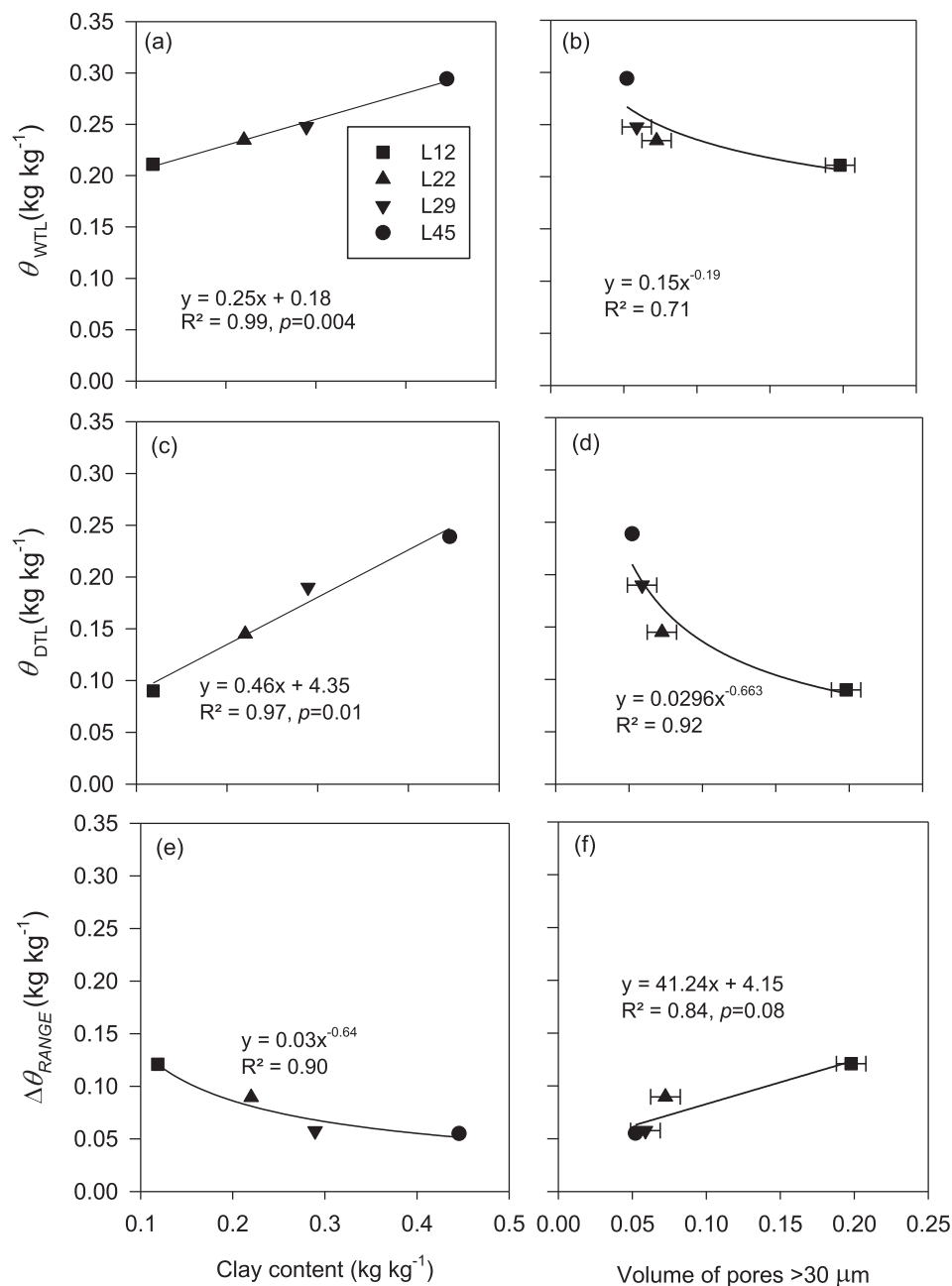
Fig. 6. Water contents for tillage: θ_{WTL} (wet or upper tillage limit), θ_{DTL} (dry or lower tillage limit) and $\Delta\theta_{RANGE}$ (the range of water contents for tillage) as a function of clay content (a, c and e) and volume of pores > 30 μm (b, d and f). Error bars indicate standard error.

(Kemper et al., 1987). The increase can also be attributed to a greater volume of smaller pores with increasing clay content, as explained previously. Our results are consistent with those of Guérif (1990) who also found a strong link between Y and the structural porosity of a clay soil.

Tensile failure of brittle materials is affected by stress concentrated at crack tips. Thus, sudden failure of a soil material occurs when stress exceeds the strength at the crack tip (Snyder and Miller, 1989). Stress concentration at the crack tip is influenced by pore characteristics such as geometry and morphology. It decreases with pore tortuosity (τ) and increases with increasing pore continuity (Munkholm et al., 2002). The strong positive and linear relationship between Y or E_{sp} and τ confirmed this (Fig. 3c, f). The weak relationship between Y or E_{sp} and PO_1 agreed with previous studies (Munkholm et al., 2002). According to Munkholm et al. (2002), the weak relationship is probably due to a large small-

scale variability of k_a. Gas transport properties such as k_a and Dp/Do can be used as indirect measures for characterizing soil pore systems. At -100 hPa, both Y and E_{sp} linearly decreased with increasing k_a or Dp/Do (Fig. 4a–d). The statistical relationship between k_a or Dp/Do and Y and E_{sp} may be due to the effect of other pore characteristics such as ε_a and τ on k_a and Dp/Do. Nevertheless, the negative relationship may indicate that soil crumbling can be enhanced when air-filled microcracks and structural pores are able to conduct gases through the soil pore system. It must be emphasized that in this study, soil pore system was characterized indirectly by measuring ε_a, θ, k_a or Dp/Do. There exists advanced techniques such as computer-assisted tomography scanning for direct measurement and characterization of the soil pore system (Taina et al., 2008).

4.3. Implications of results for tillage management and perspectives

The optimal intensity of tillage and response of soil structure to tillage operations vary across space and time due to site-specific differences in soil characteristics such as texture and water content. Nevertheless, soil workability during tillage may be assumed uniform across a field. The findings of this study show that clay content influenced soil strength and the range of water contents for tillage and can thus exacerbate cultivation problems in fields with highly variable soil textures. This suggests that in fields with variable 'tillage windows' or range of water contents for tillage, a uniform tillage operation might not be the best management option unless operations are properly scheduled. It needs to be pointed out that although most fields are not uniform in texture, a high variability as in the investigated field is uncommon. In this regard, the best option might be to divide a field into subfields, i.e. based on clay content, and to till at different times for each soil. A farmer can then carry out tillage according to site/location-specific soil workability. An advantage of this option is that it allows optimal resource utilization, for example by reducing the energy required for soil fragmentation during tillage and minimizing the risk of soil structural damage and other environmental impacts of tillage. Detailed soil mapping is a prerequisite for delineating soil workability within fields according to clay variability.

With regard to uniform tillage practices across fields, it is important that in fields with highly variable soils the operations should be scheduled for periods when the range of water contents for tillage for the whole field overlap, especially between soils that could potentially limit soil workability. For the range of clay contents investigated here, the 'common window' occurred between approximately -1800 to -3400 hPa. At this range of matric potential, the range of water contents for tillage for L12, L22, L29 and L45 overlapped. A practical significance of this option is that it allows farmers to carry out operations in a given field in one go. It does, however, require a comprehensive knowledge of matric potentials of soils in a field.

Improving the soil physical quality might be another option for increasing the soil water conditions appropriate for tillage. Increasing SOC has been shown to enhance soil workability by improving soil conditions for tillage and overall widening the $\Delta\theta_{\mathrm{RANGE}}$ (Obour et al., 2018). For the range of clay contents investigated here, it might be better for the farmer to focus on improving the physical quality of, especially, L29 and L45 through, for example, increasing SOC contents so that the range of water contents for tillage is increased. In that way, the tillage window of the whole field would become larger for soil tillage operations.

5. Conclusions

Clay had a considerable influence on tensile strength (Y), specific rupture energy (E_{sp}), soil friability and the range of contents for tillage ($\Delta\theta_{\mathrm{RANGE}}$), which consequently affected soil workability. Y and E_{sp} decreased with increasing air-filled macroporosity as well as air permeability and gas diffusivity. Our results show that uniform tillage might not be the best option for fields that exhibit high variability in terms of $\Delta\theta_{\mathrm{RANGE}}$. Proper planning and performing tillage operations based on site-specific soil workability is a prerequisite for improving soil fragmentation in tillage and for optimizing resource utilization to reduce the risk of soil structural damage from tillage. Overall findings of this study imply that management practices that increase soil macroporosity can potentially decrease aggregate strength and increase $\Delta\theta_{\mathrm{RANGE}}$ to improve soil workability, which in turn can reduce cultivation problems in agricultural soils with a wide range in clay contents.

Declarations of interest

none.

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Paper 4

Compaction and sowing date change soil physical properties and crop yield in a loamy temperate soil

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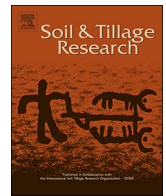
Compaction and sowing date change soil physical properties and crop yield in a loamy temperate soil

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ABSTRACT

Timing of tillage operations is of utmost importance in arable farming because tillage performed under inappropriate soil water conditions results in soil structural damage and creation of undesirable seedbeds for crop establishment and growth. In a field experiment on a loamy soil in Ås, Norway, we investigated the effect of compaction and sowing dates on (i) seedbed physical properties, (ii) crop yield, and (iii) the range of water contents for tillage. The experiment was established in 2014 and the same experimental treatments were repeated in 2015, 2016 and 2017. The sowing dates included early (A1), normal/timely (A2) and late (A3) sowing dates. The compaction treatments applied each year were done wheel-by-wheel by a MF 4225 tractor weighing 4.5 Mg with a single pass (B1) and compared with a control treatment (B0). This study reported soil physical properties for only 2016 and small grain cereal yield for the four years. The soil pore characteristics determined were soil bulk density (ρb), volumetric water content (θ), air-filled porosity (ε_a), air permeability (k_a) and pore organization indices $(PO_1 = k_a/\varepsilon_a$ and $PO_2 = k_a/\varepsilon_a^2)$; strength properties measured were tensile strength (Y), soil penetration resistance (PR), degree of soil fragmentation by drop-shatter test, and water contents for tillage by calculating the range of water content for tillage ($\Delta\theta_{RANGE}$). The interaction of compaction with sowing date, generally affected soil pore characteristics, particularly at 1–5 cm depth. The A1 treatment significantly affected the strength characteristics of seedbed by decreasing soil friability and increasing Y at 1–10 cm depth, and PR down to 27 cm depth. The A3 treatment decreased yield of spring-sown small grain cereal crops, but this may be ascribed to a shorter growing season rather than an influence of soil physical properties. The A1 and A3 decreased the range of water contents for tillage compared to the A2, although the difference was not significant at any of the depths studied. Findings of the study have practical implications for cropping regimes in colder climates where farmers can be faced with a short growing period by showing that cultivation in wet soil conditions such as early spring can adversely affect seedbed physical properties and soil workability for subsequent tillage operations.

1. Introduction

Tillage is an integral part of arable farming practices— it induces changes in soil structure that may be beneficial or detrimental to soil physical properties and crop growth. In a conventional cultivation, secondary tillage means harrowing after primary tillage with the aim of preparing the soil for seeding, also called seedbed preparation, by creating optimum physical conditions for crop establishment and growth (Arvidsson et al., 2000). In this paper, the term "tillage" without

an adjective refers to secondary tillage for seedbed preparation. One important aim of tillage is to fragment soil in order to minimize the proportion of large aggregates (Ojeniyi and Dexter, 1979). It is, generally accepted that soil aggregate size range of 1–5 mm is required for good seedbed that favors seed emergence and growth (Russell, 1961). This is because such seedbed has good aeration, water holding capacity, and improve soil-seed-contact area (Braunack and Dexter, 1989b).

Soil workability is a key condition in tillage. In seedbed preparation, soil workability is the ease with which a well-drained soil can be tilled
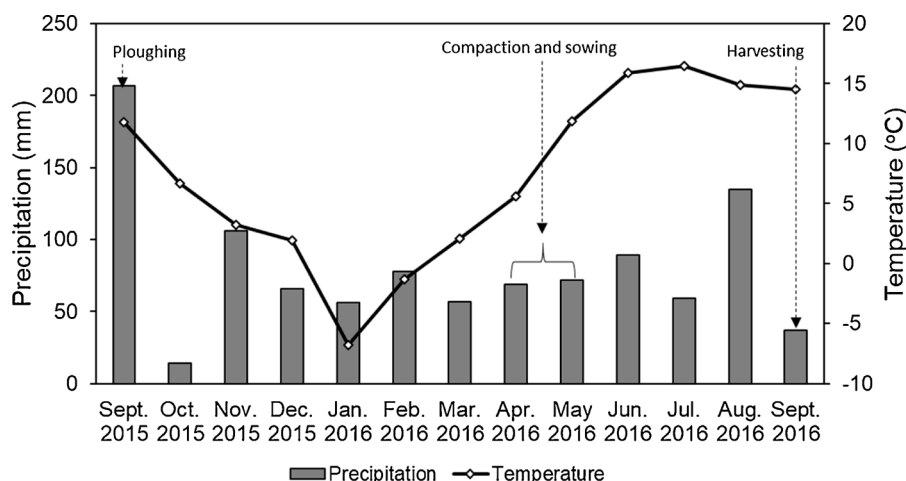

Fig. 1. Mean monthly precipitation and air temperature of the experimental site from September 2015 to September 2016.

to produce an optimum seedbed for crop establishment (Dexter, 1988). Moisture content at tillage is a major factor affecting soil workability. Soil is workable over a range of water content ($\Delta\theta_{RANGE}$) between an upper (wet tillage limit, θ_{WTL}) and a lower (dry tillage limit, θ_{DTL}). $\Delta\theta_{RANGE}$ decreases with decreasing soil organic matter content and with increasing clay content and soil bulk density (Dexter and Bird, 2001). This suggests that farmers can be faced with cultivation problems in regions with hard-setting soils (Mullins et al., 1988) and in colder climates with a short period for spring or autumn cultivation.

Improved tires and power of modern field machinery mean that farmers are able to till in less-than-ideal soil conditions such as early spring tillage in temperate regions like Northern Europe. Therefore, modern agricultural machinery might improve trafficability, that is, the ability of soil to support and withstand field traffic without irreversible soil degradation (Rounsevell, 1993), at the expense of increased risk of detrimental effects from tillage, and the farmers' decisions on tillage and sowing date become crucial.

When performed in less-than-ideal soil conditions, tillage can produce short- and long-term detrimental effects on soil. The described tillage effects on germination, emergence and growth of the current crop can be considered short-term effects. On the other hand, changes induced by tillage which persist over cropping seasons or years can be considered long-term effects. Structural degradation in the topsoil due to tillage in too wet conditions has been shown to persist until the following autumn (Munkholm and Schjønning, 2004), which can affect the water contents for tillage and seedbed preparation for a subsequent winter crop. Therefore, tillage-induced soil structural degradation in spring might reduce soil workability for autumn tillage and complicate scheduling of these operations. It must be emphasized that there is a lack of quantitative information on this effect as reviewed by Obour et al. (2017).

In addition to the short- and long-term effects, in too wet soil condition, tillage can create a seedbed composed of large and strong soil fragments because of kneading. According to Dexter and Birkas (2004), large soil fragments have less agronomic value because they do not favor good soil-seed-contact area. Further, large soil fragments can impede crop emergence and root growth (Nasr and Selles, 1995), which adversely affect crop yield. In too dry soil condition, soil becomes strong and high specific energy is required for soil crumbling. Also, tillage can produce undesirably finer fragments, which are susceptible to surface crusting, and wind and water erosion (Braunack and Dexter, 1989a). Therefore, knowledge of the effects of sowing date on seedbed physical properties is a pre-requisite for decision support for scheduling and planning tillage operations to create optimal seedbeds for crop establishment.

The objectives of the study were to quantify the effect of compaction

and sowing dates on (i) seedbed physical properties, (ii) crop yield, and (iii) the range of water contents for tillage. Tillage is most often conducted in either spring or autumn, but in this study, only spring tillage is considered. Three sowing dates, namely early, timely/normal and late, were chosen as being representative of real farming practice of carrying out early, normal and delayed spring tillage. We focused on soil strength characteristics, namely tensile strength, friability, penetration resistance and soil fragmentation to assess soil workability. We hypothesized that the strength of soil aggregates and soil fragmentation will differ for different compaction treatments and sowing dates. The hypothesis was tested by comparing the strength properties of soil after early, normal and late sowing in spring.

2. Materials and methods

2.1. The experimental site

Soil samples were collected from a compaction experiment in Ås, Norway (59° 39′ 47″ N 10° 45′ 49″ E). Mean annual precipitation and temperature in the area are 785 mm and 5.3 °C, respectively (Wolff et al., 2017). The monthly precipitation and temperature data covering the period September 2015 and September 2016 (Fig. 1) were obtained from a meteorological station located about 1 km from the experimental site. The period covers autumn plowing of the field in 2015, cultivation in the spring and harvest in autumn 2016. Daily precipitation and air temperature cycles prior to the specific field operations and sampling are also shown (Fig. 2a–d).

Soils at the site are characterized as loam over silt loam and silty clay loam and are classified as Luvic Stagnosol (Siltic) in the World Reference Base (WRB) classification system (WRB, 2006). Soil textural characteristics for the upper layer (0–15 cm depth) are: 22% clay (< 2 μm), 29% silt (2–20 μm), 29% fine sand (20–200 μm), 15% coarse sand (200–2000 μm) and 4.5% soil organic matter.

2.2. Experimental design and treatments

The experiment was established in 2014 and the same experimental treatments were repeated in 2015, 2016 and 2017. This study investigated results for soil physical properties for only 2016. The design was a randomized split-plot in two replications comprising two factors. The main plot treatment was sowing date and the split-plot treatment was compaction. The sowing dates included early (A1), normal/timely (A2) and late (A3) sowing dates (Fig. 3). The compaction treatments applied each year included no compaction (B0) and compaction by a MF 4225 tractor weighing 4.5 Mg with one pass (B1). Compaction was done wheel-by-wheel. The front and rear tires of the tractors were
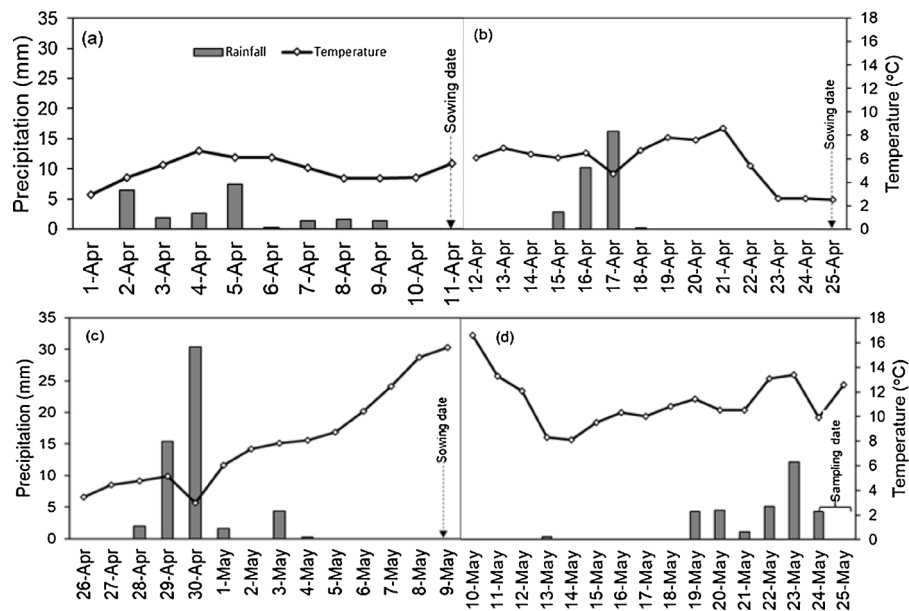
Fig. 2. Daily precipitation and air temperature before (a) early sowing date, (b) normal sowing date, (c) late sowing date and (d) sampling. No data for March 28–30, 2015.

adjusted to an inflation pressure of 1.5 bar.

Prior to the experiment in 2016, the field was plowed to ~20 cm depth the previous autumn with a reversible plow with two mold-boards. In A1, plots were either compacted or not compacted, and harrowed and seeded on the same day in the second week of April 2016 when the soil was wet to represent the worst-case scenario when farmers will sow early in spring. In the same manner, A2 plots were treated in the fourth week of April, i.e., two weeks after the A1 treatment, when the soil was expected to be in semi-moist condition. Finally, in A3, treatment was carried out in the second week of May 2016 when the soil was expected to be dry. Water content at sowing time (Table 1) was determined volumetrically in the field using a hand-held time-domain reflectometer (TDR, HH2-ML3, Delta-T Devices, Cambridge, England).

The six treatment combinations were labelled A1 + B1, A1 + B0, A2 + B1, A2 + B0, A3 + B1 and A3 + B0. Secondary tillage was done to a depth of ~5 cm using a Ferraboli rotary power harrow (rotorharv). A small grain cereal crop was established on each of the experimental plots: Wheat (*Triticum aestivum* L.*)* in 2014, barley (*Hordeum vulgare* L.*)* in 2015, oats (*Avena sativa* L.*)* in 2016 and barley in 2017. For each year, the crop was harvested at full maturity using a plot harvester. The harvested area was $9\,m^2$ ($1.5\,m \times 6\,m$) for each plot. The grain yield for each experimental plot was recorded.

Table 1
Sowing dates and soil water content during treatment in 2016.

Depth (cm)	Early sowing (April 11)	Normal/timely sowing (April 25) Water content ($m^3\,m^{-3}$)	Late sowing (May 9)
0–5	0.35	0.19	0.19
5–10	0.36	0.24	0.27

2.3. Sampling

Sampling was carried out in spring of 2016 from May 24–25, two weeks after the late sowing date. Undisturbed soil cores (9.6 cm diameter, 8 cm high, $580\,cm^3$, hereafter called 'large soil cores') and (6.1 cm diameter, 3.4 cm high, $100\,cm^3$, hereafter called 'small soil cores') were sampled. The large soil cores were sampled at only one depth (~5–15 cm), i.e., below the harrowed layer. The small soil cores were sampled from two depths: ~1–5 cm and at ~5–10 cm. Bulk soil was taken from each sampling position and depth using a spade and were placed in plastic boxes. All soil samples were covered with plastic lids and stored in a 2 °C room until laboratory analyses.
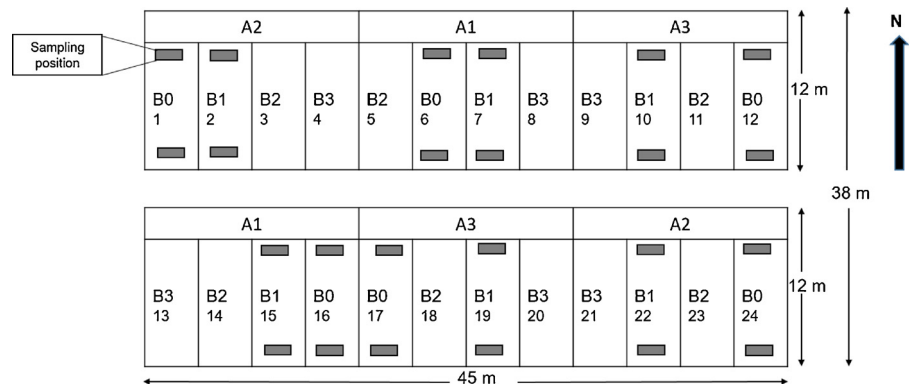
Fig. 3. Outline of experimental design used in this study. The figure also shows the sampling positions where soil samples were collected from each plot.

2.4. Penetration resistance

To determine soil strength in the seedbed layer and the layer below, soil penetration resistance (PR) was measured in the field on July 4, 2016 down to 27 cm depth with a hand-held cone penetrometer (Eijkelkamp Penetrologger 06.15.SA, Eijkelkamp Soil & Water, Giesbeek, The Netherlands). It has a cone angle of 60° and a penetration speed of $2\,cm\,s^{-1}$. Average soil water content at penetration was $0.28\,m^3\,m^{-3}$. Fifteen replicate penetration measurements were taken in each experimental plot. The geometric mean of PR was computed at the following soil depths per plot: 1–5, 7–15, 15–20 and 20–27 cm. The depths represent the seedbed layer, seedbed bottom, lower part of the tilled layer and the bottom of the plow layer, respectively. The depths were chosen on the basis that given the small size of the machinery used in this experiment, we did not expect a remarkable effect of compaction in the subsoil, below the plow layer.

2.5. Laboratory measurements

The bulk soil samples were gently fractured by hands along planes of natural weakness, and left to air-dry in a ventilated room at a temperature of ~20 °C. Portions of the air-dry soil samples were crushed and passed through a 2 mm sieve to determine soil texture and soil organic matter content. The rest of the air-dry samples were crushed using the roller method (Hartge, 1971) before sieving through a nest of sieves to obtain 8–16, 4–8, 2–4 and 1–2 mm soil aggregate size fractions. Some of the 8–16 mm aggregates were capillary-adjusted to −100, −300 and −1000 hPa matric potentials using tension tables, vacuum pots and pressure plates, respectively (Dane and Hopmans, 2002). A batch of 15 aggregates were randomly selected from each plot and size fraction to test their tensile strength (Y) using the indirect tension test (Rogowski, 1964). In brief, each of the aggregates was weighed and thereafter subjected to indirect tensile testing by crushing the aggregates between two parallel plates (Rogowski, 1964) using a mechanical press (Instron Model 5969, Instron, MA,USA) at a constant rate of displacement of $1\,mm\,min^{-1}$. The point of failure for each aggregate was automatically detected when there was a continuous crack in the aggregate. The maximum force at failure was automatically recorded.

The small soil cores were saturated and drained to −10, −30, −100, −300, and −1000 hPa matric potentials to obtain water retention data. Water content at −15,000 hPa was determined on oven-dried soil sieved to 2 mm at 105 °C for 24 h. Briefly, soil was crushed and sieved to 2 mm. Subsamples (~10 g) were placed in PVC rings on ceramic pressure plates (Richards, 1948), water-saturated and drained to −15,000 hPa. After 10 days, the subsamples were weighed before and after oven-drying. Water content was then calculated.

The large soil cores were drained to −100, −300 and −1000 hPa and thereafter subjected to a drop-shatter test (Schjønning et al., 2002) in the laboratory to determine how the soil fragmented upon energy application. The soil was removed from the metal ring using a special plastic flange so that it dropped from a height of 200 cm onto a concrete floor covered with a plastic sheet to avoid losing the soil fragments. The dropped samples were collected and left to air-dry before sieving through a nest of sieves with apertures of 16, 8, 4 and 2 mm to determine fragment size distribution. The degree of soil fragmentation from the drop-shatter test was expressed as geometric mean diameter (GMD). Following equilibrium at each water potential the small soil cores and soil fragments obtained from dropped large soil cores were oven dried at 105 °C for 24 h.

2.6. Calculations

Soil bulk density (ρb) was calculated from the oven-dried mass of each soil core (both large and small soil cores) divided by the total soil volume. Total porosity (Φ) was calculated from ρb and particle density

(ρd) as $\Phi = 1- \rho b/\rho d$. A particle density of $2.54\,Mg\,m^{-3}$ reported for the experimental site by Hofstra et al. (1986) was used. In addition, the volumetric water content (θ, $m^3\,m^{-3}$) at −100 hPa was calculated by multiplying ρb and gravimetric water content at −100 hPa. Air-filled porosity (ε_a) at −100 hPa was calculated by subtracting θ at 100 hPa from Φ.

Air permeability (k_a) was measured on the small soil cores using the Forchheimer approach for soil air permeability measurement recently developed by Schjønning and Koppelgaard (2017). Individual soil samples were attached to the measuring chamber by a polyurethane tube. The sample was kept airtight by means of an inflatable rubber O-ring. The apparatus measures air flow through the sample at a range of pressure differences across the sample. A polynomial regression of flow-pressure data was then used to determine the true Darcian flow based on the coefficient to the linear part of the relation (Schjønning and Koppelgaard, 2017). Two indices of pore characteristics were derived from the relation between k_a and ε_a (Groenevelt et al., 1984), which relate to the term pore organization (PO) (Blackwell et al., 1990): $PO_1 = k_a/\varepsilon_a$ and $PO_2 = k_a/\varepsilon_a^2$. The indices are explained in detail in Section 4.1.

Tensile strength (Y) was calculated according to Dexter and Kroesbergen (1985):

$$Y = 0.567F/d^2 \tag{1}$$

where F is the maximum force (N) required to fracture the aggregate and d is the effective diameter (m) of the spherical aggregate obtained by adjusting the aggregate diameter according to the individual masses (Dexter and Kroesbergen, 1985):

$$d = d_1(m_0/m_1)^{1/3} \tag{2}$$

where $d_1 =$ is the diameter of aggregates defined by the average sieve sizes, m_0 is the mass (g) of the individual aggregate and m_1 is the mean mass of a batch of aggregates of the same size class.

The friability index (k_Y) for the air-dry aggregates was taken as the slope of the plot of the natural logarithm of Y (kPa) for all size fractions and the natural logarithm of aggregate volume (Utomo and Dexter, 1981):

$$Ln\,(Y) = -k\,Ln\,(V) + A \tag{3}$$

where Ln is the natural logarithm, k is an estimate of friability (large value of k indicates that large aggregates are much weaker than smaller aggregates and are easily fragmented into small and stronger aggregates, whereas a small value of k shows that the strength of the large aggregates does not differ from that of smaller aggregates (Utomo and Dexter, 1981). A is the intercept of the regression and denotes the predicted Ln tensile strength (kPa) of $1\,m^3$ of bulk soil, and V (m^3) is the estimated aggregate volume. Friability of the treatments was classified according to Imhoff et al. (2002) where F < 0.1 = not friable, 0.1–0.2 = slightly friable, 0.2–0.5 = friable, 0.5–0.8 = very friable and > 0.8 = mechanically unstable.

The water contents for tillage (dry tillage limit, θ_{DTL}; optimum water contents for tillage, θ_{OPT}; and wet tillage limit, θ_{WTL}) were determined using the consistency approach described by Obour et al. (2018). The range of water contents for tillage was calculated as the difference between θ_{WTL} and θ_{DTL}.

2.7. Statistical analysis

Data analyses were done in the R software package version 3.4.1 (R Core Team, 2017). Tensile strength, air permeability and pore organization indices (PO_1 and PO_2) data were log-transformed to yield normality. The data were analyzed using a generalized linear model. The family, gaussian and link, identity functions implemented in R were used. The ANOVA F-test was used to determine the statistical significance of compaction, sowing dates and their interaction effect.

Table 2

Arithmetic mean of bulk density (ρ_b), volumetric water content (θ), air-filled porosity (ε_a), and geometric means of air permeability (k_a) and pore organization indices ($PO_1 = k_a/\varepsilon_a$ and $PO = k_a/\varepsilon_a^2$) at -100 hPa matric potential (data from small soil cores).

Depth (cm)	Treatment	ρ_b (Mg m^{-3})	$\theta, -100\,hPa$ (m^3 m^{-3})	$\varepsilon_a, -100\,hPa$ (m^3 m^{-3})	$k_a, -100\,hPa$ (μm^2)	$PO_{1,} -100\,hPa$ (μm^2)	$PO_{2,} -100\,hPa$ (μm^2)
1–5	A1 + B1	1.09	0.31ab	0.26b	539bc	2140ab	8503ab
	A1 + B0	1.10	0.32ab	0.25ab	337ac	1389ab	5721ab
	A2 + B1	1.05	0.30a	0.28b	327ab	1187a	4310a
	A2 + B0	1.05	0.31ab	0.28b	735c	2674b	9732b
	A3 + B1	1.17	0.33b	0.21a	215a	1082a	5452ab
	A3 + B0	1.11	0.30a	0.27b	415ac	1562ab	5873ab
	Average compaction						
	B1	1.10	0.32	0.25	336	1401	5846
	B0	1.09	0.31	0.27	469	1797	6889
	Average sowing date						
	A1	1.10b	0.31	0.25	426	1724	6975
	A2	1.05a	0.31	0.28	490	1782	6476
	A3	1.14b	0.31	0.24	299	1300	5658
5–10	A1 + B1	1.28d	0.38c	0.12a	32	310	3004
	A1 + B0	1.20ac	0.35ab	0.18bc	206	1254	7626
	A2 + B1	1.12a	0.34ab	0.21c	174	830	3972
	A2 + B0	1.14ab	0.35ab	0.20c	231	1162	5835
	A3 + B1	1.27cd	0.36b	0.14ab	48	350	2529
	A3 + B0	1.21bcd	0.33a	0.19c	155	830	4434
	Average compaction						
	B1	1.23	0.36	0.16	64a	448a	3113b
	B0	1.19	0.34	0.19	196b	1071b	5856a
	Average sowing date						
	A1	1.24	0.36	0.15	81a	623	4787
	A2	1.13	0.35	0.21	200b	982	4814
	A3	1.24	0.34	0.17	85ab	531	3318

Values with different letters are significantly different at $p < 0.05$. A1, early sowing date; A2, normal sowing date; and A3, late sowing date; B0, control and B1, compaction with a single pass by a tractor weighing ~ 4.5 Mg.

Table 3

Geometric means of tensile strength (Y) of 8–16 mm soil aggregates.

Depth (cm)	Treatment	Y (kPa)			
		$-100\,hPa$	$-300\,hPa$	$-1000\,hPa$	Air-dry
1–5	A1 + B1	6.9	11.4bc	24.2b	135b
	A1 + B0	5.8	12.9c	22.8b	96ab
	A2 + B1	4.3	11.4bc	19.6b	76a
	A2 + B0	4.4	6.7a	10.9a	93ab
	A3 + B1	5.3	7.4ab	19.3b	112b
	A3 + B0	4.9	9.4ac	18.3b	69a
	Average compaction				
	B1	5.4	9.9	20.9	105
	B0	5.0	9.3	16.6	85
	Average sowing date				
	A1	6.3b	12.1	23.5	114
	A2	4.4a	8.7	14.6	84
	A3	5.1ab	8.4	18.8	88
5–10	A1 + B1	7.6	18.2b	41.9c	175c
	A1 + B0	5.8	13.5b	23.3b	110b
	A2 + B1	5.5	6.9a	14.1a	98ab
	A2 + B0	4.7	11.2ab	12.1a	71a
	A3 + B1	5.8	12.9b	22.8b	87ab
	A3 + B0	6.7	11.3ab	20.8b	94ab
	Average compaction				
	B1	6.3	11.8	23.8	114
	B0	5.7	12.0	18.0	90
	Average sowing date				
	A1	6.6	15.6	31.3	138
	A2	5.1	8.8	13.1	84
	A3	6.3	12.1	21.8	91

Values with different letters are significantly different at $p < 0.05$. A1, early sowing date; A2, normal sowing date; and A3, late sowing date; B0, control and B1, compaction with a single pass by a tractor weighing ~ 4.5 Mg.

When interaction between the treatments was significant, we carried out further analyses to identify differences between treatment combinations using the Tukey method. When interaction between treatments was not significant, further analyses with interaction term excluded from the model were also carried out to identify which of the main effects was significantly different. We applied $p < 0.05$ as a criterion for statistical significance. A parallel lines test was conducted to determine if the regression slopes indicating friability index were significantly different from each other.

3. Results

3.1. Soil pore characteristics

At 1–5 cm depth, sowing date significantly affected soil soil bulk density (ρb) ($p < 0.001$). The early (A1) and late (A3) sowing treatments had higher ρb values compared to the normal/timely sowing (A2) treatment (Table 2). Neither the compaction × sowing date interaction nor compaction on its own significantly affected ρb ($p > 0.05$). The parameters volumetric water content (θ), air-filled porosity (ε_a), air permeability (k_a), and pore organization indices (PO_1 and PO_2) at -100 hPa were significantly affected by the compaction × sowing date interaction ($p < 0.05$). The θ and ε_a at -100 hPa are taken to represent the volume of pores below and above the 30 μm tube-equivalent pore diameter, respectively (Hillel, 1982). Overall, the results for the interaction effect at 1–5 cm depth were inconsistent (Table 2).

At 5–10 cm depth, ρb was higher for the A1 + B1 treatment than for A1 + B0, A2 + B0 and A2 + B1. Further, the A1 + B1 treatment had the highest volume of pores < 30 μm. For A1 + B1, ε_a was significantly reduced compared to the other treatments, except A3 + B1 (Table 2). Compaction significantly reduced k_a, PO_1 and PO_2 ($p < 0.001$), and the A1 treatment had a lower k_a than A2 ($p = 0.04$).
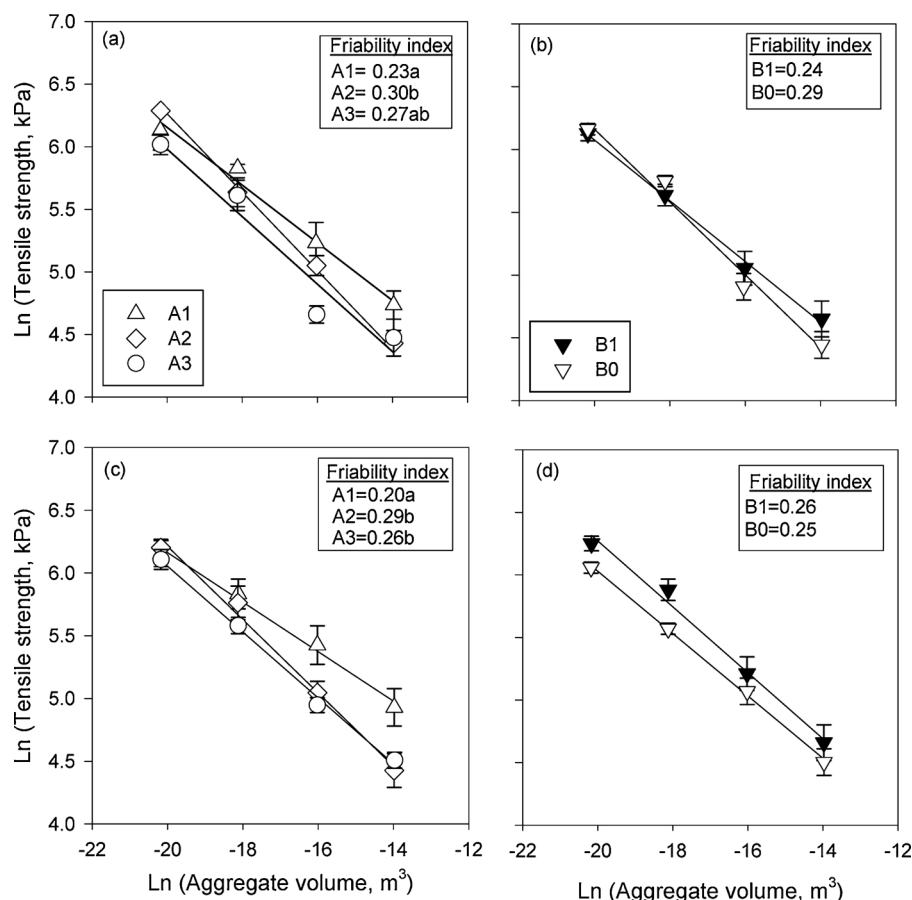
Fig. 4. Natural logarithm (Ln) of tensile strength, Y (kPa), as a function of Ln aggregate volume, V (m³), for air-dry aggregates. Soil friability index (k_Y), determined as the slope of the regression equation, is shown for each treatment: Averages of k_Y for sowing dates (a and c) and for compaction (b and d). A1, early sowing date; A2, normal sowing date; and A3, late sowing date. B0, control and B1, compaction with a single pass by a tractor weighing ~4.5 Mg. Values with different letters are significantly different at $p < 0.05$. Error bars indicate the standard errors of the mean.

3.2. Tensile strength

At -100 hPa, sowing date significantly affected Y ($p = 0.03$), but only at 1–5 cm depth. Tensile strength was lower for A2 than for the A1 treatment (Table 3). At both 1–5 and 5–10 cm depths, the interaction effect of compaction × sowing date was significant ($p < 0.05$) when Y was tested at -300 and -1000 hPa and in the air-dry state. At 1–5 cm depth, Y was consistently lower for A2 + B0 than for A1 + B1, A1 + B0 and A2 + B1 when tested at -300 and 1000 hPa. At 5–10 cm depth, A1 + B1 consistently yielded a higher Y than the other treatments at -1000 hPa and in the air-dry state (Table 3).

3.3. Friability indices and soil fragmentation

At 1–5 cm depth, higher friability (k_Y), indicated by the steepest slope, was found for the A2 treatment, and for the A2 and A3 treatments at 5–10 cm depth (Fig. 4a and c). Regardless of depth, there was a significant difference of k_Y between the compacted and control soil (Fig. 4b and d).

There was a significant ($p < 0.05$) compaction × sowing date interaction effect on soil fragmentation at all the matric potentials studied. At -100 hPa, the A1 + B1 treatment resulted in poor fragmentation compared to the other treatments, indicated by the larger geometric mean diameter (GMD) values, i.e., soil cloddiness (Table 4). However, at -300 hPa, the GMD for the A1 + B1 treatment significantly differed only from A3 + B0 (Table 4). A similar trend of significantly larger GMD values was obtained at -1000 hPa for the A1 + B1 compared to the A1 + B0 and A3 + B0 treatments. Further, the poor fragmentation of the A1 + B1 treatment is illustrated by a generally smaller proportion of small soil fragments (< 5 mm in diameter) and larger proportion of large soil fragments (> 32 mm in diameter) for the matric potentials studied (Table 4).

3.4. Grain yield

Compaction and late sowing significantly affected yield of wheat and barley ($p < 0.05$) in 2014 and 2015, respectively (Table 5). There was a trend showing that compaction and late sowing reduced yield of oats in 2016, and barley in 2017 compared to the control and the early and normal sowing treatments, respectively, albeit not statistically significant ($p > 0.05$). Yield of the small grain cereals for the A1 and A2 treatments, however, did not differ significantly for any of the years studied (Table 5).

3.5. Drop-shatter results, soil pore and aggregate characteristics vs yield

Across all treatments, the yield of oats in 2016 negatively related to the GMD of soil fragments and Y tested at -100 hPa. On the other hand, there was a positive linear relationship between yield of oats and total porosity (Φ). Overall, only 27% of the variation in the yield of oats can be explained by the GMD of soil fragments produced from dropped soil cores at -100 hPa, and 37% and 51% by Φ and Y, respectively (Fig. 5a–c).

3.6. Soil penetration resistance and yield

There was a significant effect of sowing date and depth on penetration resistance (PR) ($p = 0.002$) (data not shown). The early sowing date treatment consistently had a higher PR in the seedbed layer (1–5 cm depth) and below (at 5, 15, 20 and 27 cm depth). In contrast, the PR for the compacted treatment was higher than the control only at 15 cm depth (data not shown). In general, mean PR measured on July 4, 2016 in the topsoil for all experimental plots was 0.43 and 1.02 MPa for 1–5 and 7–15 cm depth, respectively.

Yield of oats was significantly and inversely related to PR at 1–5 cm

Table 4
Fragmentation of soil cores dropped at −100, −300 and −1000 hPa matric potentials (data from large soil cores). Geometric mean diameter (GMD) and the fraction of soil fragments < 5 and > 32 mm in diameter after the drop-shatter test are shown.

Treatment	−100 hPa GMD (mm)	Soil fragments		−300 hPa GMD (mm)	Soil fragments		−1000 hPa GMD (mm)	Soil fragments	
		< 5 mm	> 32 mm		< 5 mm	> 32 mm		< 5 mm	> 32 mm
A1 + B1	50.5b	0.03a	0.84b	52.3b	0.03a	0.86b	51.3c	0.03a	0.85b
A1 + B0	29.4a	0.09ab	0.48ab	41.1ab	0.06ab	0.68ab	34.8ab	0.09ab	0.58b
A2 + B1	27.8a	0.11ab	0.43a	32.4ab	0.11ab	0.55ab	–	–	–
A2 + B0	25.9a	0.14ab	0.44a	24.7a	0.14ab	0.39a	–	–	–
A3 + B1	25.7a	0.15b	0.38a	39.8ab	0.08ab	0.68ab	37.6bc	0.08a	0.64b
A3 + B0	23.1a	0.13ab	0.34a	21.7a	0.15b	0.30a	20.7a	0.15b	0.30a
Average compaction									
B0	26.1	0.12	0.42	29.2	0.12	0.46	27.8	0.12	0.44
B1	34.6	0.09	0.55	41.5	0.07	0.70	44.4	0.05	0.75
Average sowing date									
A1	39.9	0.06	0.66	46.7	0.05	0.77	43.0	0.06	0.72
A2	26.9	0.12	0.44	28.6	0.12	0.47	–	–	–
A3	24.4	0.14	0.36	30.7	0.12	0.49	29.2	0.12	0.47

Values with different letters are significantly different at $p < 0.05$. A1, early sowing date; A2, normal sowing date; and A3, late sowing date; B0, control and B1, compaction with a single pass by a tractor weighing ~ 4.5 Mg.

Table 5
Yield of spring-sown small grain cereal crops (2014–2017).

Treatment	Yield (Mg ha^{-1})			
	2014 (Wheat)	2015 (Barley)	2016 (Oats)	2017 (Barley)
A1 + B0	5.5	7.3	5.8	5.0
A1 + B1	5.2	6.9	5.5	4.9
A2 + B0	5.8	7.8	6.5	5.9
A2 + B1	5.1	6.8	6.8	5.2
A3 + B0	5.0	7.0	6.5	5.0
A3 + B1	4.8	6.1	5.9	4.8
Average compaction				
B1	5.0a	6.6a	6.1	5.0
B0	5.5b	7.3b	6.3	5.3
Average sowing date				
A1	5.3b	7.1b	5.7	5.0
A2	5.5b	7.3b	6.6	5.5
A3	4.9a	6.5a	6.2	4.9

Values with different letters are significantly different at $p < 0.05$. A1, early sowing date; A2, normal sowing date; and A3, late sowing date; B0, control and B1, compaction with a single pass by a tractor weighing ~ 4.5 Mg.

3.7. Water contents for tillage

At both 1–5 and 5–10 cm depths, the range of water contents for tillage ($\Delta\theta_{RANGE}$) was similar for the compacted and the control treatments. With respect to sowing date, the early and late sowing reduced $\Delta\theta_{RANGE}$ compared to the normal sowing, although the difference was not significant at any of the depths studied (Fig. 7a–d). $\Delta\theta_{RANGE}$ was positively related to soil total porosity at both 1–5 and 5–10 cm depth, although not statistically significant (Fig. 8a and b).

4. Discussion

4.1. Effect of compaction and sowing dates on seedbed physical properties

To assess the effect of treatment on pore structure characteristics of the seedbed, soil bulk density, water retention, aeration and pore organization indices (k_a/ε_a (PO_1) and k_a/ε_a^2 (PO_2)) were determined. At 1–5 cm depth, the compaction × sowing date interaction significantly affected volumetric water content (θ), air-filled porosity (ε_a), air permeability (k_a) and pore organization indices (k_a/ε_a (PO_1) and k_a/ε_a^2 (PO_2)) although not bulk density (ρb) (Table 2). The effects observed were not consistent for all the treatment combinations. A higher volume of pores < 30 μm and lower volume of pores > 30 μm were found for the A3 + B1 compared to, for instance, the A2 + B1 and A3 + B0 treatments. This may be interpreted as compaction combined with late

(p = 0.004) and 7–15 cm depth (p = 0.021). A similar – although not significant – negative relationship between yield and PR was found at 15–20, 20–27 cm as well as the overall PR at 1–27 cm depth (Fig. 6a–e).
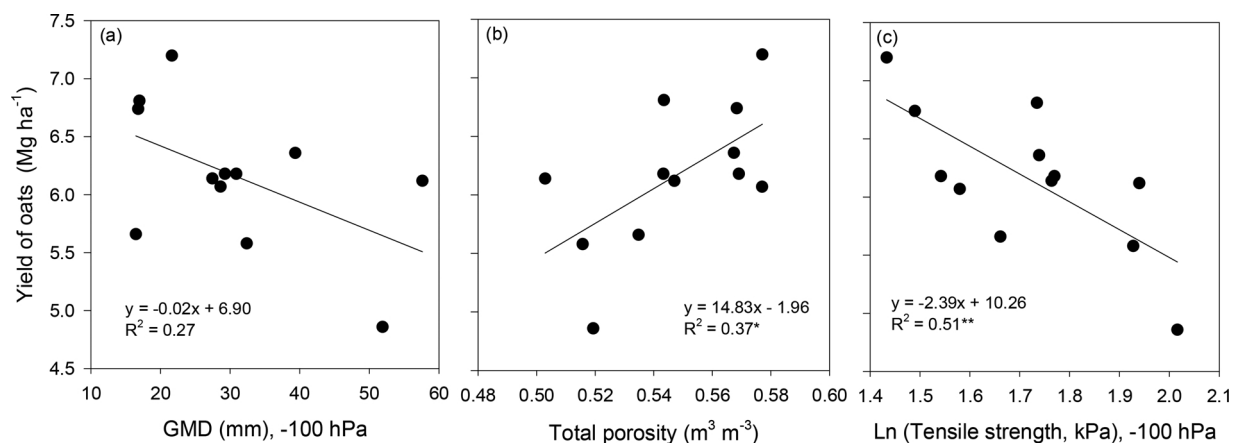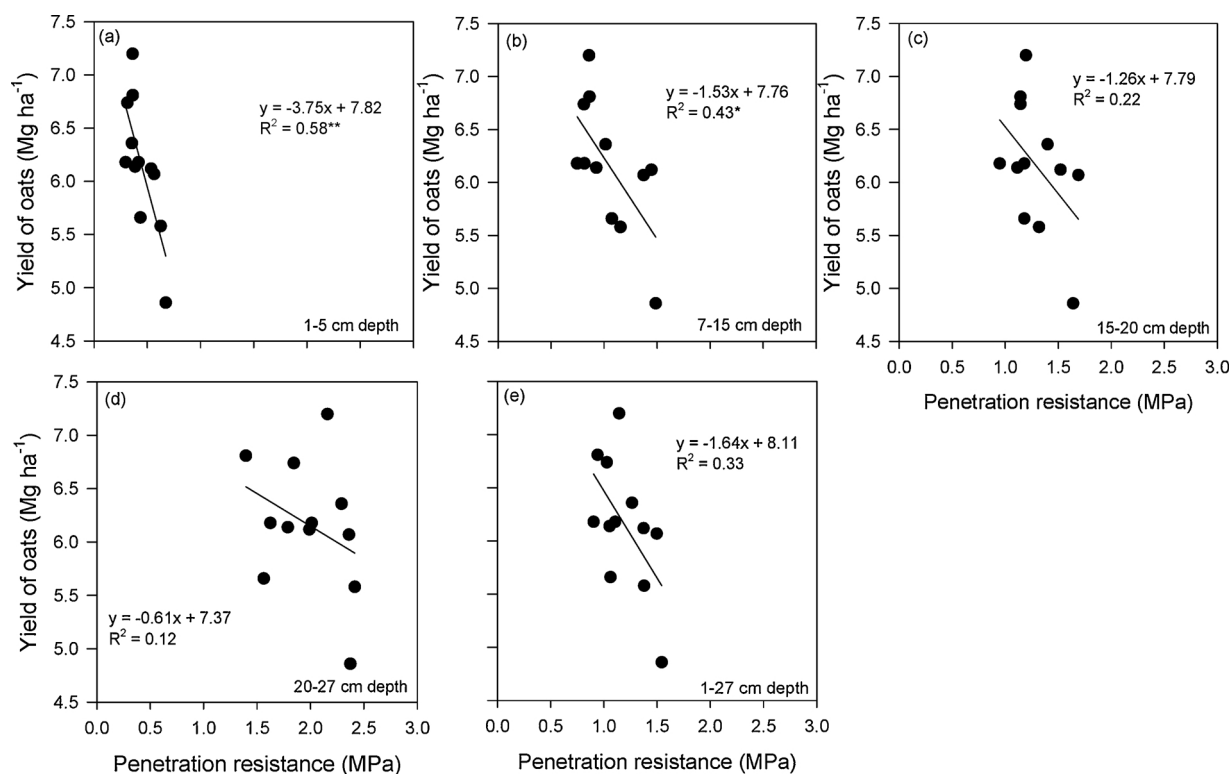

Fig. 5. Relationship between yield of oats and (a) geometric mean diameter (GMD) of soil fragments produced from drop-shatter test at −100 hPa, and (b) total porosity and (c) tensile strength of aggregates from 1 to 10 cm depth measured at −100 hPa. ** p < 0.01 and *p < 0.05.

Fig. 6. Yield of oats related to penetration resistance (PR) at (a) 1–5, (b) 7–15, (c) 15–20 cm, (d) 20–27 cm depth and (e) average PR at 1–27 cm. Data points show observation for each individual experimental plot. Penetrometer measurements were done on July 4, 2016 which means 56, 70 and 84 days after the establishment of A3, late sowing date; A2, normal sowing date and A1, early sowing date, respectively. Lines indicate regression. **p < 0.01 and *p < 0.05.
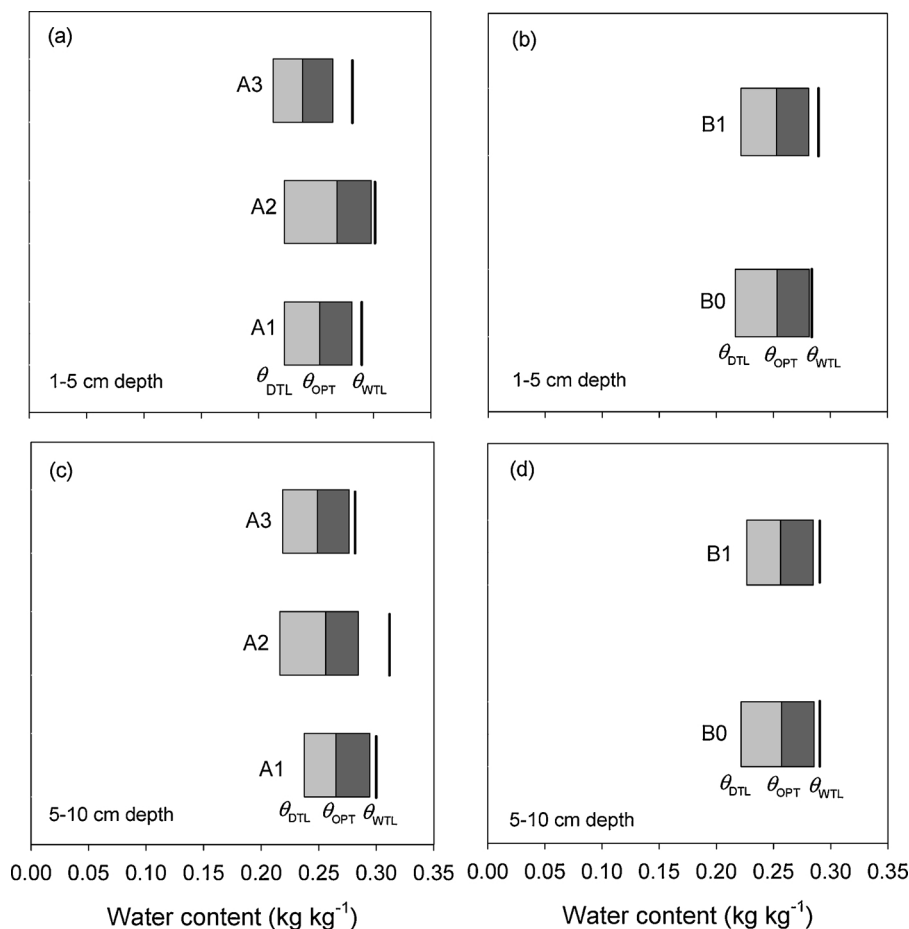
Fig. 7. Water contents for tillage. A1, early sowing date; A2, normal sowing date; and A3, late sowing date; B0, control and B1, compaction with a single pass by a tractor weighing ∼ 4.5 Mg. θ_{DTL}: dry tillage limit, θ_{OPT}: optimum water content for tillage and θ_{WTL}: wet tillage limit. Solid short vertical lines show water contents at −100 hPa.
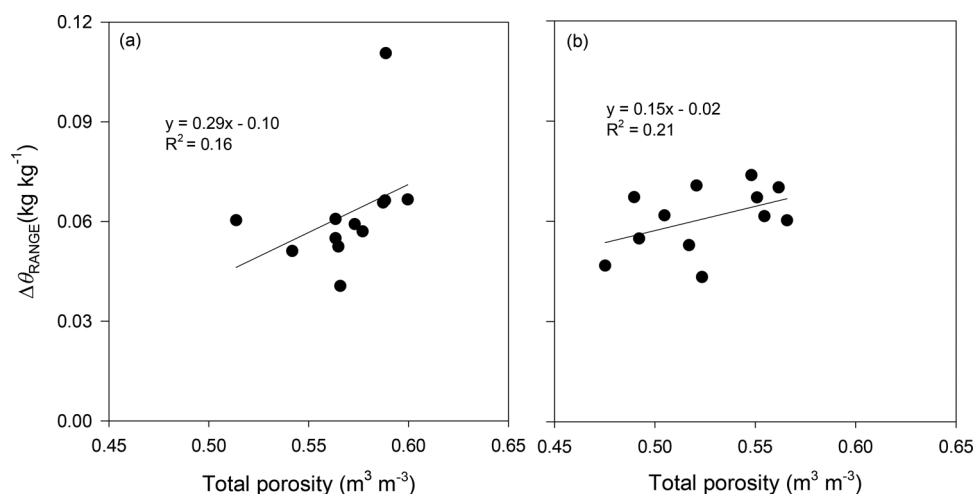
Fig. 8. Range of water contents for tillage as a function of total porosity at (a) 1–5 cm and (b) 5–10 cm depth.

sowing (A3) reducing ε_a at -100 hPa.

The pore organization indices, PO_1 and PO_2, can be used to describe the effects of soil management on pore size distribution, tortuosity and continuity of ε_a (Groenevelt et al., 1984). These authors proposed that soils with similar PO_1 values have identical pore-size distributions and pore continuities because k_a is normalized only with respect to the volume of air-conducting pores. Soils with similar PO_2 values, on the other hand, only have identical pore size distributions. This implies that the difference between PO_1 and PO_2 mainly relates to the pore continuity, independent of the pore size distribution (Ball et al., 1988). At 5–10 cm depth, compaction reduced k_a, PO_1 and PO_2 (Table 2). Generally, a value of k_a of less than 1 µm^2 has been suggested as a critical limit, inferring soil impermeability, which restricts water and air transport necessary for many biological processes. The results showed k_a values above the critical limit in all cases (Table 2).

Effect of compaction and sowing dates on soil strength characteristics of seedbed was quantified by measuring the tensile strength (Y) of aggregates and soil penetration resistance (PR). At -100 hPa, compaction and sowing date affected Y of aggregates. For the latter, the difference was only significant between early sowing date (A1) and normal sowing date (A2) at 1–5 cm depth (Table 3). At both 1–5 cm and 5–10 cm depths, Y was lower for the A2 + B0 treatment, whereas the A1 + B1 treatment, in general, increased Y at -300, -1000 hPa and at air-dry state (Table 3). The higher Y for the compacted and A1 treatments can be explained by structural damage due to kneading by tillage implements in wet conditions, which consequently increased Y following the drying of soil fragments produced by tillage (Watts et al., 1996). The results are consistent with the Munkholm and Schjønning (2004) study. These authors also showed that the effect of structural damage on Y can be persistent, and further found that after six months, aggregates produced by intensive rotary tillage when soil was too wet for optimal tillage remained stronger than a reference soil, which was tilled when the soil had dried to a friable condition. Håkansson et al. (1988) found that the effects of compaction in the topsoil may persist even after mechanical loosening such as plowing and harrowing.

The results in this study showing significant effects of the compaction × early sowing interaction on Y tested at -300, -1000 hPa and in air-dry state at 1–5 cm depth are, however, surprising, because such a significant interaction effect was not observed for ρb at the same depth (Table 2). This can be explained by Y, unlike ρ_b, being highly affected by the particle-particle bonds participating in the particular mode of failure as well as the presence of micro-cracks serving as planes of weakness to initiate tensile failure (Chakraborty et al., 2014).

Interestingly, even though the A2 and A3 treatments had similar water contents at 1–5 cm depth at the time of compaction and/or

sowing operations (Table 1), Y differed between the two treatments. For instance, Y at -1000 hPa for A2 + B0 was significantly different from A3 + B0 at 1–5 cm depth (Table 3). This may be ascribed to soil 'memory' of antecedent precipitation events prior to treatments and sampling. Thus, maximum rainfall amounts of 10.2 and 16.2 mm on April 16–17, 2016 before the A2 treatment (Fig. 2b) compared to 15.4 and 30.4 mm on April 29–30, 2016 prior to the A3 treatment (Fig. 2c) may have differently influenced the spontaneous and mechanical dispersion of clay as well as wetting and drying cycles, which in turn affect the temporal variation of Y (Kay and Dexter, 1992).

Penetration resistance was significantly affected by sowing date ($p < 0.05$). The A1 treatment had a higher PR in the seedbed and down to 27 cm depth compared to the A2 and A3 treatments (data not shown). As expected, compaction increased PR down to 27 cm depth, although the effect was significant ($p = 0.02$) only at 7–15 cm depth (data not shown). de Toro and Arvidsson (2003) also found an increased PR down to a depth of 18 cm after harrowing operations for seedbed preparation were performed on clayey soil in Sweden at different water contents in spring. In the upper soil layers, tire inflation pressure is the major driver of stresses exerted on soil by agricultural machinery (Schjønning et al., 2012). Thus, the effect of the A1 treatment on PR measured at 1–5 cm and below the seedbed down to 27 cm depth can be due to stresses exerted by tractor wheels and tillage implement, but could also be an accumulated effect over the three years of experimental treatments (Håkansson et al., 1988) despite soil loosening by plowing each autumn as well as freezing and thawing cycles prior to the experimental treatments in spring.

In general, the soil aggregates studied can be described as friable according to the classification by Imhoff et al. (2002). Notwithstanding this, the A1 treatment reduced friability (k_Y) at both soil depths studied compared to the A2 treatment. Compaction also reduced k_Y, particularly at 1–5 cm depth, although not significantly (Fig. 4). The results illustrate that tilling soil in wet condition reduces k_Y due to soil structural degradation. Higher k_Y values for the A2 treatment imply that bulk soil or soil clods produced after primary tillage can be more easily fragmented into smaller fragments, whereas smaller aggregates are difficult to further fragment into undesirably smaller elements (Munkholm, 2011).

Measurement of soil fragmentation at 5–15 cm depth, i.e., below the seedbed, yielded information on soil compaction and fragment size distribution. Compaction × early sowing date resulted in poor soil fragmentation, evidenced by the large geometric mean diameters (GMD) of soil fragments, the smaller proportion of small soil fragments (< 5 mm in diameter) and larger proportion of soil clods (> 32 mm in diameter) (Table 4). Seedbeds consisting of fragments < 5 mm in size

increase the number of plants and crop yield of small grain cereals by 5% compared to coarse seedbeds in silty soil in Sweden (Håkansson et al., 2002). Our results showed that, in general, the proportion of soil fragments < 5 mm in diameter produced from the dropped soil cores was small (maximum of 15% at all the matric potentials studied). This implies that, in practice, larger number of successive seedbed harrowings, including their negative impact on soil physical properties, would be required to fragment the soil into a suitable seedbed for spring-sown small grain cereal crops.

4.2. Effect of compacton and sowing dates on crop yield

Compaction and late sowing reduced the yield of spring-sown small grain cereal crops, but the effect was significant only in 2014 and 2015 for wheat and barley, respectively (Table 5). This may be ascribed to a short growing season rather than the influence of soil physical properties. Riley (2016) also explained a yield loss after late sowing by a shorter growing season. Likewise Perez-Bidegain et al. (2007) found that the yield of corn in Newton, USA was not significantly affected by sowing date in the first two years, but was in the third year. However, their study did not include compaction treatment, in contrast to our study. The insignificant effect of compaction and sowing dates in 2016 and 2017 for oats and barley, respectively, can be interpreted as multiple factors affecting the final yield of crops (Perez-Bidegain et al., 2007) —not least the specific weather conditions during the growing season.

Simple regression analyses showed that when tested at −100 hPa, the yield of oats in 2016 was negatively related to the GMD of soil fragments produced from the drop-shatter test and to Y, but positively related to total porosity (Φ) (Fig. 5a–c). In relation to soil strength, the yield of oats was negatively related to PR (Fig. 6a–e). Overall, the relationship was significant for Φ and Y as well as for PR at 1–5 and 7–15 cm depth, explaining 37–58% of the variation in the yield of oats. The negative and significant relationship between yield and Y and PR can be explained by the effect of soil strength on root growth and penetration, which can adversely affect crop yield (Taylor et al., 1966). The negative and weak linear relation between yield and GMD is indicative of the generally negative effect of poor soil fragmentation on plant growth.

4.3. Effect of compaction and sowing dates on water contents for tillage

Compaction, and early and late sowing dates reduced the range of water contents for tillage ($\Delta\theta_{RANGE}$), but the effect was not significant at any of the depths studied (Fig. 7a–d). $\Delta\theta_{RANGE}$ was positively related to Φ (Fig. 8a and b), which agrees with the results of Dexter and Bird (2001) who showed that the range of water contents for tillage and its upper (θ_{WTL}) and lower limits (θ_{DTL}) decrease with increasing soil bulk density (ρ_b), an indication of a reduced Φ. However, in their study, θ_{WTL} and θ_{DTL} were predicted using pedotransfer functions, in contrast to the consistency approach used in this study.

From our results it could be deduced that compaction and early sowing date reduce macroporosity. Air-filled pores and cracks elongate and coalesce under mechanical stress, resulting in soil fragmentation during tillage (Dexter and Richard, 2009). This means soil structural degradation due to disturbances by tillage implements and stresses exerted by the wheels of machinery in less-than-ideal soil moisture conditions will increase soil ρ_b and, consequently, reduce the $\Delta\theta_{RANGE}$.

It should be pointed out that the presented results only provide a snap-shot of soil workability, assessed as the $\Delta\theta_{RANGE}$ within which tillage can be executed satisfactorily after a secondary tillage in spring. As mentioned previously, we expect a relatively small residual effect of treatment on soil workability in the following spring after plowing and freezing and thawing cycles during the winter. Nevertheless, a narrowing of the $\Delta\theta_{RANGE}$ for the early and late sowing can reduce the water contents at which soil is suitable for primary tillage in the

following autumn (Munkholm and Schjønning, 2004). Findings of the study indicate that a combination of quantitative information on soil structural and strength characteristics provide useful criteria for assessing soil workability and fragmentation during tillage.

5. Conclusions and practical implications of the results

Results from this study confirmed, to some extent, the hypothesis that soil fragmentation and the strength of soil aggregates differ for different compaction treatments and sowing dates. The main conclusions were that the interaction of compaction with sowing date significantly affected soil pore characteristics, particularly at 1–5 cm depth, although the effect was not consistent for all treatment combinations. Compaction combined with early sowing increased tensile strength at both 1–5 and 5–10 cm depth, whereas the dropped soil cores, in general, fragmented poorly for all treatments and at all matric potentials studied. Early sowing significantly decreased soil friability and increased soil penetration resistance in the seedbed layer and down to 27 cm depth. Late sowing decreased yield of spring-sown small grain cereal crops, but this may mainly be ascribed to a shorter growing season rather than an influence of soil physical properties and compaction. Finally, early and late sowing decreased the range of water contents for tillage, which can reduce soil workability for subsequent tillage operations, especially autumn plowing.

The overall findings of the study have practical implications for cropping regimes in colder climates, where the growing period for cereals is short by showing that cultivation in less-than-ideal moisture conditions such as early spring when soil is still wet limits the capacity of soil to produce desirable seedbeds after tillage. It also adversely affects soil physical properties of a seedbed, which in turn affect crop yield. Present and future farm managers need to consider the implications of compaction and sowing dates on soil physical conditions even more than in the past.

Conflicts of interest

None.

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Paper 5

Soil water contents for tillage: a comparison of approaches and consequences for the number of workable days

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Soil water contents for tillage: a comparison of approaches and consequences for the number of workable days

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Abstract

Knowledge of soil water content for tillage is important to avoid tillage-induced soil structural degradation, creating undesirable seedbed for crop establishment, and using high energy inputs because soil is not workable. We propose a new approach (NA), which we compare with the water retention approach (WRA) and the consistency approach (CA) for estimating the water content at wet tillage limit (θ_{WTL}), optimum water content for tillage (θ_{OPT}) and the water content at dry tillage limit (θ_{DTL}). Unlike the WRA and CA, the new approach uses soil water content at an air-filled porosity of 0.10 m^3 m^{-3} to estimate θ_{WTL} and an aggregate tensile strength of 50 kPa to estimate θ_{DTL}. The optimum water content for tillage is estimated using the double-exponential water retention function as the soil water content at the break point between the textural and structural pores where in general, the structural pores have drained and the textural pores remain filled with water. The three approaches were compared using a soil with a range of soil organic carbon contents (SOC), and a soil with a range of clay contents. The number of workable days for tillage for seedbed preparation for these soils were estimated using a decision support tool for assessing soil workability. Workable days were limited by the soil being either too wet or too dry. For the soil with a range in SOC (Highfield), θ_{WTL} estimated by NA was generally wetter than that for WRA and CA, whereas for the soil with a range in clay (Lerbjerg) NA was identical to values estimated by WRA. Workable days were strongly influenced by SOC content, clay content, and the approach used for estimating tillage limits. The estimated average workable days in the spring and the autumn seasons over the period from 2014 to 2018 increased with increasing SOC content (from 2 workable days for the Bare Fallow treatment with low SOC to 40 workable days for the Grass treatment with high SOC), and decreased with increasing clay content (from 38 workable days for L12 with low clay to 0 workable day for L45 with high clay) although there was an exception for WRA. Average workable days for the period investigated were more for θ_{WTL} and θ_{DTL} estimated by WRA and NA compared to CA. Further studies are needed to test the use of fixed values of 0.10 m^3 m^{-3} and 50 kPa defined in NA for estimating θ_{WTL} and θ_{DTL}, respectively for all soils. Future studies could also investigate whether the fixed values of 0.10 m^3 m^{-3} and 50 kPa need to be refined. Field validation on a range of soil textures and in different climates could be the subject of further research to investigate the robustness of the approaches for estimating θ_{WTL} and θ_{DTL}.

Keywords: Soil organic carbon; clay gradient; workable days

1. Introduction

The ease with which a well-drained soil can be tilled to produce a desirable seedbed consisting of fragments that are neither too coarse nor too fine for crop establishment describes its workability (Dexter, 1988). For tillage to produce ideal seedbeds for crop establishment without causing irreversible damage to soil structure, it is important that operations are executed within a defined range of water contents ($\Delta\theta_{RANGE}$) over which the soil is workable. The $\Delta\theta_{RANGE}$ is bounded by the upper tillage limit, also called wet tillage limit (θ_{WTL}) and the lower tillage limit, also called the dry tillage limit (θ_{DTL}).

Soil becomes plastic at water content above θ_{WTL}. When tillage is performed at water content above plastic limit shearing, soil puddling and soil structural damage can occur. More so, tillage under such conditions creates seedbeds constituted by large fragments, which results in poor crop establishment (Dexter and Birkas, 2004). When tillage is attempted at water content below θ_{DTL}, machine operations may require high energy due to the relative higher strength of the soil. Also, excessive tillage in very dry condition can create tiny or dust particles which is a serious environmental and health issue causing respiratory diseases. From the agronomic standpoint, seedbeds dominated by too fine particles are less favorable for crop establishment because such seedbeds have poor inter-aggregate aeration and are susceptible to surface crusting as well as wind and water erosion (Braunack and Dexter, 1989). At optimum water content for tillage (θ_{OPT}), soil friability, i.e. "the tendency of a mass of unconfined soil to break down and crumble under applied stress into a particular size range of smaller fragments" (Utomo and Dexter, 1981) is maximum. Tillage at θ_{OPT} produces desirable fragments that are neither too fine nor too large, which in turn facilitate seed emergence and radicle extension.

The ideal seedbed in terms of fragment size distribution has been proposed by different authors. For small-seeded crops, Russell (1973) suggested that soil fragments not less than 0.5–1 mm and not coarser than 5–6 mm create ideal conditions for crop establishment. Håkansson et al. (2002) found that an ideal seedbed for growing small grain crops should have at least 50% of soil fragments <5 mm.

Information on the optimum and range of water contents for tillage is important in planning and scheduling tillage operations to produce seedbeds that favor crop establishment, and this information should be an integral part of future farm management information systems and decision support systems (Sørensen et al., 2010). In practice, the pseudo plastic limit for tillage operations has been assessed from experience by farmers in the field, e.g., by crumbling and

molding soil by hand to evaluate whether soil sticks to the palms. Farmers may also till a small area in the field to evaluate the fragments produced by tillage and whether the soil sticks to the implement. Based on these evaluations, a farmer would then decide whether the soil is workable. Even though these practical approaches for evaluating the water contents for tillage provide a fairly precise information on soil workability and many farmers have an excellent "feeling" for soil workability, the approach can be laborious, specifically in the case of multiple large fields requiring evaluation concurrently. Further, with these approaches, it is difficult to transfer knowledge from one operator to another without the inherent risk of long-term soil damage. Predicting the water content for tillage can be a rapid and user-friendly way to determine if soil is workable for tillage compared to the field test used by farmers. The estimated water contents for tillage is a key prerequisite for developing a decision support system (DSS) for planning tillage operations in the field.

Various quantitative laboratory approaches for determining θ_{WTL}, θ_{OPT} and θ_{DTL} have been proposed. A comprehensive review of the approaches for determining the water contents for tillage, including their respective strengths and drawbacks are provided in Mueller et al. (2003) and Obour et al. (2017). The "water retention approach (WRA)" (Dexter and Bird, 2001; Dexter et al., 2005) and the "consistency approach (CA)" (Obour et al., 2018) have been used for estimating the range of appropriate water contents for tillage. Throughout this paper, WRA refers to the water contents for tillage estimated from the parameters of the water retention curve using the van Genuchten (1980) equation (here termed vanG) as described in Obour et al. (2018). The "consistency" terminology was originally used by Atterberg (1911) to refer to the ability of a soil to resist rupture and deformation. Consistency approach (CA) is based on a combination of soil plastic limit and an estimate of tensile strength of aggregates at different water contents as described by Obour et al. (2018) — The water content at the wet tillage limit is estimated as water content at plastic limit (θ_{PL}), i.e. $\theta_{WTL} = \theta_{PL}$. The optimum water content for tillage is estimated as $0.9\theta_{PL}$ according to Dexter and Bird (2001). The water content at dry tillage limit is estimated according to Dexter and Bird (2001) as the water content at which the strength of the soil is twice the strength at θ_{OPT}.

While both these approaches have their respective merits, they also have some drawbacks, which limit their applications. The vanG used in WRA to estimate the water contents for tillage implicitly assumes a uni-modal pore size distribution (PSD) of soil. Consequently, vanG fits less well with water retention data of structured soils with bi-modal PSD (Dexter et al., 2008; Dexter and Richard, 2009). The dual-porosity approach implies pore spaces defined by both soil texture and

pore spaces defined by soil structure, thus is more suitable. For CA, θ_{WTL} is based on estimated water content at the plastic limit (θ_{PL}). However, θ_{PL} is determined on a remolded soil whereby soil structure is first destroyed. Therefore, θ_{PL} does not consider pre-existing micro-cracks and structural pores that are air-filled, which are important in soil fragmentation during tillage (Dexter and Bird, 2001). Furthermore, both WRA and CA provide only an arbitrary way of determining θ_{DTL} because no specific soil strength value is defined. There is a need for a new approach for estimating the θ_{WTL} and θ_{DTL} that takes into account soil structure. At θ_{WTL}, soil fragmentation is expected to be limited by air-filled cracks while at θ_{DTL} it is expected to be limited by soil strength. Therefore, it will be ideal for the new approach to use a certain value of air-filled porosity to estimate the water content at wet tillage limit (da Silva et al., 1994) and a fixed value of tensile strength to estimate the water content at dry tillage limit (Munkholm, 2011). Soil organic carbon and clay content strongly affect the water contents for tillage. An increase in SOC increases $\Delta\theta_{RANGE}$, whereas increase in clay content decreases $\Delta\theta_{RANGE}$ (Dexter and Bird, 2001). However, there is limited quantitative information on the consequences of these properties on workable days. Such information will provide farmers with a better understanding of soil workability of fields with highly variable SOC or clay contents. A "better understanding" will also improve our ability to predict whether and when a variable field is workable. The pseudo plastic limit test in the field works at an operational – on-the-go - level – i.e. a +/- field test. More advanced tools are needed to be able to predict when a specific field is workable (as described in the different approaches) (tactical planning).

The objectives of this paper were to: (i) propose a new approach for determining θ_{WTL} and θ_{DTL} based on a fixed value of air-filled porosity and soil strength, respectively, (ii) compare the "WRA" and "the CA" with the new approach (NA) for estimating the water contents for tillage, and (iii) simulate the number of workable days for soils with a range of SOC and clay contents based on the θ_{WTL} and θ_{DTL} estimated by WRA, CA and NA. The motivation for this paper is to better predict the water contents for tillage thereby offering the possibility of significantly reducing soil structural damage and tillage energy. This knowledge can then be used in a decision support system for scheduling tillage operations.

2. New approach: theoretical concepts, experimental evidence and illustrations
2.1. Soil mechanical behavior as a function of water content and matric potential

Soil water content and matric potential are important factors influencing soil mechanical behavior. Field soils can be found in several mechanical states depending on their water content, ranging from cemented at the dry end through friable and plastic states to a viscous liquid at the

very wet end (Fig. 1). When subjected to mechanical stress a soil will fail in different ways depending on its mechanical state. A dry soil exhibits solid behavior due to cementation and effective stress (Mullins and Panayiotopoulos, 1984). Effective stress is the stress that keeps particles together (Terzaghi, 1923), and this increases as the matric potential becomes more negative. An important consideration in tilling a dry soil is how much mechanical energy needs to be expended for soil fragmentation during tillage because increase in effective stress increases the specific rupture energy. Soil consistency changes from semi-solid state where soil mechanical behavior is friable to plastic state where soil behaves plastically with increasing water content.

Soil fragmentation, i.e. the process of crumbling of soil fragments under applied stress (Munkholm., 2002) is controlled by the amount of air-filled micro-cracks and structural pores (pores with equivalent cylindrical diameter >30 μm). Stress concentration at the tip of a crack results in localized increase in stress leading to a rapid growth of a crack followed by failure of a material. For a wet soil, the water-filled cracks and pores will not exhibit stress concentration because the load exerted on the cracks are uniformly borne by the pore water (Snyder and Miller, 1985; Snyder and Miller, 1989). An application of stress on a wet soil leads to a considerable plastic deformation and loss of pore continuity instead of fragmentation. Also, when wet, soil at the tip of a crack has the ability to flow and rearrange (Hallett and Newson, 2001; Ghezzehei, 2012) resulting in compaction. Between the shrinkage limit and the plastic limit, soil has a friable state. Soil friability at that water content is because of the ability of the air-filled structural pores to expand and the low strength between the micro-cracks and structural pores (Dexter and Richard, 2009).

2.2. Dry tillage limit

Munkholm (2011) proposed that θ_{DTL} may be determined as water content at which tensile strength of a soil core or a standard spherical soil aggregate (e.g., 8–16 mm size) exceeds a specific value. However, the author did not provide any value defining the dry tillage limit.

The predefined value used here is based on the Soil Science Division Staff (2017) classification of resistance to rupture of a 25 to 30 mm blocklike soil specimen in a natural state. Rupture resistance gives information on the stress that is required to break the specimen. Force is applied onto the soil specimen until rupture. According to the classification of Soil Science Division Staff (2017), a 25–30 mm blocklike soil specimen is classified as "firm" when it fails under applied stress from 20 to 40 N, whereas a "very firm" soil block fails under high stress of 40 to 80 N.

We used 40 N, i.e. the transition from "firm" to "very firm" to define the dry tillage limit. The tensile strength at 40 N for a 25–30 mm blocklike soil specimen is about 50 kPa. The water content at the dry tillage limit can then be estimated using the following procedure:

Estimate the effective stress (σ_e, kPa) at predefined matric potentials covering the wet and dry ends of the water retention curve. Here, data from saturation to air-dry (0 to ~ −166 MPa) were used. In the absence of an external mechanical stress, σ_e has two components: matric suction (ψ) and surface tension (γ) (Towner and Childs, 1972). The contribution of γ to soil strength is important when the degree of saturation (χ) is <0.3 (Vepraskas, 1984). In our case, χ ranged from 0.05 to 0.95 therefore, both ψ and γ were used:

$$\sigma e = \chi \psi + \frac{0.3}{\alpha}\left[\left(\frac{\psi_2 + \psi_1}{2}\right)(\chi_1 - \chi_2)\right] \qquad [1]$$

where χ_1 is the initial degree of saturation, and χ_2 is the final degree of saturation due to change in matric suction. The first term on the right-hand side is generated by pore water pressure and the second term by the surface tension forces.

χ was calculated according to Dexter et al. (2007):

$$\chi = \left(\frac{\theta - \theta_{RES}}{\theta_{SAT} - \theta_{RES}}\right) \qquad [2]$$

where θ is the gravimetric water content at a given matric suction, θ_{RES} is the residual water content estimated by van Genuchten equation was set equal to zero and θ_{SAT} is the water content at saturation.

$$\alpha = \left(\frac{\theta - \theta_{RES}}{\theta_{SAT}}\right) \qquad [3]$$

Determine the tensile strength of soil aggregates size of 8–16 mm at the predefined matric potentials in step 1. Here tensile strength of aggregates was determined at −10 kPa, −30 kPa, −100 kPa and at air-dry state using the indirect tension test (Rogowski, 1964). Make tensile strength vs. effective stress relationship. Estimate σ_e at 50 kPa using a linear interpolation.
Create a matric potential vs. effective stress relationship. Use the relationship to estimate the matric potential corresponding to the σ_e estimated in step 2 using a linear interpolation.
Water content at dry tillage limit is then estimated using a water retention function, as the water content corresponding to the matric potential estimated in step 3.

2.3. Optimum water content for tillage

We used the Dexter and Richard (2009) approach to estimate θ_{OPT} using the double-exponential function (DE) (Dexter et al., 2008) fitted to the water retention data. The DE considers the textural and structural pore space in the soil. The θ_{OPT} occurs when the textural pore space is saturated, but the structural pore space is drained and air-filled.

$$\theta = C + A_1 e^{\left(-h/h_1\right)} + A_2 e^{\left(-h/h_2\right)} \qquad [4]$$

where C is the asymptote of the equation, A_1 and A_2 are the amount of textural and structural pore space, and h_1 and h_2 are characteristics of the pore water suctions at the textural and structural pores, respectively. The pore size distribution is obtained by differentiating Eq. [4] with respect to matric potential (Jensen et al., 2019a):

$$\frac{d\theta}{d(\log_{10}h)} = -\frac{A_1}{h_1} e^{(-h/h_1)} h \ln 10 - \frac{A_2}{h_2} e^{(-h/h_2)} h \ln 10 \qquad [5]$$

The parameters of the DE are estimated by nonlinear regression analysis to obtain the smallest residual sum of squares. The optimum water content for tillage is the water content at the break point between textural and structural pores (Dexter and Richard, 2009). This can be determined graphically. Examples are shown in Fig 2a and b.

2.4. Wet tillage limit

Soil can only fragment if air-filled pores are present. The air-filled pores elongate, expand and coalesce under mechanical stress resulting in fragmentation (Dexter and Richard, 2009). When soil is too wet, tillage smears soil. Experimental data from Hungarian (Dexter and Birkas, 2004) and Swedish soils (Keller et al., 2007) showed that at θ_{OPT} where tillage produced the maximum proportion of small fragments < 8 mm, air-filled porosity was > 0.10 m^3 m^{-3} (Table 1). The experimental results confirm that soil fragmentation is controlled by air-filled pores. Therefore, it is possible to define a lower limit of air-filled porosity in the soil required for soil fragmentation. The water content at that air-filled porosity can then be taken as the wet tillage limit.

The pore space in soil is vital in the provision of many soil functions and air-filled pores are a pre-requisite for soil fragmentation (Dexter et al., 2008). The structural pores are important for air

and water transport in the soil. An air-filled porosity of 0.10 m^3 m^{-3} has been suggested as a critical limit in relation to aeration for soil biological functions (Grable, 1971).

Here, we used a soil water content at an air-filled porosity of 0.10 m^3 m^{-3} as the wet tillage limit. At this lower limit of air-filled porosity, for most soils, the textural pores will be water-filled while structural pores are (partly) air-filled. For soils with low macroporosity, e.g., compacted soils or soils with large clay contents characterized by a large volume of intra-aggregate pores, the wet tillage limit estimated from the new approach (θ_{WTLNA}) will occur at a more negative matric potential than for a non-compacted soil or a soil with small clay content. The illustration in Fig. 3 shows the relationship between matric potential (ψ) at θ_{WTLNA} and clay content. Continuous pedotransfer functions were used to predict the hydrological properties for the mean texture and bulk density of each textural class. Clay content of the soils ranged from 0.03 kg kg^{-1} to 0.60 kg kg^{-1}.

3. Materials and methods

3.1. Comparison of approaches

To compare the water retention approach (WRA) and the consistency approach (CA) with the new approach (NA) proposed for estimating the water contents for tillage, data on soils with a range of SOC contents (Obour et al., 2018) and clay contents (Obour et al., 2019) were used.

3.1.1. Soil with a range of SOC

We used a silt loam soil from Highfield, Rothamsted Research, UK. Soil was sampled from 6–15 cm depth. The soil has a uniform texture, but a range of SOC due to different long-term management for the Bare fallow (BF), Continuous arable rotation (A), Ley-arable (LA) and Grass (G) treatments in the order: G>LA=A>BF (Table 2). For more information on the Highfield treatments, please consult Jensen et al. (2019b) and Obour et al. (2018). We used data on water contents for tillage estimated by the WRA and CA published in Obour et al. (2018) (Table 4). In addition, water retention and tensile strength data were used to estimate the water contents for tillage based on NA.

3.1.2. Soil with a clay gradient

We investigated a soil with a naturally occurring texture gradient from an arable field near Lerbjerg, Denmark. Soil samples were retrieved from 5–15 cm depth. The clay contents were 0.12, 0.22, 0.29 and 0.45 kg kg^{-1}. These have been called L12, L22, L29 and L45, respectively to indicate

their clay contents. We used water retention data and tensile strength data and data on the water contents for tillage estimated by WRA (Table 4) published in Obour et al. (2019). Basic characteristics of the investigated soils are given in Table 2.

3.1.3. Estimation of water contents for tillage

We revisited published data on estimated water content at wet tillage limit (θ_{WTL}), optimum water content for tillage (θ_{OPT}) and the water content at dry tillage limit (θ_{DTL}). For Highfield, the data were obtained from Obour et al. (2018). For Lerbjerg soil, data published in Obour et al. (2019) were used (Table 4).

Water retention approach

For water retention approach (WRA) θ_{WTL}, θ_{OPT} and θ_{DTL} were estimated from the parameters of the soil water retention curve using the van Genuchten equation (Dexter and Bird, 2001):

$$\theta_{WTL} = \theta_{INFL} + 0.4(\theta_{SAT} - \theta_{INFL}) \tag{6}$$

where θ_{INFL} is water content at the inflection point of the soil water retention curve and θ_{SAT} is the water content at saturation.

The optimum water content for tillage was estimated as water content at θ_{INFL}:

$$\theta_{INFL} = \theta_{SAT} \left[1 + \frac{1}{1-(1/n)} \right]^{1-(1/n)} \tag{7}$$

where n is a fitted parameter that controls the shape of the curve and $m = 1 - 1/n$ (Mualem (1976) restriction).

The water content at the dry tillage limit was calculated as:

$$\theta_{DTL} = \theta_{SAT} \left[1 + (\alpha h_{DTL})^n \right]^{1-(1/n)} \tag{8}$$

Consistency approach

For the consistency approach θ_{WTL}, θ_{OPT} and θ_{DTL} were estimated according to Dexter and Bird (2001):

$\theta_{WTL} = \theta_{PL}$ [9]

where θ_{PL} is the water content at plastic limit.

$\theta_{OPT} = 0.9\ \theta_{PL}$ [10]

The dry tillage limit was determined as water content at which the strength of soil is twice the strength at θ_{OPT}. It was estimated graphically from the relation between natural logarithm of tensile strength (*Y)* of 8–16 mm soil aggregates and gravimetric water content measured at different matric potentials (Munkholm. et al., 2002).

New approach

As for the new approach, the θ_{WTL}, θ_{OPT} and θ_{DTL} were estimated as described in section 2. For the three approaches presented here, the range of water contents for tillage ($\Delta\theta_{RANGE}$) were calculated as the difference between θ_{WTL} and θ_{DTL}.

3.1.4. Matric potential and water content at wet and dry tillage limits

The matric potential corresponding to water content at the wet tillage limit and the dry tillage limit estimated by WRA, CA and NA for the Highfield and Lerbjerg soils was calculated from the relationship between matric potential vs. water content.

3.1.5. Pore size distribution

To obtain information on dominant pore size emptied of water (i.e. air-filled pores) at θ_{WTL} and at θ_{DTL}, the average pore size was calculated from the approximate relation:

$$d = \frac{-3000}{\psi}$$ [11]

where d is the equivalent cylindrical pore diameter (µm) and Ψ is the soil matric potential (cm H_2O).

3.2. Simulation of workable days

Soil workability was simulated using the decision support tool proposed by Edwards et al. (2016). The tool uses three types of dataset, namely "collected" such as weather data and data on

operation selection, "collected or generated" such as current soil data and crop development, and "generated" such as soil status. Details of the specific data and the methods used for the simulation are as followed:

3.2.1. Weather data

The daily weather data for Highfield were recorded at the main Rothamsted Research meteorological site, located less than 300 m from the study site: e-RA database (Rothmet). For the Lerbjerg field, the daily weather data were collected from the Ødum meteorological station located about 12 km from the investigated site. Precipitation and air temperature data covering the period 1961 to 1990 were used to calculate the long-term average precipitation and temperature in the spring (March to May) and the autumn (August to October), which was compared with the years 2014–2017 for both sites. For the Lerbjerg site, due to missing data from 1987 to 1990, data covering 1961 to 1986 were used to calculate long-term averages. In addition, data on daily dry bulb temperature, wet bulb temperature, wind speed, maximum air temperature, minimum temperature, soil temperatures, relative humidity, rainfall, and solar radiation covering the period 2014 to 2018 were collected and used to simulate soil water content and the number of workable days. The data were provided in MS Excel files, which were then transferred to a dataset formatted for the decision support tool for modeling soil workability as described by Edwards et al. (2016). Table 3 shows the long-term average for precipitation and air temperature by months and, the monthly precipitation and temperature in 2014, 2015, 2016 and 2017 for the Highfield and Lerbjerg sites.

3.2.2. Soil water content

The DAISY model (Abrahamsen and Hansen, 2000) was used to calculate soil water content over the simulation period for the Highfield and Lerbjerg soils. The DAISY model was used over other soil crop balance models for predicting the soil water content because it is more robust (Edwards et al., 2016). The model used the weather data covering 2014 to 2018 and data on soil properties to estimate the soil matric potential which is then linked to the soil water content using the van Genuchten equation:

$$\theta = (\theta_{SAT} - \theta_{RES})\left[1 + (\alpha h)^n\right]^{1-(1/n)} + \theta_{RES} \qquad [12]$$

θ_{RES} is the residual water contents, $h=\infty$, respectively, and α is a scaling factor for h, θ_{SAT} is the water content at saturation and n is a fitted parameter that controls the shape of the water

retention curve. For detailed information on the simulation procedure, please consult Edwards et al. (2016).

3.2.3. Estimating workable days

The number of workable days were estimated for spring and autumn periods. Simulations of soil workability were run for each year between 2014 and 2018 using the soil data and weather for the given years. The spring period was set as March 1 to May 15, and the autumn set as September 1 to October 15. Soil workability at 1 to ~10 cm depth of soil investigated in Highfield and in Lerbjerg for secondary tillage for seedbed preparation were determined based on the upper and lower tillage limits estimated from WRA, CA and NA. In brief, the soil water content was simulated at 3, 6 and ~10 cm depth. These depths were chosen to simulate soil workability of the topsoil. The soil water content was then filtered and a binary decision variable was produced for each soil or treatment and for each depth, being 1 if the soil water content was within the tillage range and elsewise 0. An overall binary decision variable for soil workability was determined by considering the binary variables for all the three layers, being 1 if the decision variables for all the three layers were 1, and elsewise 0. More information on the method is provided in Edwards et al. (2016).

4. Results

4.1. Water contents for tillage – a comparison of the approaches

4.1.1 Wet tillage limit

The water content at wet tillage limit (θ_{WTL}) for the investigated soils estimated by the three approaches is presented in Table 4. For the Highfield soil with a range of SOC content, θ_{WTL} estimated by the water retention approach (WRA) ranged from 0.23 to 0.36 kg kg^{-1} for the Arable (A) to Grass (G) treatments (Table 4). These corresponded to water contents at -130 for the A treatment and -37 kPa for the G treatment (Table 5). For the Lerbjerg soil, θ_{WTL} estimated by WRA ranged from 0.27 to 0.38 kg kg^{-1} for L12 to L45, corresponding to water contents at -1 and -23 kPa, respectively. For the consistency approach (CA), θ_{WTL} ranged from 0.19 to 0.34 kg kg^{-1} for BF to the G treatment, and from 0.21 to 0.29 kg kg^{-1} for the L12 to L45, whereas for the new approach (NA), θ_{WTL} ranged from 0.25 for BF to 0.41 kg kg^{-1} for G soil, and from 0.26 to 0.37 kg kg^{-1} for L12 to L45. The corresponding matric potential at θ_{WTL} estimated for CA and NA are shown in Table 5.

4.1.2 Optimum water content for tillage

The optimum water content for tillage (θ_{OPT}) estimated by WRA, CA and NA are shown in Table 4. The θ_{OPT} estimated by CA were generally drier than those estimated by WRA and NA. The results showed that in general, the θ_{OPT} estimated by WRA, CA and NA were similar to the water content measured at −30 kPa for the Highfield and Lerbjerg soils (Table 4).

4.1.3 Dry tillage limit

For Highfield soils, θ_{DTL} estimated by WRA were 0.21, 0.08, 0.22 and 0.18 kg kg⁻¹ for BF, A, LA and G treatments, respectively. Using CA and NA, θ_{DTL} ranged from 0.16 to 0.24 kg kg⁻¹ and 0.18 to 0.30 kg kg⁻¹, respectively for the BF to G treatments (Table 4). The θ_{DTL} estimated by WRA was drier for A (0.08 kg kg⁻¹, corresponding to water content at −2278 kPa) compared to that estimated by CA (0.18 kg kg⁻¹, corresponding to water content at −307 kPa) and NA (0.24 kg kg⁻¹, corresponding to water content at −105 kPa) (Table 5). For the L12 soil, θ_{DTL} estimated by WRA was wetter (0.19 kg kg⁻¹, corresponding to water content at −9 kPa) than those estimated by CA (0.09 kg kg⁻¹ corresponding to −359 kPa) and NA (0.08 kg kg⁻¹ corresponding to water content at −563 kPa) (Table 5).

4.1.4. Equivalent cylindrical pore diameter at estimated wet and dry tillage limits

The equivalent cylindrical pore diameter (EPD) at θ_{WTL} and θ_{DTL} is shown in Table 6. For the Highfield soil, EPD at θ_{WTL} estimated by WRA ranged from 2.3 to 635.1 µm for A to BF whereas it ranged from 13.3 to 279.0 for L45 to L12. Similar wide range of EPD were found for wet and dry tillage limits estimated by NA (Table 6).

4.1.5. Relationship between the range of water contents and SOC and clay content

The range of water content for tillage will be referred to as $\Delta\theta_{RANGE-WRA}$, $\Delta\theta_{RANGE-CA}$, and $\Delta\theta_{RANGE-NA}$ to indicate the specific approach used, i.e. WRA, CA and NA, respectively. Linear regression was used to relate $\Delta\theta_{RANGE-WRA}$, $\Delta\theta_{RANGE-CA}$, and $\Delta\theta_{RANGE-NA}$ to SOC content for the Highfield soils (Fig. a–c). For the Lerbjerg soil, linear regression was used to relate $\Delta\theta_{RANGE-WRA}$ to clay content (Fig. 4d) and non-linear regression used for $\Delta\theta_{RANGE-CA}$, or $\Delta\theta_{RANGE-NA}$ and clay content (Fig. 4e and f). Fig. 4a–c showed that the $\Delta\theta_{RANGE}$ estimated by the three approaches all significantly increased with increasing SOC ($p<0.05$). The coefficient of determination was highest for CA ($R^2=0.87$) and WRA ($R^2=0.63$) and lower for NA ($R^2=0.35$). $\Delta\theta_{RANGE-CA}$, and $\Delta\theta_{RANGE-NA}$ strongly decreased with increasing clay content (Fig. 4e and f) whereas $\Delta\theta_{RANGE-WRA}$ was poorly related to clay content (Fig. 4d).

4.2. Workable days

Soil workability from September 2015 to May 2016 is presented for the BF and G treatments, and for the L12 and L45 soil. For the examples shown, the BF treatment is deemed workable only in May according to the θ_{WTL} and θ_{DTL} estimated by WRA and NA— the earliest workable day was May 6. For all the other months, the soil was wetter than the estimated wet tillage limit and therefore, not workable. Based on the limits estimated by CA, the soil was not workable throughout the investigated period (Fig. 5a, c and d) because it was too wet. For the G treatment, based on the limits estimated by NA, the soil was workable throughout the autumn and the spring seasons in 2015 and 2016 — the earliest date of soil workability was March 1, whereas based on the θ_{WTL} and θ_{DTL} estimated by WRA the soil was workable only in mid-September and early October 2015, and from May 4 to May 15, 2016. For all other months, the soil was too wet and therefore not workable. Similar to the BF, the limits estimated by CA indicated that the G soil was not workable during the investigated period because it was too wet for tillage.

For the Lerbjerg soil, based on θ_{WTL} and θ_{DTL} estimated by CA and NA, the L12 was workable from September 1, 2015 to May 2016, whereas based on θ_{WTL} and θ_{DTL} estimated by WRA, it was almost not workable throughout the investigated period. Based on the wet and dry tillage limits estimated by WRA, the L45 was workable almost throughout the investigated period whereas based on the workability limits estimated by CA and NA, the soil was not workable (Fig. 6a–f).

The average number of workable days in the spring and the autumn seasons from 2014 to 2018 are shown in Table 7. For the Highfield soil, the average workable days in the spring and the autumn seasons for tillage operation were more for the G and LA compared to A and BF treatments regardless of the approach used. For the Lerbjerg soil, the workable days estimated from the CA and NA decreased from L12 to L45, whereas the WRA limits showed the opposite (Table 7). The relationship between workable days in the spring and the autumn over 2014 to 2018 and SOC (for Highfield soil) and clay contents (for Lerbjerg soil) are presented in Fig. 7a–f. In general, the estimated workable days increased with SOC. This trend was consistent for all the three approaches. Surprisingly, the workable days estimated from the WRA limits increased with increasing clay content, whereas based on the CA and NA, soil workability decreased with increasing clay content— the decrease of workable days from L12 to L45 was sharper for the NA than CA.

5. Discussion

5.1. The new approach for estimating the water contents for tillage

In the new approach (NA), θ_{WTL} is estimated as water content corresponding to an air-filled porosity of 0.10 m^3 m^{-3}. Air-porosity is calculated from water retention data on undisturbed soil cores. Unlike CA, the newly defined limit for estimating θ_{WTL} takes soil structure into account and highlights the underlying role of air-filled structural pores in soil fragmentation by tillage. The air-filled porosity value chosen for estimating the wet tillage limit is because it has been used as a threshold value in relation to soil functions. However, in relation to tillage, whether this value should be 0.10 m^3 m^{-3} still remains an open question, which could be a subject for further research.

The new approach proposed for estimating θ_{DTL} uses a fixed soil strength of 50 kPa for all soils, which makes it fundamentally different from the approach proposed by Dexter and Bird (2001) who defined the dry tillage limit as "the water content at which the strength of the soil is twice the strength at the optimum water content". Even though the absolute value (50 kPa) used in the new approach may be somewhat arbitrary, it gives a quantitative threshold of stress required for fragmentation. The information on stress will be useful to quantify energy requirement for tillage. The applicability of the fixed strength value defined for different soils could be a subject for future studies. As mentioned previously, WRA used vanG for estimating θ_{OPT}. However, the uni-modal vanG implicitly assumes a uni-modal pore size distribution. Therefore, vanG may be too simplistic for estimating θ_{OPT} for structured soils with bi-modal pore size distribution (Dexter and Richard, 2009). In the new approach, we suggest estimating θ_{OPT} using the double-exponential equation (DE) as proposed by Dexter and Richard (2009), which takes into account bi-modal pore size distribution and provides physical basis for understanding soil behavior during tillage.

A major benefit of the new approach over the WRA and CA for estimating the water contents for tillage is that it emphasizes the important role of air-filled pores and soil strength which are important factors limiting soil fragmentation at θ_{WTL} and θ_{DTL}, respectively (Munkholm, 2011). A challenge with the new approach is that it uses "independent" estimates for the wet limit (based on a given air-filled porosity), optimum water content for tillage (textural and structural pores) and the dry limit (based on a given tensile strength). The examples shown for the investigated Highfield and Lerbjerg soils indicated that $\theta_{\text{WTL}} > \theta_{\text{OPT}} > \theta_{\text{DTL}}$ for NA. Further work is needed to test whether this applies to all soils and soil conditions.

5.2. Comparison of WRA, CA and NA for estimating the water contents for tillage

The three approaches were compared on two soils: a soil with a similar texture and a range in SOC (0.009–0.033 kg kg^{-1}) in the topsoil due to contrasting long-term management (Highfield), and a soil with identical SOC but with a naturally occurring clay gradient (0.12–0.45 kg kg^{-1}), Lerbjerg. For the Highfield soil, θ_{WTL} estimated by NA was wetter than those estimated using WRA and CA (Table 4). For the Lerbjerg soils, the θ_{WTL} estimated by NA were identical to those estimated by WRA, but slightly wetter than the CA estimates. The lower values for θ_{WTL} estimated by CA compared to NA could be because CA estimates θ_{WTL} as the water content at the plastic limit i.e. remolding soil which may not reflect the water content for a soil with an intact soil structure (Dexter and Bird, 2001). The optimum water content for tillage (θ_{OPT}) can be estimated using DE as proposed by Dexter and Richard (2009) — θ_{OPT} is the water content at the break point between textural and structural pores.

In terms of ease of usage for the three approaches, as for the WRA, water retention and tensile strength data are needed to estimate the wet tillage limit, optimum water content for tillage and the dry tillage limit using NA, whereas the plastic limit used in CA as the wet tillage limit is relatively simple, fast and cheap to measure. An advantage of NA over CA is that θ_{WTL} and θ_{DTL} are estimated on intact soil.

5.3 Number of workable days as a function soil organic carbon and a clay contents

Results showed the strong influence of SOC and clay content on soil workability (Fig. 7a–f). Average workable days in the spring and the autumn seasons from 2014 to 2018 were more for the G and LA treatments in Highfield compared to the BF and A soil, and for the L12 and L22 than the L29 and the L45 (Table 7). Results here support the findings of Dexter and Bird (2001), who predicted that that the range of water content for tillage increases with increasing SOC content, but decreases with increasing clay content. The increase in number of workable days with increasing clay content for the WRA was however, surprising and unrealistic. However, we do not have a specific explanation for this.

The average workable days in the spring and the autumn from 2014 to 2018 for the three approaches showed that for the Highfield soil, the CA provided fewer workable days compared to the WRA and NA (Table 7). For example, for the period investigated, the BF, A and LA practically had no workable day when tillage can be executed in the spring and the autumn using CA, whereas the WRA and NA showed otherwise. Based on θ_{WTL} and θ_{DTL} estimated by WRA, the LA had

average of 15 workable days in the spring and based on NA, there were average of 56 workable days for tillage operations in spring for LA (Table 7). The reason for the fewer workable days for CA compared to WRA and NA is because the simulated soil water content was, in general, wetter than the upper workability limit estimated by CA (Fig. 5c and d and Fig. 6d). For the Lerbjerg soil, the CA generally provided more workable days than the WRA and NA. This implies that there were more days when the water content of all the layers investigated (3, 6 and ~10 cm depth) were within the range enclosed by the θ_{WTL} and θ_{DTL} estimated by CA than that estimated by the WRA and NA. Recently, Obour et al. (2018) reported that the CA provided more reliable estimates of the water contents for tillage for the Highfield soils than the WRA. Even though results here suggest that CA underestimated the upper workability limits, field validation of the approaches is needed to better understand the applicability and robustness of the approaches. This can be done by performing tillage at the water contents estimated by the approaches and quantifying the fragment size distribution produced by tillage. The sharp decrease in average workable days from L12 to L45 based on the limits estimated by NA reflects the non-linear relationship between clay content and the range of water contents for tillage (Fig. 4e and f).

Edwards et al. (2016) argued that soil workability can be limited when soil is either too wet or too dry. The examples shown for L12 (Fig 6a) and L45 (Fig. 6f) illustrate that too dry soil condition can result in soil being unworkable for tillage. It must be pointed out that soil can be worked even when its strength exceeds the 50 kPa limit set at the dry tillage limit in the new approach. Increasing tillage intensity may be options available to the farmer. The important consideration will be how much energy and time a farmer is prepared to use for tillage operations in their fields (Dexter et al., 2005).

6. Conclusions and perspectives

A new approach for estimating the soil water content for tillage was proposed, which we then compared to the water retention and the consistency approaches. An advantage of the new approach over the consistency approach is that it takes into account soil structure in estimating θ_{WTL}. Unlike the water retention approach and the consistency approach, the new approach uses a fixed strength value (50 kPa) for all soils which gives a quantitative threshold of the stress required for soil fragmentation at θ_{DTL}. However, the absolute value defined may need to be refined. The new approach takes into account the presence of air-filled structural pore space, which is a prerequisite for soil fragmentation during tillage. The new approach also uses an absolute air-filled porosity of 0.10 $m^3\,m^{-3}$ as the wet tillage limit which may also need to be refined in the future. In general, the average yearly workable days in the spring and the autumn were

more for soils with high SOC compared to soils with low SOC contents. The average number of days when the soil was workable decreased with increasing clay content although the reverse was found for water retention approach. Our findings suggest that the number of workable days strongly depends on the approach used to estimate the tillage limits. Field validation of the approaches could be a subject for further research. Further studies on evaluating the workability limits in field conditions for a range of soil textures and in different climates is recommended to establish the robustness of the approaches, particularly the new approach.

Acknowledgements

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Table 1. Optimum water content for tillage and corresponding air-filled porosity for five Hungarian and four Swedish soils. Tillage was performed using a moldboard plow. Water content at plastic limit (θ_{PL}) is also shown.

Soil type	θ_{PL} (kg kg⁻¹)	Optimum water content for tillage	Air-filled porosity (m³ m⁻³)
Soil 1[a]	0.33	0.22	0.16
Soil 2 [a]	0.36	0.21	0.12
Soil 3 [a]	0.45	0.22	0.19
Soil 4 [a]	0.52	0.22	0.19
Soil 5 [a]	0.32	0.22	0.17
Säby 1[b]	0.27	0.25	0.24
Säby 2[b]	0.33	0.22	0.25
Ultuna 1[b]	0.33	0.25	0.14
Ultuna 2[b]	0.28	0.27	0.17

[a] Data from Dexter and Birkas (2004).

[b] Data from Keller et al. (2007)

1   Table 2. Basic properties of the investigated soils

Soil/Treatment	Site	Clay (<2 μm)	Silt (2–20 μm)	Sand (20–2000 μm)	Soil organic carbon	Bulk density	Plastic limit	Reference
		kg kg⁻¹				Mg m⁻³	kg kg⁻¹	
BF	Highfield, UK	0.27	0.25	0.48	0.009	1.45	0.19	Jensen et al. (2019b) and Obour et al. (2018)
A		0.26	0.26	0.48	0.017	1.39	0.24	
LA		0.26	0.26	0.48	0.022	1.21	0.25	
G		0.26	0.27	0.47	0.033	1.13	0.34	
L12	Lerbjerg, Denmark	0.12	0.04	0.84	0.014	1.41	0.21	Obour et al. (2019)
L22		0.22	0.07	0.71	0.014	1.43	0.23	
L29		0.29	0.09	0.62	0.014	1.37	0.25	
L45		0.45	0.12	0.43	0.016	1.22	0.29	

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11 Table 3. Monthly precipitation, average monthly air temperature in 2014, 2015, 2016 and 2017, and long-term average by months for

12 precipitation and air temperature (Highfield: 1961–1990 and Lerbjerg: 1961–1986) for the investigated sites.

Site	Month	Precipitation (mm)					Air temperature (°C)				
		2014	2015	2016	2017	Long-term average	2014	2015	2016	2017	Long-term average
Highfield	March	28.1	26.3	84.3	40.5	62.8	8.1	6.5	5.5	8.8	5.3
	April	31.4	31.1	61.8	12.0	58.6	10.5	9.2	7.7	9.0	7.6
	May	82.9	68.5	39.3	70.1	58.2	12.4	11.3	12.6	13.2	10.9
	August	113.4	83.2	30.1	66.5	58.8	15.7	16.3	17.8	16.0	15.8
	September	16.0	45.3	70.1	86.8	60.3	15.6	12.7	16.3	13.6	13.6
	October	96.0	64.6	30.0	31.1	72.5	12.9	11.0	10.8	12.3	10.4
Lerbjerg	March	29.5	48.6	35.4	52.7	39.1	5.6	4.4	3.6	4.5	1.0
	April	30.0	18.2	98.2	60.3	39.7	8.5	6.7	5.8	6.0	4.5
	May	99.4	83.4	43.0	25.0	51.3	11.4	9.2	12.6	11.8	10.1
	August	98.0	70.8	64.7	92.6	63.2	15.3	17.0	15.5	15.5	14.9
	September	42.6	81.9	16.7	88.8	63.2	14.0	12.6	15.8	12.8	11.5
	October	98.3	19.7	82.7	81.2	67.5	11.6	9.1	8.5	9.4	7.9

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19 Table 4. Water contents for tillage (the wet tillage limit, θ_{WTL} the optimum water contents for tillage, θ_{OPT}; and the dry tillage limit, θ_{DTL})

20 for the Highfield and Lerbjerg soil estimated using the water retention approach, the consistency approach and the new approach.

21 Water content at -30 kPa matric potential is also shown.

Soil/Treatment	Wet tillage limit			Optimum water content for tillage				Dry tillage limit		
	Water retention approach	Consistency approach	New approach	Water retention approach	Consistency approach	New approach	Water content at -30 kPa	Water retention approach	Consistency approach	New approach
	kg kg^{-1}									
BF	0.27[a]	0.19[a]	0.25	0.24[a]	0.18[a]	0.21	0.20	0.21[a]	0.16[a]	0.18
A	0.23[a]	0.24[a]	0.27	0.18[a]	0.21[a]	0.26	0.26	0.08[a]	0.18[a]	0.24
LA	0.33[a]	0.25[a]	0.36	0.28[a]	0.23[a]	0.30	0.30	0.22[a]	0.20[a]	0.25
G	0.36[a]	0.34[a]	0.41	0.29[a]	0.31[a]	0.35	0.37	0.18[a]	0.24[a]	0.30
L12	0.27	0.21[b]	0.26	0.24	0.19[b]	0.14	0.15	0.19	0.09[b]	0.08
L22	0.27	0.23[b]	0.25	0.23	0.21[b]	0.23	0.24	0.20	0.15[b]	0.21
L29	0.31	0.25[b]	0.28	0.27	0.22[b]	0.27	0.28	0.24	0.19[b]	0.26
L45	0.38	0.29[b]	0.37	0.34	0.26[b]	0.35	0.37	0.30	0.24[b]	0.35

22 Bare fallow (BF), Arable (A), Ley arable (LA) and Grass (G) have soil organic carbon contents of 0.009, 0.017, 0.022 and 0.033 kg kg^{-}

23 ^{1}, respectively. L12, L22, L29 and L45 have clay contents of 0.119, 0.220, 0.289 and 0.446 kg kg^{-1}, respectively.

24 [a] Data published in Obour et al. (2018).

25 [b] Data published in Obour et al. (2019).

Table 5. Matric potential at the water contents at wet and dry tillage limits for the Highfield and Lerbjerg soils estimated by the water retention approach, the consistency approach and the new approach.

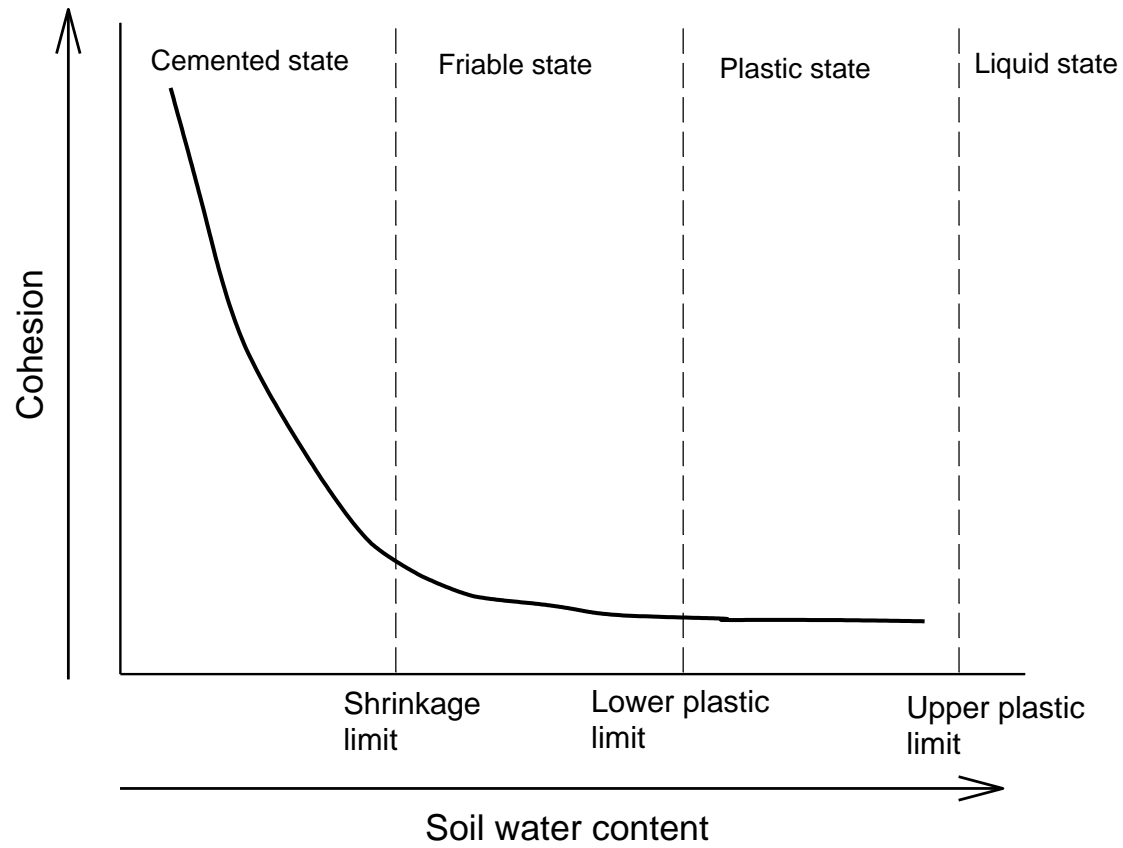| Soil/treatment | Matric potential (kPa) at wet tillage limit | | | Matric potential (kPa) at dry tillage limit | | |
	Water retention approach	Consistency approach	New approach	Water retention approach	Consistency approach	New approach
	kPa					
BF	−0.5	−88	−0.8	−17	−210	−114
A	−130	−116	−19	−2278	−307	−105
LA	−7	−125	−1	−227	−316	−125
G	−37	−70	−10	−616	−308	−141
L12	−1	−7	−2	−9	−359	−563
L22	−11	−48	−22	−164	−467	−133
L29	−13	−122	−32	−134	−341	−98
L45	−23	−185	−38	−174	−412	−66

Bare fallow (BF), Arable (A), Ley arable (LA) and Grass (G) have soil organic carbon contents of 0.009, 0.017, 0.022 and 0.033 kg kg^{-1}, respectively. L12, L22, L29 and L45 have clay contents of 0.119, 0.220, 0.289 and 0.446 kg kg^{-1}, respectively.

Table 6. Equivalent cylindrical pore diameter (EPD) at wet and dry tillage limits of Highfield and Lerbjerg soils estimated by the water retention approach, the consistency approach and the new approach.

Soil/treatment	EPD at wet tillage limit			EPD at dry tillage limit		
	Water retention approach	Consistency approach	New approach	Water retention approach	Consistency approach	New approach
	µm					
BF	635.1	3.4	357.2	18.1	1.4	2.6
A	2.3	2.6	15.7	0.1	1.0	2.8
LA	43.1	2.4	226.9	1.3	0.9	2.4
G	8.0	4.3	29.7	0.5	1.0	2.1
L12	279.0	46.2	152.5	33.8	0.8	0.5
L22	28.7	6.3	13.5	1.8	0.6	2.3
L29	23.7	2.5	9.5	2.2	0.9	3.1
L45	13.3	1.6	7.9	1.7	0.7	4.5

Bare fallow (BF), Arable (A), Ley arable (LA) and Grass (G) have soil organic carbon contents of 0.009, 0.017, 0.022 and 0.033 kg kg^{-1}, respectively. L12, L22, L29 and L45 have clay contents of 0.119, 0.220, 0.289 and 0.446 kg kg^{-1}, respectively.

Table 7. Average yearly workability during the spring and autumn over 2014 to 2018 for the investigated soils in Highfield and Lerbjerg. Workability limits estimated using the water retention approach (WRA), the consistency approach (CA) and the new approach (NA).

Site	Soil/treatment	Workability limits-WRA		Workability limits-CA		Workability limits-NA	
		Workable days in spring	Workable days in autumn	Workable days in spring	Workable days in autumn	Workable days in spring	Workable (days) in autumn
Highfield	BF	7 (0–10)	10 (2–25)	0 (0)	0 (0)	3 (0–9)	2 (0–7)
	A	0 (0)	0 (0)	1 (0–4)	0 (0)	0 (0–1)	4 (0–11)
	LA	15 (0–32)	15 (5–28)	0 (0)	0 (0)	56 (39–76)	39 (37–41)
	G	21 (0–44)	17 (6–31)	13 (0–38)	7 (1–21)	63 (41–76)	40 (31–45)
Lerbjerg	L12	1 (0–2)	1 (0)	35 (0–69)	37 (23–45)	36 (0–71)	38 (24–45)
	L22	13 (0–20)	11 (4–15)	47 (0–66)	34 (21–44)	8 (0–13)	8 (3–11)
	L29	10 (0–15)	10 (3–13)	32 (0–46)	24 (17–31)	1 (0–3)	1 (0–1)
	L45	22 (0–36)	17 (10–25)	0 (0–1)	0 (0)	0 (0)	0 (0)

Bare fallow (BF), Arable (A), Ley arable (LA) and Grass (G) have soil organic carbon contents of 0.009, 0.017, 0.022 and 0.033 kg kg^{-1}, respectively. L12, L22, L29 and L45 have clay contents of 0.119, 0.220, 0.289 and 0.446 kg kg^{-1}, respectively. The range in the parenthesis refer to the minimum and maximum number of workable days in the period 2014 – 2018.

Fig. 1. Variation in soil consistency state with water content. Modified from Spoor (1975).
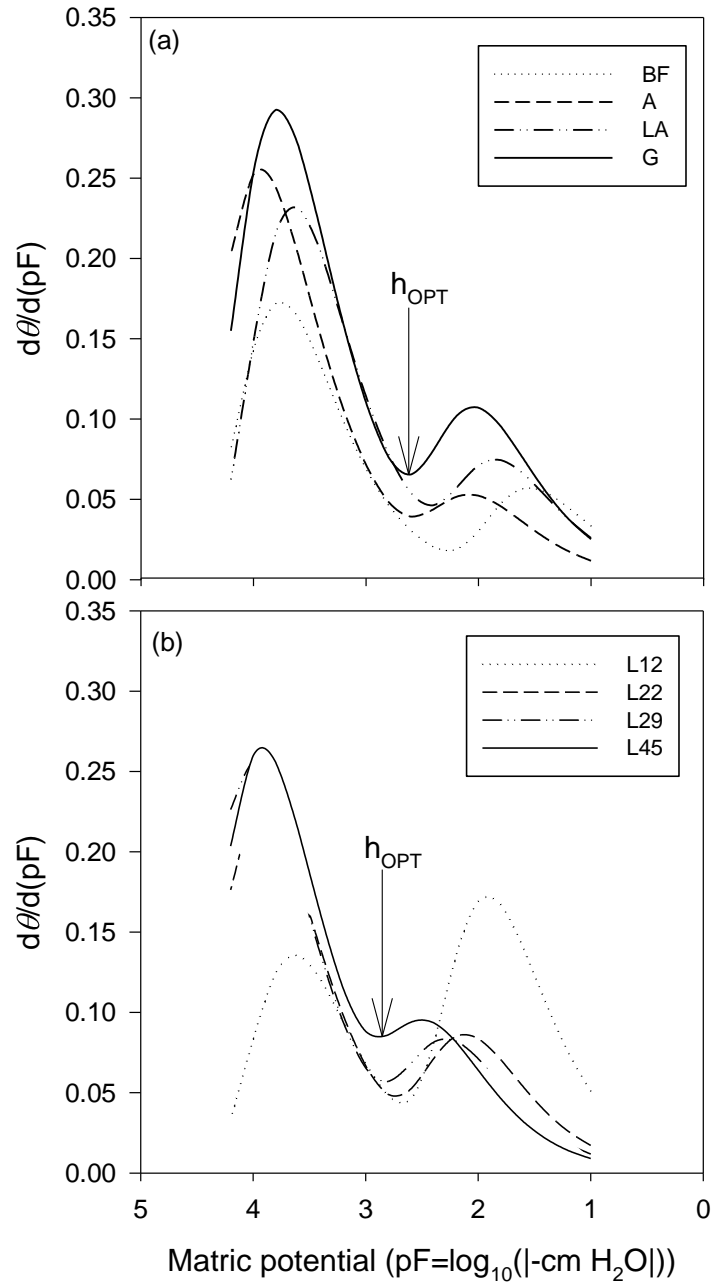
Fig. 2. Pore size distribution (dθ/d(pF) as a function of matric potential (in pF) for (a) Highfield soil and (b) Lerbjerg soil. Bare fallow (BF), Arable (A), Ley-arable (LA) and Grass (G) treatments (Jensen et al., 2019a) have soil organic carbon contents of 0.009, 0.017, 0.022 and 0.033 kg kg^{-1}, respectively. L12, L22, L29 and L45 have clay contents of 0.119, 0.220, 0.289 and 0.446 kg kg^{-1}, respectively. Arrows show how the matric potential (Ψ) at the optimum water content for tillage (θ_{OPT}) is determined graphically.

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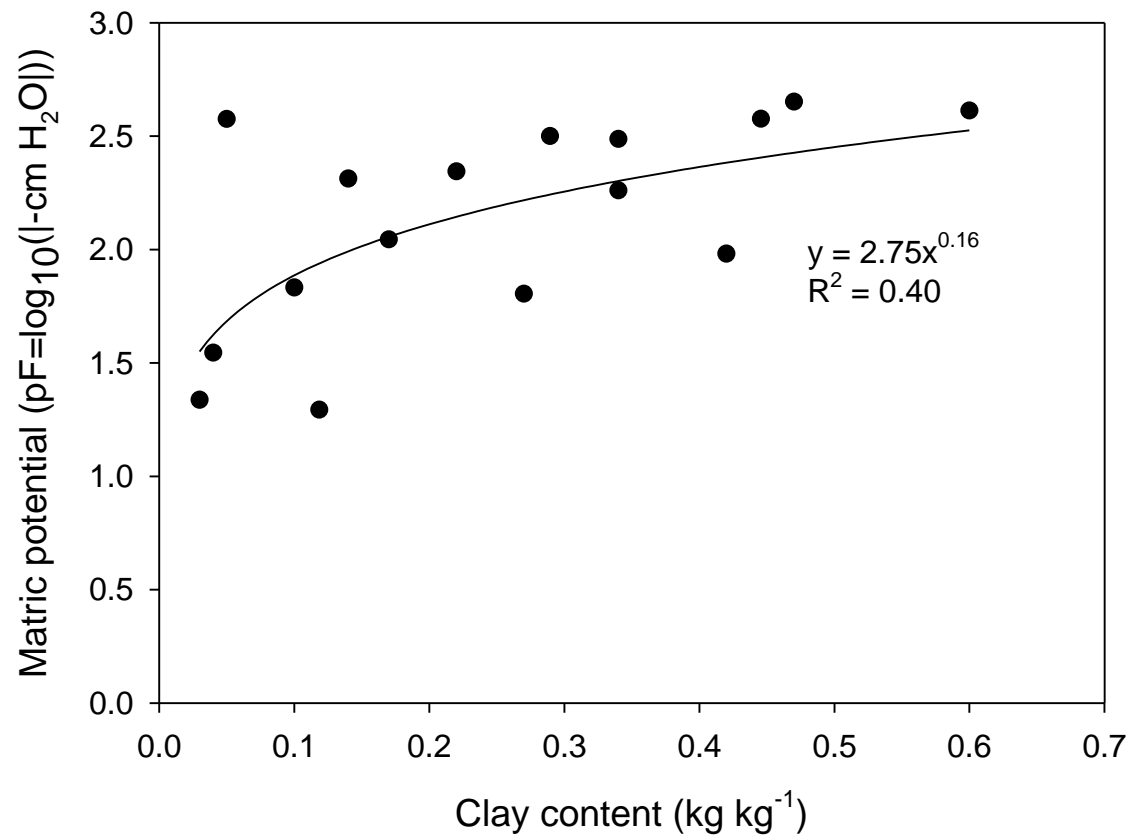
Fig. 3. Matric potential (expressed in pF) at wet tillage limit estimated from the proposed approach (θ_{WTLNA}) (water content at soil air-filled porosity of 0.10 m³ m⁻³) as a function of clay content.
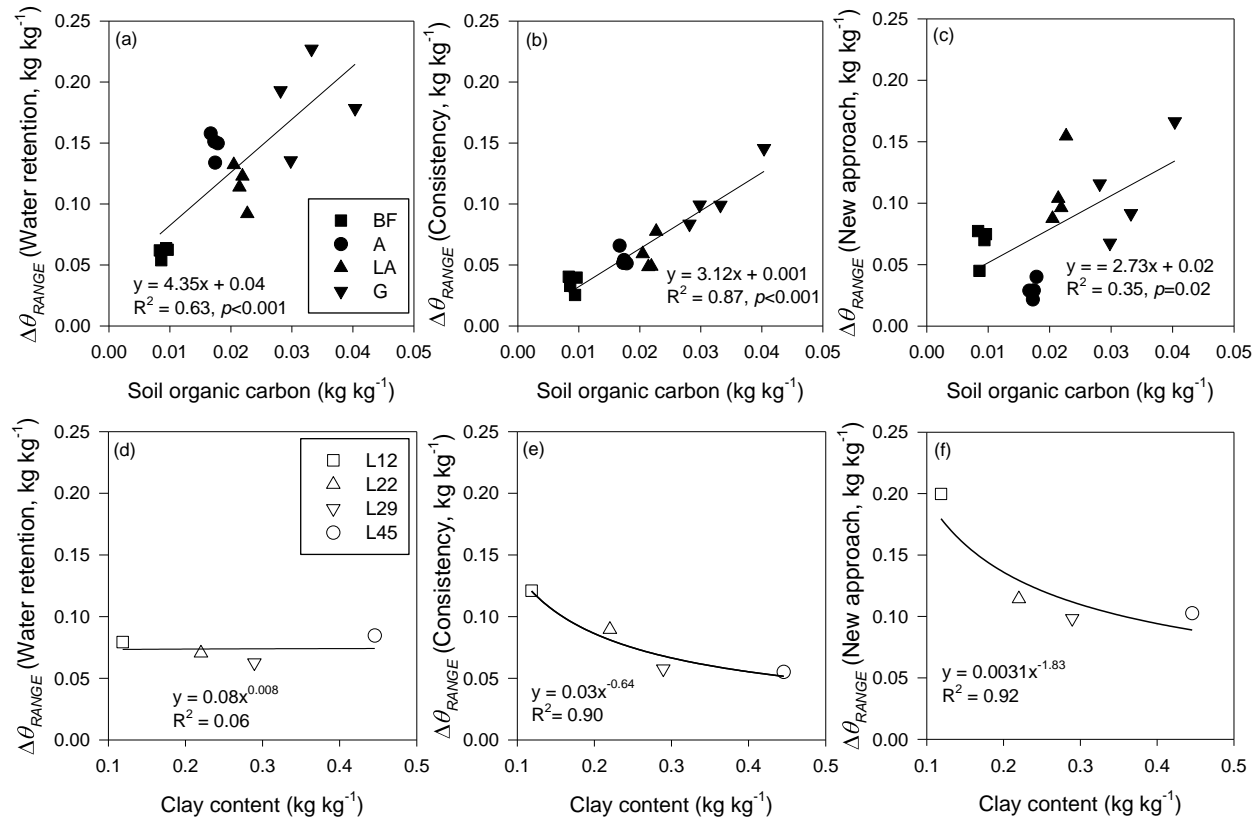
Fig. 4. The range of water contents (calculated difference between the wet and dry tillage limits estimated by the water retention approach, the consistency approach and the new approach) as a function of soil organic carbon content (a–c) and clay content (d–f) for the Highfield and Lerbjerg soil. Bare fallow (BF), Arable (A), Ley arable (LA) and Grass (G) have soil organic carbon contents of 0.009, 0.017, 0.022 and 0.033 kg kg⁻¹, respectively. L12, L22, L29 and L45 have clay contents of 0.119, 0.220, 0.289 and 0.446 kg kg⁻¹, respectively. Fig. 4a and b reproduced from Obour et al. (2018) and Fig. 4e from Obour et al. (2019).
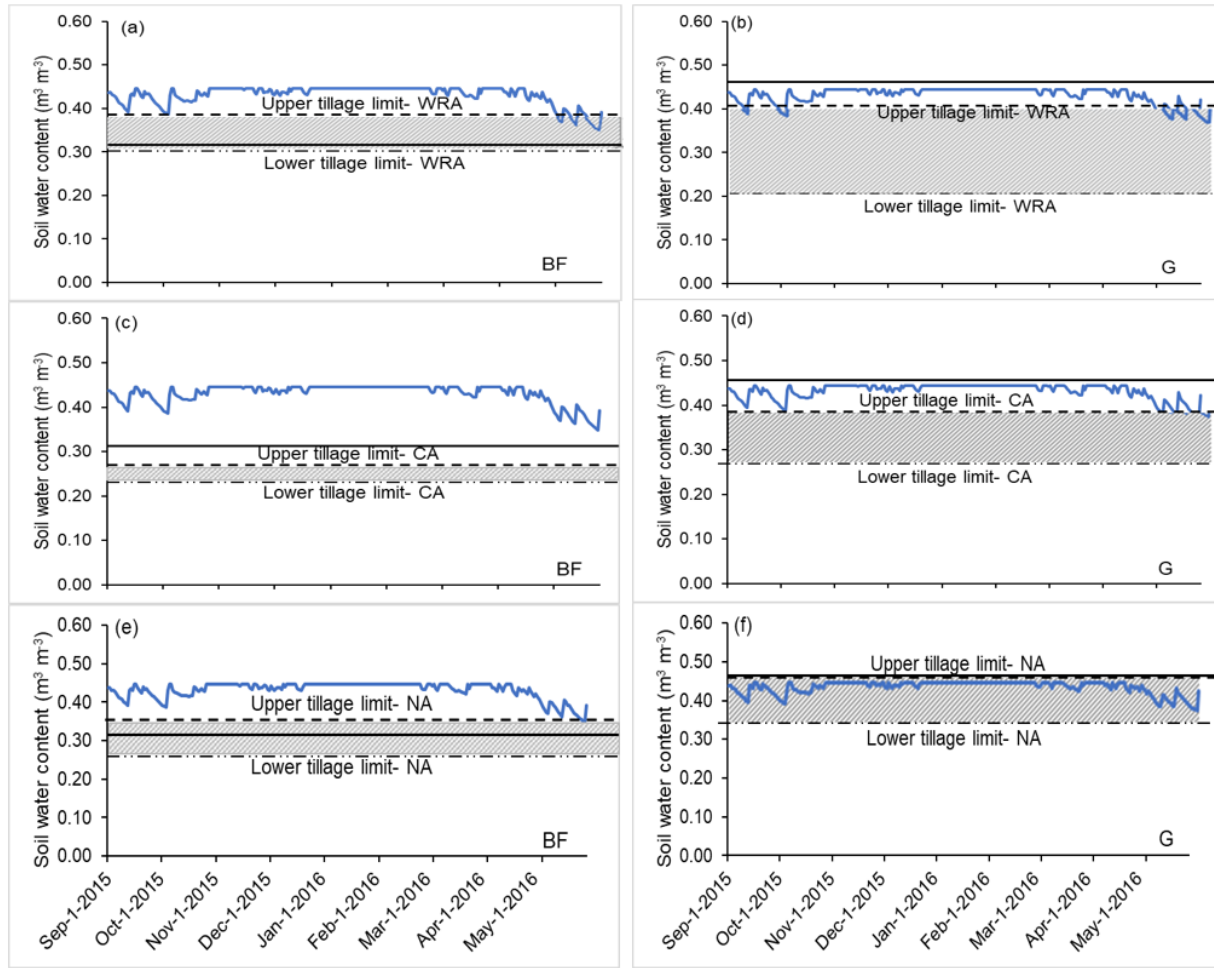
Fig. 5. Example of the workability limits (estimated using the water retention approach, WRA, the consistency approach, CA and the new approach, NA) at ~ 10 cm depth imposed on conventional tillage for the BF (Bare fallow) treatment (a, c and e) and the G (Grass) treatment (b, d and f in Highfield in the autumn 2015 to the spring season in 2016. Solid horizontal line indicate volumetric water content at −10 kPa matric potential, blue lines indicated the simulated soil moisture content and the grey shading area is the range of water content for tillage.
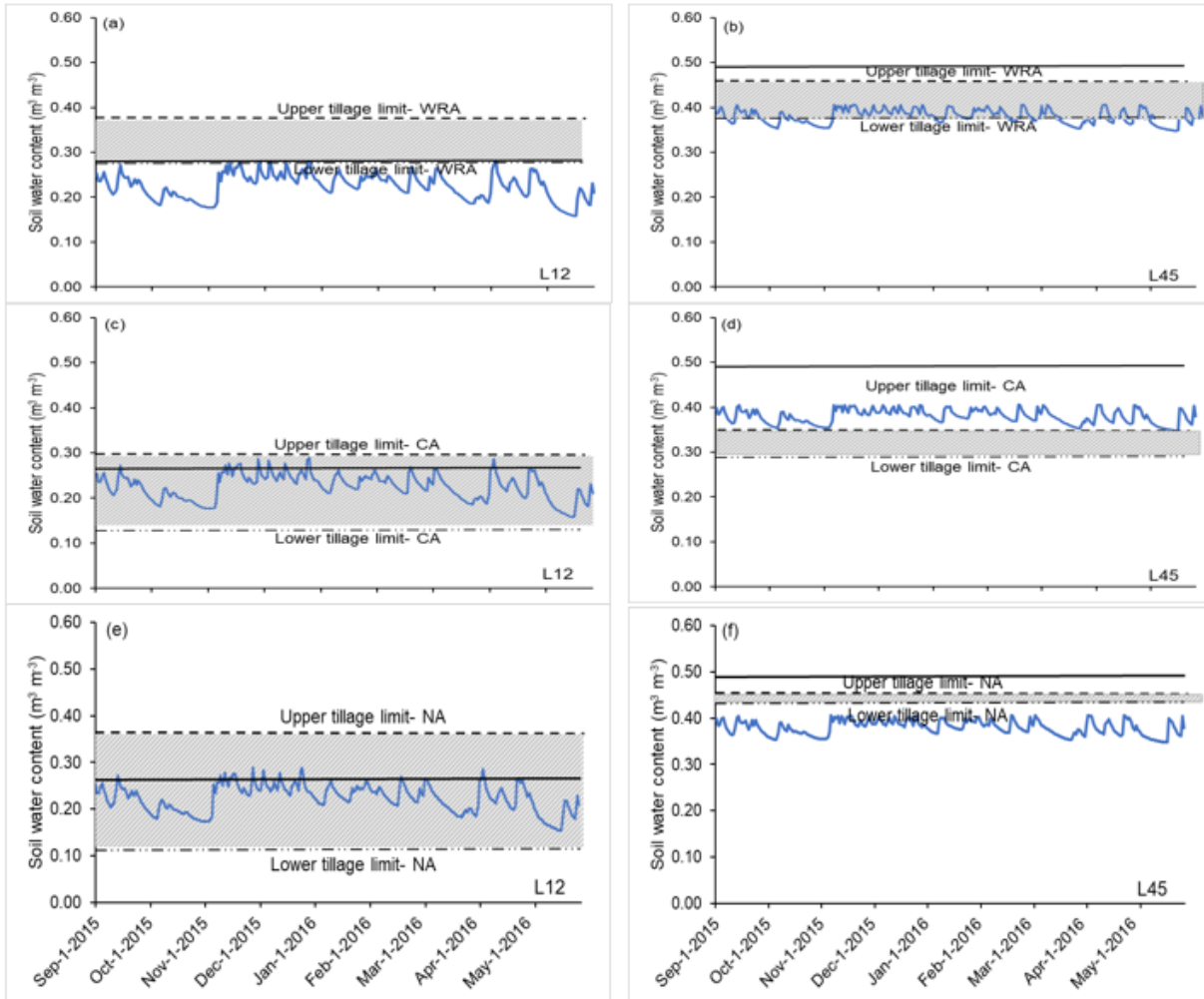
Fig. 6. Example of the workability limits (estimated using the water retention approach, WRA, the consistency approach, CA and the new approach, NA) at ~ 10 cm depth imposed on conventional tillage for the L12 (a, c and e) and the L45 (b, d and f in Lerbjerg in the autumn −10 kPa matric potential, blue lines indicated the simulated soil moisture content and the grey shading area is the range of water content for tillage.
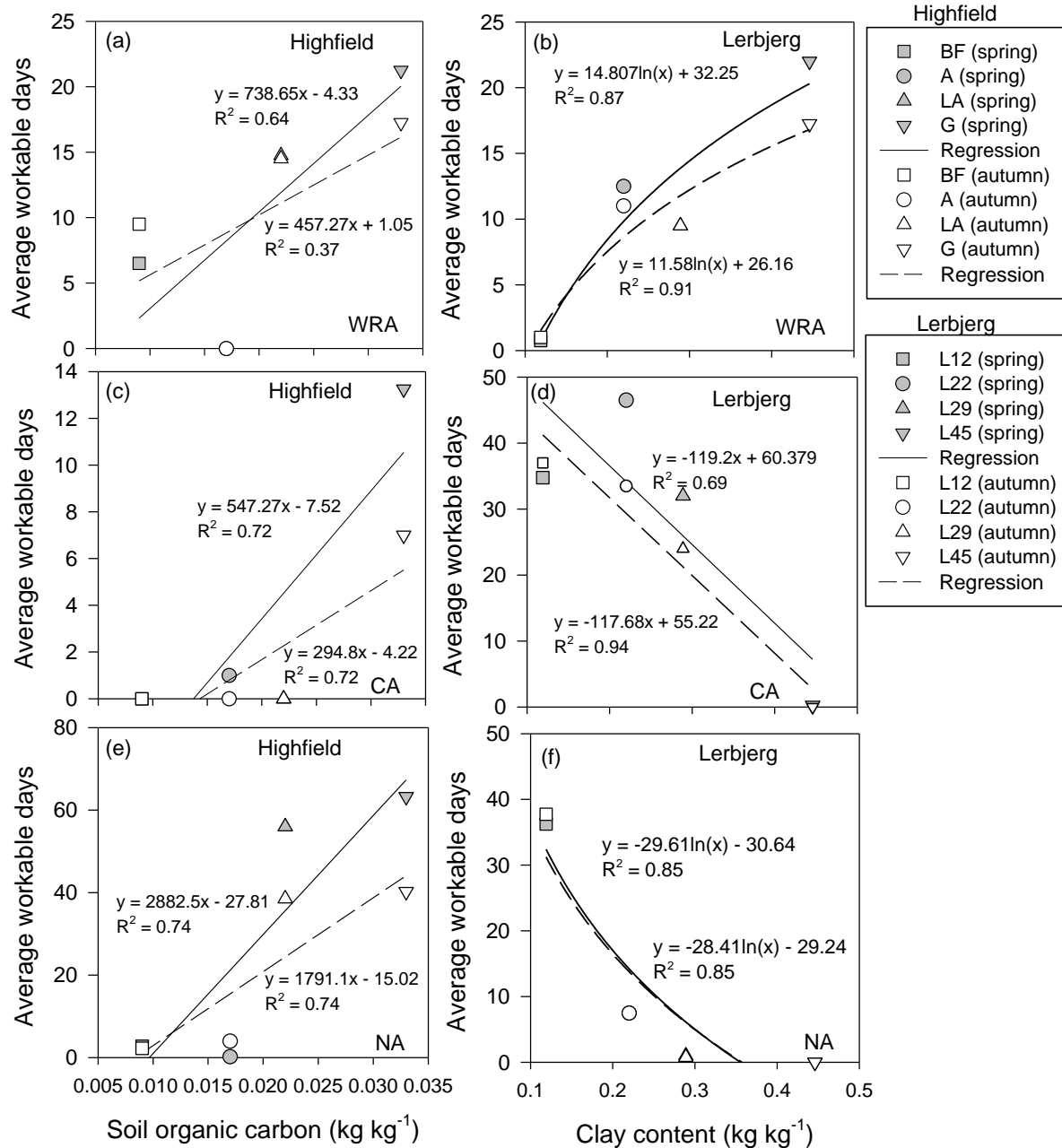
Fig. 7. Average workable days in the spring and autumn from 2014 to 2018 as a function of soil organic carbon (a, c and e), and as a function of clay content (b, d, and f). Tillage limits were estimated using the water retention approach (WRA), the consistency approach (CA), and the new approach (NA). Bare fallow (BF), Arable (A), Ley arable (LA) and Grass (G) have soil organic carbon contents of 0.009, 0.017, 0.022 and 0.033 kg kg^{-1}, respectively. L12, L22, L29 and L45 have clay contents of 0.119, 0.220, 0.289 and 0.446 kg kg^{-1}, respectively. Please note the differences in scale on the y-axis.

12 Additional publications

I have also worked or contributed to the following manuscripts/published papers during my PhD tenure:

1. Daraghmeh, O., Petersen, C., Munkholm, L.J., Znova, L., **Obour, P.B.,** Nielsen, S.K., Green, O., (2019). Impact of tillage intensity on clay loam soil structure. *Soil Use and Management* (Accepted). doi.org/10.1111/sum.12501

2. Munkholm, L.J., Pulido-Moncada, M., **Obour, P.B**., (2019). "Soil tilth and management". In *Oxford Research Encyclopedia of Environmental Science.* Oxford University Press (In Press).

3. **Obour, P.B.,** Dadzie, F.A., Arthur, E., Munkholm, L.J., Saba, C.K.S., Rubæk, G.H., Owusu, K. (2018). Integration of farmers' knowledge and science-based assessment of soil quality for peri-urban vegetable production in Ghana. *Renewable Agriculture and Food Systems*. 1–12. doi.org/10.1017/S17421705180003

4. **Obour, P.B.,** Schjønning, P., Peng, Y., Munkholm L.J. (2017). Subsoil compaction assessed by visual evaluation and laboratory methods. *Soil & Tillage Research* 173: 4–14. doi.org/10.1016/j.still.2016.08.015

5. Schjønning, P., McBride, R., Keller, T., **Obour, P**. (2017). Predicting soil particle density from clay and soil organic matter contents. *Geoderma* 286: 83–87. doi.org/10.1016/j.geoderma.2016.10.020

6. Owusu, K., Yankson, P. W. K., Asiedu, A. B., and **Obour, P. B**. (2017). Resource utilization conflict in downstream non-resettled communities of the Bui Dam in Ghana. *Natural Resources Forum*, 41: 234–243. doi.org/10.1111/1477-8947.12139

7. **Obour, P.B.,** Owusu, K, and Teye, J.K. (2017). "From seasonal migrants to settlers: climate change and permanent migration to the transitional zone of Ghana". In: S. Tonah and M. Setrana (Eds.), *Migration and Development in Africa: Trends, Challenges, and Policy Implications*, pp. 147–164 Lexington Books: London.

8. Owusu, K., **Obour, P.B.,** and Nkansah, M. A. (2016). Downstream effects of dams on livelihoods of river-dependent communities: the case of Ghana's Kpong Dam. *Geografisk Tidsskrift-Danish Journal of Geography*, 117(1): 1–11. doi.org/10.1080/00167223.2016.1258318