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Soil compaction

- effects on soil functions and strategies for prevention

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Preface

The present publication is a compilation of the abstracts for the presentations at the NJF seminar 448: Soil compaction – effects on soil functions and strategies for prevention held in Helsinki, Finland, 6–8 March 2012.

Traffic by agricultural machinery imposes a stress field in the soil profile, which may create persistent deformation of the soil. Soil compaction is a global problem, which affects several important soil functions relevant to crop production, as well as environmental and socio-economical issues.

Increase in wheel loads has increased the magnitude of stresses reaching subsoil layers, thus increasing the risk of long-term or even permanent soil compaction.

A solution to the compaction problem calls for cooperation between authorities, stakeholders, farmers and scientists. We need to improve the empirical basis for modelling and decision support tools. Models for the compaction process and for compaction impact on soil functions need to be refined and incorporated in modern ICT decision support tools.

The overall objective of this seminar was to bring together researchers, governmental authorities and stakeholders for reviewing state-of-the-art knowledge concerning (sub)soil compaction, its short- and long-term effects on soil functioning, and the strategies and measures for the prevention of compaction.

The seminar consisted of five topics:
Societal concern and upcoming regulations
Understanding of soil compaction processes
Soil functions – crop production
Soil functions – environmental impacts
Soil compaction prevention strategies

The seminar was organized as a part of the inter-Nordic project 'POSEIDON' (2009–2012; www.poseidon-nordic.dk) supported by the Nordic Joint Committee for Agricultural and Food Research (NKJ).

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Soil compaction: Societal concerns and upcoming regulations

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Introduction

The scientific soil science community needs to be realistic. In a time when it is already difficult to mobilize societal concerns about the environment and climate change, soil compaction is certainly not a topic that tickles the imagination. There simply is no societal nor political concern about soil compaction. The problem is real enough but faces the same challenge as soil science itself, its invisibility. A decrease of biodiversity or extreme weather conditions can be observed and physically experienced. But whatever happens in the soil remains hidden below the surface. Effects of excessive soil compaction may, of course, be painfully visible in terms of reduced crop production or increased erosionand environmental pollution but its causes are only known to soil specialists. They face, therefore, a serious challenge to communicate the problem to society in a convincing manner avoiding the doomsday approach that has so evidently backfired in the climate-change debate. The communication challenge is particularly relevant in our modern society where information is freely available and where new ways of communication increasingly dominate discussions.

The Thematic Strategy for Soil Protection from the Commission of the European Communities (CEC, 2006a) recognizes soil compaction as one of the threats to soil quality. So far, this Strategy has not been followed up by a legally binding Framework Directive, but this may come in future. The scientifc community should therefore be prepared to address the issue of soil compaction in such a manner that guidance is provided to avoid or mitigate soil compaction , while convincing society of its relevance, which, if succesfull, should ultimately result in bindinglegislation omn soil protection.

The Thematic Strategy for Soil Protection

The Thematic Strategy for Soil Protection (CEC, 2006a), distinguishes a number of soil threats. Erosion, organic matter decline, salinisation, compaction and landslides are grouped in one category. A procedure is proposed to characterize each one of these threats in a proposed Framework Directive as follows: (i) defining common criteria; (ii) establishing a monitoring system, to be supported by modeling; (iii) establishing risk acceptability in each member State; (iv) identification of areas that are at risk; (v) defining targets for risk areas; (vi) adoptation of measures in each member State to achieve targets, and (vii) reporting to the European Commission.

The approach recognises that compaction occurs in specific risk areas which must be identified by member States, which will be required to take specific measures to address compaction but the Directive will leave them ample freedom on implementation. This means that risk acceptabiliy , the level of ambition regarding the targets to be achieved and the choice of measures to reach those targets are left to member states. The *subsidiarity principle* applies, therefore,which states that measures should be taken at the lowest possible governmental level. In other words: do as much as possible at national or lower governmental level. But according to CEC (2006a) a general framework at EC level is still needed. The still unanswered key question is how detailed this should be and how the issue should be addressed at EU level.In another document (CEC, 2006b, Annex 1, section 3) suggestions are presented for “common elements for the identification of areas at risk of compaction”, consisting of soil type, soil texture, organic matter content, climate, land cover and use and topography. This has further been worked out in a EU-wide study, initiated by the European Parliament (Louwagie et al., 2009). Also the *proportionality principle* applies to the compaction issue, which indicates that measures to be taken should be in balancewith the severity of the problem being considered. In other words: avoid regulatory overkill.

The current state of affairs provides excellent opportunities for compaction research by: (i) following the CEC (2006a) scheme defining areas within a given country where compaction occurs, including associated risks, and as yet uncompacted areas where compaction represents a serious risk, and (ii) communicating results in a convincing manner to society to create awareness that may result in binding legislation.

How to define compaction risks

Compaction can be defined in terms of an increase of the bulk density (g/cm-3) of a soil as compared to its natural uncompacted state (e.g. Gupta et al., 2002). This does not necessarily imply, however, that compaction constitutes a threat, which only occurs when densities reach a critical value above which soil behavior is affected significantly. Such critical densities are different for different soils in different climatic zones. The risk concept of CEC (2006a) has two elements which are as yet not clearly distinguished: (i) what is the risk that compaction may occur in as yet uncompacted soils, and (ii) once compaction has occurred, (which is the actual condition in many areas) what are the risks for environmental quality and how can such risks be reducedto acceptable levelsby mitigation measures.The risk that compaction occurs (point i) is a function of the type of soil, the moisture regime and the type of soil traffic that is part of a given management scheme. Compaction is most likely when soils are wet and when travelled by heavy machinery. The moisture content at the Lower Plastic Limit has been used to indicate a critical moisture content above which compaction is likely. Higher organic matter contents make a soil stronger but at the same time increase its moisture content. This may lead to a higher vulnerability for compaction despite of its greater inherent strength. The balance between moisture and organic matter content in relation to compactability is different for different soils (e.g. Droogers et al, 1996). Once compaction has occurred, risks (point ii) can best be defined in terms of its effects on soil functions. (e.g Bouma, 2010). Functions most strongly affected by compaction are (CEC, 2006b, page 14): (i) biomass production; (ii) storing, filtering and transformation of nutrients, substances and water, and (iii) biodiversity and carbon pool.

Effects for *biomass production* mainly result from restricted rooting and soil wetness as a result of lower permeabilities of compacted soils. But effects differ among different soil types while climatic conditions are also very important (see CEC, 2006b and Louwagie et al, 2009). Compaction may occur at the soil surface or as a plowpan below the plowed layer. In sandy and silty soils compaction results in a massive soil which roots cannot penetrate while in swelling clay soils, compact structural elements may be formed with vertical shrinkage cracks with roots that cannot penetrate into the soil matrix. To calculate effects (and to estimate risks), the traditional models for water extraction by roots do not suffice. More sophisticated models are needed, considering water uptake as a continuous function of the water potential and accessibility of water in compacted soil , next to availability linked to the water potential (e.g. Bouma, 2010). Compaction also results in a lower saturated hydraulic conductivity and this may result in water stagnation with adverse effect for plant roots due to oxygen depletion. But for plant growth the unsaturated conductivity is usually more important. Compaction of subsoil in a sandy loam soil resulted, for example, in a higher unsaturated conductivity and also higher potato growth in a dry season as water moved more rapidly upwards from the water table to the rootzone (Feddes et al., 1988).

Storing, filtering and transformation of compounds may be improved by compaction, as travel times of liquid in compacted soil are usually longer than in uncompacted soil. Longer travel times result in longer contact times and more effective filtering (e.g. Bouma, 2010). It depends on the climate whether or not this presents a problem. When precipitation rates are higher than infiltration rates into the soil, temporary soil saturation may occur with negative results for filtering as free water may move laterally over the surface to surface waters. Also erosion of topsoil is likely in sloping areas. But no problems may occur at lower precipitation rates. Again, different soil types act quite differently and each one has characteristic critical travel times for purification as a function of the flow regime (e.g. Bouma, 2010).

The *biodiversity* and *carbon pool* will generally be negatively affected by excessive soil wetness as a result from compaction, but this does, again, depend on climatic conditions. Remember that peats form major carbon pools in the world and result from excessive wetness which does not allow complete decomposition and humification of plant material. On the contrary, in a dry climate, compact soil may stay moist for a longer period of time, certainly when the very topsoil is loose, which is favorable for biodiversity.

How to communicate a seemingly dull issue such as soil compaction

A certain degree of modesty is required when communicating the negative aspects of soil compaction. There is no potential for " scaring them to death" considering the possible impact of compaction.This is fortunate because such an approach is likely to backfire. Following the CEC (2006a,b) suggestions, the best procedure would be a business-like communication in quantitative terms of the effectsof compaction in different soils in different climatic zones of the EU, including a survey of actual conditions. A focus on the effect on soil functions would provide a transparant approach in terms of: (i) How much of a problem is there already (in terms of reduced soil functions); (ii) what is the potential to improve the functions to an acceptable level applying certain mitigation measures, and (iii) how can compaction be avoided in areas where so far the problem does not exist. What are critical degrees of compaction in different soils?

Bouma (2002) proposed a soil quality measure based on the ratio between potential production of a standard crop and its water-limited yield (x100 to obtain a value between 0 and 100). He also estimated the possible effects of compaction on biomass production and concluded for threemajor soil types in the tropics that percentages varied between 6 and 40%. Such values are useful for communication purposes, if only to conclude that compaction should not be much of an issue when effects are low. A value of 40% , however, is likely to have a major impact when seen in the light of food security, a major issue in the international policy arena.

Communication should also include attention to mitigation illustrating whether problems can be overcome and, if so, at reasonable cost. Loosening of soil or deep plowing appears to be a logical measure to consider but experiences in the Netherlands have, for example, shown that if loosening is not followed by different types of soil management than before, new compaction may result that is much worse than before (van Lanen et al., 1986).

Finally, the quite different behavior of soils in different countries of the EU make it attractive to present results of compaction studies for specific soil types that citizens can associate with. This in contrast to a focus on "soil" in general (see also CEC, 2006b and Louwagie et al, 2009). The distinction of soil types in soil classification focuses on permanent soil properties as formed by soil genesis while effects of management are not considered. To overcome this problem, Droogers and Bouma (1997) suggested use of *phenoforms* (expressing effects of soil management on a specific genetically determined soil type) versus the *genotype* , the genetic soil type. Each genetic soil type has a characteristic range of *phenoforms*as a result of different types of management ("each soil has a characteristic story line") and this presents an interesting future study object for pedology that will also be useful in expressing the relative importance of compaction in different countries as well as its possible mitigation.

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Soil compaction: Societal concerns and upcoming regulations

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Different EU policies (for instance on water, waste, chemicals, industrial pollution prevention, nature protection, pesticides, agriculture) are contributing to soil protection. But as these policies have other aims and other scopes of action, they are not regarded as sufficient to ensure an adequate level of protection for all soil in Europe. For these reasons, the Commission adopted a Soil Thematic Strategy (COM(2006) 231) and a proposal for a Soil Framework Directive (COM(2006) 232) on 22 September 2006 with the objective of ensuring sustainable use of soils across the EU and protecting them from a series of key threats that include: biodiversity decline, compaction, contamination, erosion, landslides, organic matter decline, salinisation and sealing.

The Soil Thematic strategy is based on four pillars: framework legislation, integration of soil protection in the formulation and implementation of national and Community policies, closing the recognized knowledge gap in certain areas of soil protection and increasing public awareness of need to protect soil. The strategy takes a form of a Communication from the Commission and it is not as such a legislative proposal and therefore not a subject to a formal process of adaption.

In the proposal for a Soil Framework Directive erosion, organic matter decline, salinisation, compaction and landslides are addressed taking a risk area approach. Member States should identify risk areas on the basis of common elements, set risk reduction targets and establish programmes of measures to reach them. Risk acceptability and measures would vary in response to the severity of the degradation processes, local conditions and socio-economic considerations. Member states could choose the appropriate geographical scale and administrative level. What comes to contamination the Member States would be required to identify contaminated sites and establish a national remediation strategy. Member States would also be required to take appropriate national measures to limit sealing or to mitigate its effects. The proposal for a Directive is subject to the co-decision procedure. This means that both the European Parliament and the Council have to agree on a common text on the basis of a proposal. The Council has so far been unable to reach a qualified majority on the proposal due to the opposition of a number of Member States constituting a blocking minority. Their opposition is based on grounds of subsidiarity, excessive costs and administrative burden. The last discussions in the Council were held during the Spanish Presidency during first half of 2010).

Even though the proposal for the Directive still remains on the Council´s table, the implementation of the other pillars of Thematic Strategy is ongoing. The current situation is described in the recent report from the Commission (COM (2012) 46 final). According to this report soil degradation in Europe continues. Whilst Soil Strategy has helped raise the profile of these issues, there is still no systematic monitoring and protection of soil quality across Europe. This means that knowledge about the status and quality of soils remains fragmented and soil protection is not undertaken in an effective and coherent way in member states. The Commisison will for its part continue activities in line with the strategy. On legislation it will now address soil protection as part of a review of the environmental impact directive and new rules on emissions from land use, land-use change and forestry (LULUCF), which are due to be put forward shortly.

Other interesting recent report is published by Commission´s Joint Research Centre (reference report 2012). This report gives an overview of problems facing the EU, using data supplied to the European Environment Agency for its 2010 State of the Environment and Outlook Report and material produced since. This report calls for better data collection and further research into the economic and environmental benefits of soil function.

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Risk assessment and effects of soil compaction: Research chains at work

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Agriculture in a changing world

Modern agriculture puts stresses to the soil resource. Mechanization of field operations is developed with a full focus on optimization of economic profitability. Farming units increase in size, and often contractors are hired for the field operations. This means that the farmers' attention to soil quality aspects decreases, and that the staff driving the machinery is forced to focus competitiveness in e.g. slurry application rather than optimization of the soil as a growing medium for crops.

Developments in science

Due to scarcity of economical resources in modern, industrialized societies, governments tend to interfere with university priorities, and many sectorial research institutes have been amalgamated with classical universities. This tends to turn focus towards either classical 'descriptive' branches of science and/or to intensify research in focus-areas pointed out by the governments. In post-industrial societies competing with upcoming industrializing countries, agriculture and sustainability in farming operations are seldom among the new focus areas.

Science and society

While research in agricultural systems hence is reduced, sustainability aspects of modern agriculture are the focus of some non-governmental organizations (NGOs) as well as of super-national political agencies like the EU Commission. This creates a situation with researchers generally poorly qualified for advising the implementation of guidelines and rules for e.g. traffic in the fields that are sustainable from a soil protection point of view.

Research chains

To solve sustainability problems in modern agriculture, science has to interact with society in a novel way, which can be achieved by identifying interdisciplinary research groups for well defined tasks. The protection of the soil from irreversible deformation by wheel traffic requires expertise from a range of research branches. In order to efficiently solve the task for the society, there is a need for explicit identification of the compaction process and knowledge gaps needed to be further examined in order to arrive at decision support for farmers and the authorities responsible for a sustained soil and environmental quality.

Bouma (1997) suggested the term ‘research chain’ for such a collection of research groups and individuals. The basic idea is first to make a holistic, inter-disciplinary analysis of the problem to be studied, and next follow-up by reductionistic basic research in relevant areas. The specific research may comprise scales ranging from the country or even world level (regulations) to the micrometer level (interaction between soil particles).

Qualitative, empirical knowledge of yield reduction as well as an understanding (qualitative/quantitative as well as empirical/mechanistic) of compaction-affected soil functions both relate to the traffic systems (machinery) used in the field (Fig. 1). Agricultural engineers may then differentiate the aspects of the machinery affecting soil, i.e. em-pirical, quantitative research on the tyre-soil interactions. The stressses propagating down the soil profile need to be quantified and the mechanistic process of stress-induced soil deformation understood. This again relates back to the soil functions (Fig. 1).

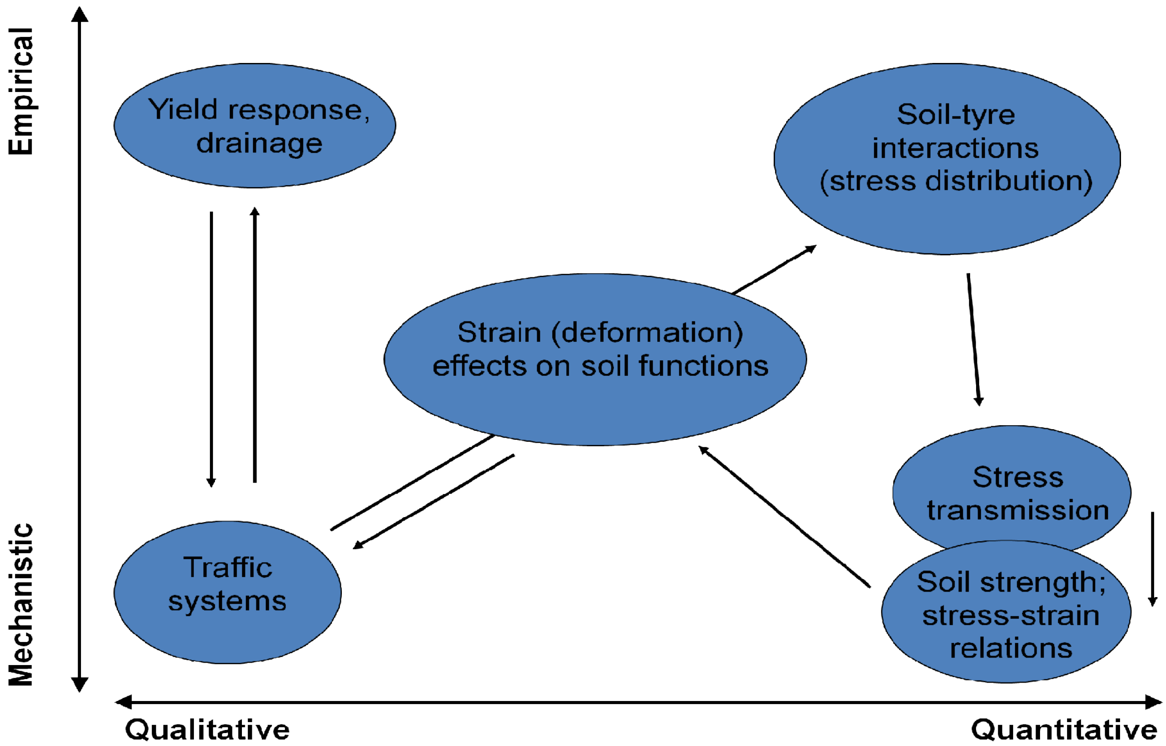

Figure 1. Research topics and their interconnection in research chains when addressing soil compaction.

Creating and taking knowledge to work

An international research group is currently following the path illustrated in Fig. 1 towards an improved platform for decision support by farmers, agricultural advisers and the public authorities. The work is economically supported by national funding bodies as well as by international organizations (project 'POSEIDON' including Denmark, Sweden, Finland and Norway: www.poseidon-nordic.dk; project 'PredICTor' including Denmark, Switzerland, Finland, Germany and The Netherlands). Our results indicate persistent compaction effects on important soil functions (e.g. Regina et al., 2011; Berisso et al., 2012). We have suggested rules of thumb for direct use *on site* by the farmer based on stress-strain studies under running wheels (Keller et al., 2012; Schjønning et al., 2012). An online decision support tool (Terranimo) for detailed advice on the sustainability of any planned traffic in the field is under development (Lassen et al., 2012; Stettler et al., 2012). Finally, our work comprises European-wide maps of the wheel load carrying capacity for selected soil water contents, tyre types, and depth of allowable soil deformation. Novel interactions between farmer consultants, agricultural engineers, soil scientists, and experts in soil data bases have created the basis for this important delivery for national as well as super-national public authorities (e.g. the EU Joint Research Centre).

The presentation will include an introduction to risk assessment of soil compaction in general terms as well as specific examples from the work in progress.

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Assessing soil compaction risk using a Bayesian Belief Network

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Abstract

Soil compaction is considered a serious threat, especially in highly managed agricultural systems. The adverse effects associated with soil compaction are many and include decreases in crop yield and increasing management costs. There is growing evidence that compaction, particularly of subsoils where amelioration is difficult, has been exacerbated by trends towards using larger and heavier machinery. Methodologies for assessing soil compaction risk are needed to reduce this threat and protect soil quality for future generations. An assessment of the risks, however, is hampered by the complex nature of soil compaction, which results from the sometimes poorly understood interaction of various soil physical properties, climatic factors and land management practices. We present here a Bayesian Belief Network (BBN) for assessing soil compaction risk. BBNs are graphical probabilistic models that are effective for integrating quantitative and qualitative information, and thus can strengthen decisions when empirical data are lacking. The developed BBN combines analytical and morphological data from standard soil surveys with qualitative expert knowledge to estimate the soil compaction risk. The BBN structure follows a standard risk assessment approach, where the risk is quantified by combining assessments of vulnerability and exposure. The soil's vulnerability to compaction is determined from inherent soil and site characteristics and from climatic factors influencing the soil water content, while the exposure is estimated from an evaluation of the stresses inflicted by land management. The BBN is applied to quantify and map the risk of compaction for Scotland using data from the National Soils Inventory of Scotland.

From soil stress to soil deformation: current state of the research

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Soil compaction (i.e. reduction of soil porosity) due to agricultural field traffic is one of the major threats to sustainable soil quality. Compaction not only reduces pore volume, but also modifies the pore geometry. This affects important soil properties and functions, e.g. soil hydraulic properties, gas-phase transport or root growth. Soil compaction is therefore associated with many environmental and agronomic problems, such as erosion, leaching of agrochemicals to receiving water bodies, emissions of greenhouse gases and crop yield losses.

The soil compaction process can be divided into the following steps (Fig. 1). First, stress is exerted on the soil surface by agricultural machinery (e.g. by a tyre). Second, stress is propagated into the soil. Third, soil deforms as a reaction to the stress, whereupon the deformation is dependent on the mechanical strength of the soil. Finally, the deformation of the soil leads to a modification of the soil structure and soil pore system. However, we have to be aware of that these four steps are interrelated: the stress-strain behaviour of soil influences the stresses at the soil surface and the stress propagation, deformation of the soil pore system changes soil water potential which affects soil strength, etc.

The aim of this lecture is to give an overview of the current state of the research in the chain of cause presented in Fig. 1, with focus on stress propagation and stress-strain relationships. Knowledge of stress propagation and information of relationships between stress and deformation (stress-strain relationships) are needed for two purposes. First, in order to understand the relationships between cause (soil stress due to mechanical loading) and effect (changes in soil pore functioning). And second, to develop prediction models and decision support tools that can help farmers in prevention of soil compaction.

Two questions are of major interest: 1) what are the stresses at a certain point in the soil? And 2) how does the soil react to these stresses (i.e. does the soil deform under the imposed stress state, and, if so, how much)?

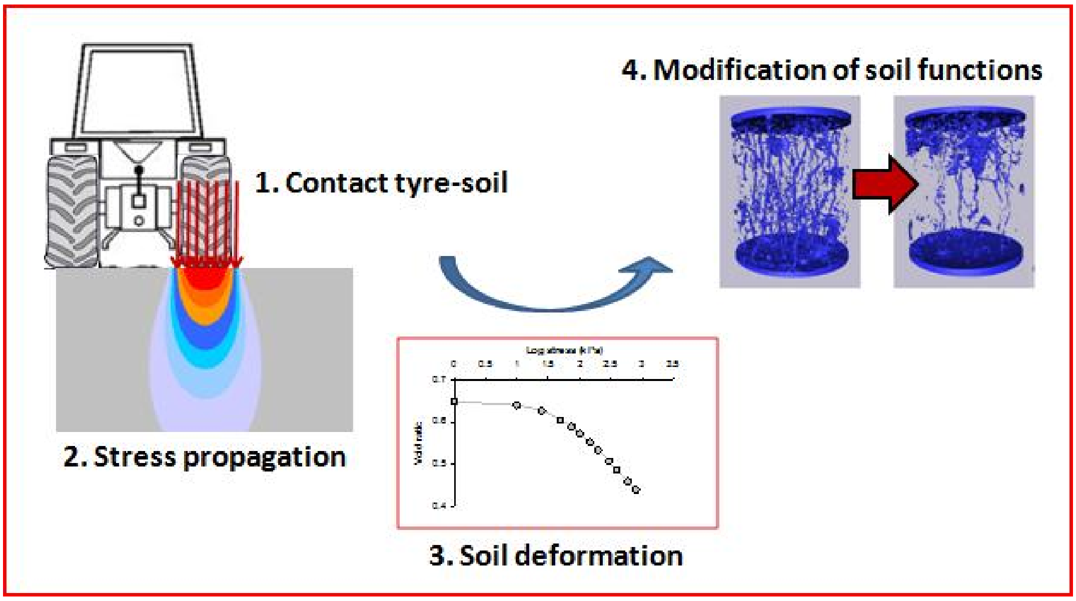

Figure 1. Concept of the chain of cause from soil stress to soil deformation and modification of soil functions.

Stress propagation in agricultural soil is typically modelled based on the problem of a normal loading of the surface of an isotropic elastic halfspace, for which the analytical solution is due to Boussinesq (1885). Most often, the equation of Fröhlich (1934) is used, which allows the alteration of the decay pattern of the vertical stress due to Boussinesq's solution by introducing a "concentration factor". Reasonably good agreement with soil stress measurements are obtained, although the basic model assumptions (elasticity) are not met by soil. Numerical solutions such as finite element models (FEM) that can deal with non-linear elastic, plastic and viscous soil properties are relatively little used in soil compaction research. One reason could be that they require much effort for a thorough characterization of the mechanical properties based on soil testing. Approaches from granular matter science, which are incorporated in distinct element models (DEM), are hardly used in soil compaction research to date. However, we advocate that both FEM and DEM should be used in soil compaction research more frequently, especially to address fundamental questions such as "how is stress transmission affected by soil strength".

Soil strength is derived from stress-strain relationships. Strength is defined as the critical stress below which strain is reversible. Precompression stress is generally accepted as compressive strength. However, the precompression stress is controversially discussed in the literature: while it is used in soil compaction risk assessment (Horn and Fleige, 2009), it is shown that its determination is biased by mathematical artefacts (Keller et al., 2011) and that irreversible strain is observed at stresses below the precompression stress (Kirby, 1994; Keller et al., 2012). Reasons for the latter may be found in the time (loading rate) and scale-dependency of soil strength. Therefore, we call for a re-evaluation of the precompression stress concept.

Only few studies address the quantitative relationships between soil deformation and soil functions. Exceptions are e.g. the work of Assouline (2006a, b), who proposed empirical models for predicting the effect of an increase in bulk density on water retention characteristics and hydraulic conductivity, or the work of Dexter et al. (2008), who present empirical relationships between bulk density and characteristics of the water retention curve. Still, our knowledge on impacts of soil deformation on the soil pore architecture and associated functions is very limited.

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Development of a way to determine the physical recovery potential of compacted subsoils

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Introduction

Subsoil compaction is especially problematic because it often cannot be ameliorated by cultivation (Jones et al., 2003; Gregory et al., 2007). Kuan et al., (2007) report that despite the negative impact of compaction on soil physical properties, some soils have an inherent ability to recover partially, particularly in their upper horizons.

Soil resilience is reported to be a key component of environmental sustainability. Kuan et al. (2007) define soil resilience as the ability of a soil to recover from different external stresses that may occur through agricultural and industrial land use. In literature soil resilience is defined in many different ways (e.g. Lal., 1993; Kay et al., 1994; Seybold et al., 1999; Tobias et al., 2001). For this research soil resilience is defined as: “the capacity of a system to continue to function without change throughout a disturbance and resilience is measured by the rate and level of recovery from a disturbance” (Seybold et al., 1999.) Research by Griffiths et al. (2005) has shown that the resilience of a single soil to physical and biological stresses varies considerably and that biological and physical resilience in soil can be interdependent properties.

One of the problems that arises from literature is that currently no standard method of routinely assessing or quantifying soil resilience is available (Lal, 1997). Therefore Kuan et al. (2007) stress that the development of practical methods of assessing soil resilience is required, as this would provide a means of predicting the long- and short-term consequences of soil disturbance on a given site, such as compaction (O’Sullivan et al., 1999) and soil management (Giller et al., 1997).

The main objective of the research presented is to develop a method to quantify, for clayey and loamy soils, what the rate of (potential) physical recovery is by shrinkage. Thereby trying to answer the question whether clayey and loamy soils in the Netherlands can recover from (subsoil) compaction and subsequently at which rate.

Methods and Materials

Measurements were performed on 5 locations in the Netherlands with loamy and clayey soils. We concentrated on the ploughpan. To determine the state of compaction infiltration rate, saturated hydraulic conductivity, air filled pore volume, soil penetration resistance and dry bulk density were measured. Large samples with a height of 10 cm and a diameter of 19 cm were used to determine the saturated conductivity Ksat in the laboratory. After sampling the Ksat samples were saturated during 2 weeks before the Ksat was measured.

To determine the potential recovery by shrink and swell we focussed on Ksat. After the determination of Ksat the samples were dried out at the air up to a water suction of 80 kPa. Then the samples were saturated during two weeks. After that Ksat was measured again.

Results and Discussion

About 50% of the considered subsoils were overcompacted in the sense that Ksat was smaller than the threshold value of 10 cm/day (Lebert et al., 2007). After a shrink swell cycle still about 50% of the samples had a Ksat < 10 cm/day, however, extreme low Ksat's increased and several Ksat's > 10 cm/day decreased below 10 cm/day. Several samples of a location with clayey soil samples were loosened by the swell cycle, so recovering from compaction. However, the Ksat of these samples decreased and Ksat became smaller than 10 cm/day.

Conclusions

The findings presented in this research indicate that shrinkage and swell have in general positive effects on soils to recover from subsoil compaction, however, not in all cases and more research is needed.

It should be noticed that the research performed is just a first step in the development of a method to determine the soil physical recovery potential of compacted subsoils. Further research is required to make it a standard method.

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Crop responses to soil compaction

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Abstract

An increasingly large amount of wheel traffic, from a variety of heavy machines and transporters, is progressively more used for management and harvesting of crops. Evidence is presented to indicate the interactive relationships between the amount of soil compaction and crop performance and yield. Research has shown that any deterioration in soil and subsoil structure brought about by traffic leads to impaired root growth, water and nutrient uptake, protein content and crop yield, to a greater extent in dry than wet growing seasons. The reduced nitrogen uptake by crops in compacted and high N fertilized soil induces a hazard of denitrification and leaching. The adverse crop responses are more pronounced in soils with higher clay content. The deformations in general shape and cells of plant roots imply that strength distribution around the roots is more uneven in compacted than uncompacted soil. The influence of soil compaction on crops can be moderated by development of biopore system using tap-rooted crop species. The role of root-to-shoot signalling for plant adaptation to dense soil is discussed.

Introduction

Soil compaction is one of the major problems facing modern agriculture. The immense majority of soil compaction in modern agriculture is due to vehicular traffic. An important component of progressive subsoil damage is the increase in weight of farm machinery in recent decades (Håkansson, 2005; Schjønning et al., 2009). Compaction influences crop growth and yield by changing important soil physical and chemical properties. Effects of soil and subsoil compaction on crop responses in relation to growth stage, weather and climatic conditions, fertilizer applications will be presented.

Crop emergence and establishment

The main soil physical conditions influencing crop growth before establishment include: water and oxygen availability, strength and temperature of seedbed layer at emergence and soil below during later growth. Their effects are related to climatic conditions. In temperate regions, soil strength is frequently the critical stress (Whalley et al., 2008). Excessive soil strength above developing seedlings can be induced by soil compaction due to machinery traffic at seedbed preparation and sowing. The influence of seedbed strength on crop establishment can vary greatly in terms of soil aggregation and subsequent pore size distribution (Håkansson, 2005).

As shown by Atkinson et al. (2009) soil structures with larger pores are responsible for reducing establishment due to mostly poor soil-seed contact and lack of water and nutrient capture from large pores. Therefore presswheels and rolling are used to increase soil seed contact and final emergence (Håkansson et al., 2002).Optimum structural conditions for establishment occurred between ranges for macroporosity of 10–19% and average pore size of 8–12 mm^2. In dry surface seedbed layer, good crop emergence of small grain crops can be achieved, when the seed was placed directly onto a firm seedbed base and was covered by a 4 cm deep seedbed with >50% aggregates <5 mm (Håkansson et al., 2002). In the cold and wet climate limited the early root and shoot growth can be a resultant of low seedbed temperatures and/or oxygen deficiency while in hot climates of high temperatures and/or high soil strengths. Moreover, the conditions for establishing crops in compacted soil can be indirectly affected by reduced the number of workable days due to poor drainage (Schjønning et al., 2009)

Established crops

Most important soil physical factors influencing growth of roots and shoots of established crops include water status, penetration resistance and aeration. The penetration resistance of 3 MPa and air-filled porosity of 10% v/v are usually regarded as critical for plant growth. The range of matric potential, in which aeration and mechanical impedance do not limit *crop* growth, termed as least limiting water range (LLWR) (Da Silva et al., 1997) becomes narrower with increasing soil density (Håkansson and Lipiec, 2000). The use of the degree of compactness (i.e. ratio of the actual bulk density to a specified reference bulk density for the same soil, obtained by static load of 200 kPa when the soil is wet, Håkansson, 1990) instead of bulk density enhances the performance and applicability of the LLWR by reducing differences in its values between different soil types (Da Silva et al., 1997; Reichert et al., 2009). In coarse-textured soils, root growth may be further restricted by rough surface of the sand particles, which resist particle displacement by slippage (Gliński and Lipiec, 1990).

Response of crop yield to compaction is most often parabolic with the highest yield obtained on moderately compacted soil (Håkansson, 2005; Czyż, 2004; Reichert et al., 2009). However, in soil of relatively high initial soil compactness under droughty climatic conditions the yield can decrease with increasing soil compaction (Lipiec and Hatano, 2003).

In studies of Whalley et al. (2006, 2008) the yield of wheat was linearly related with soil strength and accumulated soil moisture data during growing season. There was a reduction in yield of 336-372 g m^{-2} for an increase in topsoil penetration resistance (PR) of 1 MPa. A highly significant negative relationship between PR and maize grain yield (reduction by up to 33%) and harvest index was also recently observed in variously textured compacted soils by Gregorich et al. (2011). In wet and compacted soil, crop yield can be reduced due to deficient soil aeration (Czyż, 2004) and associated low transpiration, shoot growth rates, wilting, leaf epinasty and senescence and premature termination of growth (Gliński and Stępniewski, 1985).

Soil compaction can decrease nodulation efficiency of the nodules in fixing nitrogen, N uptake and subsequent yield in legume crops (Sweeney et al., 2006; Siczek and Lipiec, 2011), protein content in annual crops (Alakukku, 2000; Siczek and Lipiec, 2011) and sugar content in sugar beets (Birkás, 2008). In well-structured and fine-textured soils, the negative effects of soil compactness can be partly compensated for by development of a continuous macropore system (Lipiec and Hatano, 2003).

Effect of soil type

Studies conducted under the same weather conditions showed that crop responses to compaction are considerably affected by soil type and the associated differences in soil texture and structure. In several experiments compaction-induced yield reductions were negatively correlated with clay content (Håkansson et al., 1988; Lapen et al., 2002; Gregorich et al., 2011) and were attributed to increasing soil strength and relative compaction (Gregorich et al., 2011). The negative effect of compaction on crop growth was depressed in soils resistant to compaction that can be affected by surface roughness of the grains in sandy soils, stiff aggregates in fine-textured soils (Horn et al., 2003; Alaoui et al., 2011) and intrinsic internal strength e.g. in rendzinas and other calcareous soils (Batey, 2009).

Weather effects

The effect of a given level of compaction is related to both weather and climate (Lipiec et al., 2003; Birkás, 2008; Batey, 2009). Negative effect of excessive soil compaction on barley yield was mostly reflected in years with unfavourable sowing-shooting weather conditions (scarce rainfalls, high sunshine and air temperature) and associated high soil strength on (Lipiec et al., 2003). This interactive effect is primarily important in predicting crop yield of coarse-textured soils where strength problems are enhanced by low available soil water content and rate of the soil water movement deeper in the soil profile (Busscher et al., 2001). In wet growing seasons insufficient aeration can be of importance (Lipiec et al., 2003; Czyż, 2004).

Effect of nitrogen application

In general, nitrogen uptake is reduced by soil compaction due to lower accessibility for plants (Håkansson, 2005; Gregorich et al., 2011). The larger applications of fertilizers, in particular nitrogen, are practiced on compacted soil to overcome crop yield losses. However, the reduced N uptake during the growing season and consequent high post-harvest soil N levels in compacted soils induce a risk of further N loss by denitrification or leaching (Alakukku, 2000; Gregorich et al., 2011) and increase production cost (Hamza and Anderson, 2005). This effect can be enhanced by clay content (Gregorich et al., 2011).

Plant roots

A common response of root system to increasing compaction level is a decreased root size, retarded root penetration and smaller rooting depth. Decreased root size results in greater distances between the neighbouring roots and leads to reduced water and nutrient uptake and crop yield (Lipiec and Hatano, 2003; White and Kirkegaard, 2010). The root response to high soil strength depends on the presence and distribution patterns of pores having diameter equal to or greater than the root tip (approximately 200 μm). A soil matrix with macro-pores will offer greater potential for undisturbed root growth because the roots can by pass the zones of high mechanical impedance (Lipiec et al., 2003).The percentage of roots grown into existing pores and channels increases in deeper and stronger layers where they can be the only possible pathways for root growth. The preferential root growth into macro-pores (Lipiec and Hatano, 2003; White and Kirkegaard, 2010) will lead to increasing critical limits of soil compactness (Etana et al., 1999; Håkansson and Lipiec, 2000) and soil strength. The larger pores are also beneficial in poorly aerated soils since they drain at higher water potential (less negative) and remain air-filled for longer compared to smaller pores. This results in decreasing critical values of air-filled porosity even though part of the soil matrix can be anoxic (Zausig et al., 1993; Håkansson and Lipiec, 2000).

Bio-pores created by roots can be used as low resistance pathways by the roots of the following crops. It has been suggested that thicker tap roots compared to thinner roots of fibrous-rooted species better penetrate compacted soil (Chen and Weil, 2010) and therefore forage radish and rapeseed can be expected to perform better than rye when used as a biological tillage tool (Chen and Weil, 2011). The authors reported that rye as a cover crop providing a thick mulch in combination with forage radish could allow both' biological subsoil tillage' and the water conservation under the stand of the subsequent summer crop (Chen and Weil, 2011).

Reduced root growth of plants in compacted regions results in lower total water uptake despite increased water uptake rate (per unit of root) due to a greater root–soil contact and to a higher unsaturated hydraulic conductivity. Similarly, greater nutrient inflow rate per unit length and root-soil contact area without additional nutrient application were not sufficient to compensate for reduced total nutrient uptake (Lipiec et al., 2003). Soil compaction also reduced crop water use efficiency due to delayed soil water extraction at depth (Radford et al., 2001).

Strong environments in compacted soil are frequently reflected in different anatomical deformations (White and Kirkegaard, 2010; Lipiec et al., 2012). The primary responses of roots to soil compaction were invaginations and associated deformation of root cells (Lipiec et al., 2012). These responses indicate that the strength of the local environment around the roots is more heterogeneous in compacted than in uncompacted soil. Recent advances in the thin section technique of roots with surrounding environment and non-invasive techniques, including X-ray micro-tomography with high spatial resolution allow more detailed examination of local changes in soil structural pore space characteristics due to soil deformation (Peth et al., 2010; Vogel et al., 2010) and soil-root interface (Gregory et al., 2003).

Subsoil compaction

A series of long-term field trials with subsoil compaction caused by heavy vehicles was carried out in an international collaboration in the moist, temperate climatic zones of northern Europe and North America (Håkansson, 1994, 2005). The results indicated that yield responses to soil compaction in plough layer lasted for five years, the 25-40 cm layer compaction effects were alleviated in a 10-year period whereas the compaction effects on layers deeper than 40 cm were persistent in spite of annual winter soil freezing. The mean crop yield reduction was 2.5% and varied considerably between sites, years and crops. For example maize yield reduction due to persistent subsoil compaction due to high axle load was 6% in Minnesota and 12% in Quebec (Voorhees, 2000) whereas only slight yield effects of sugar beet was observed in Sweden after use of a heavy self-propelled six-row sugar beet harvester (Arvidsson, 2001). Alakukku (2000) reported that the yield reductions were greater in wet than dry growing seasons and concomitant reduction of rooting depth resulted in lower harvested nitrogen Schjønning et al. (2009) indicated that so far obtained results on subsoil compaction effects mostly relate to wheel loads of ~50 kN, which was considered an extreme load when the international experiment was planned in the early 1980s. However, currently wheel loads as high as 120 kN are found for some machines (e.g. sugar beet harvesters). This needs to be included in further studies.

Root-to-shoot signalling

Frequently soil compaction results in reduced both shoot growth and stomatal conductance, particularly in droughty and wet periods (Lipiec and Hatano, 2003). Ali et al. (1999) reported that the increased leaf stomata resistance occurred even before a measurable change in leaf water potential. These responses were correlated with enhanced ethylene evolution in tomato plants (Hussain et al., 1999a) and xylem sap ABA concentration in barley plants (Hussain et al., 1999b). In study of Tardieu et al. (1992) ABA xylem-concentration was associated with matric potential rather than soil strength. Bingham (2001) indicates that similar systems of signalling are considered to be involved in the response and adaptation of leaves to soil compaction or drying although they may engage a different set of signal molecules.

Concluding remarks

Main soil physical factors influencing growth of roots and shoots in compcted soil include water status, penetration resistance and aeration. Response of crop yield to compaction is most often parabolic with the highest yield obtained on moderately compacted soil. In temperate regions the crop yield was frequently linearly negatively related with soil strength whereas in wet zones or growing seasons with insufficient aeration. Compaction-induced yield reductions were enhanced by clay content. Excessive soil compaction leads to reduced crop total water and nutrient uptake, water use efficiency and protein content. The negative effects of soil compaction can be partly compensated for by development of a biopore system. Reduced crop N uptake and associated high post-harvest soil N levels in compacted soils induce a risk of N loss by denitrification or leaching. The shapes of roots and anatomical deformations indicate that the strength around the roots is more heterogeneous in compacted than in uncompacted soils. Responses of stomatal conductance indicate root-to-shoot signaling in compacted soil. Subsoil compaction results in long-term or even permanent reduction of crop yield and lower harvested nitrogen. Further studies of soil compaction effects should include: (i) crop response to currently applied high wheel load traffic, (ii) effects of multiple stresses from different parts of the root system on shoot growth and (iii) opportunities for increased use of main and cover crops with high capacity to penetrate strong soils.

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Sensitivity of different crops to soil compaction

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Introduction

Compaction is generally regarded as negative for crop production, mainly due to effects on root growth and soil aeration. However, it is also generally recognized that some recompaction after soil loosening is beneficical for crop yield. Different crops have different sensitivity to compaction but there are few systematic studies on this subject. The present study aimed at analyzing results from field experiments with topsoil compaction including different crops. The results were compared with yield data from experiments with shallow tillage. The hypothesis was that crops which reacted negatively to compaction also would give lower yield in a tillage system without mouldboard ploughing.

Methods

A large number of field experiments concerning topsoil compaction were carried out in Sweden, mainly during the period 1970-1977. In these, different levels of tractor traffic were applied in connection to sowing. Crop yield was determined as a function of the degree of compactness, which is the soil bulk density in percent of a reference value (Håkansson, 1990). In the present study, yield data was analyzed concerning the effect on different crops.

Yield data were also analyzed from 825 experimental years with shallow tillage compared to mouldboard ploughing for the period 1986-2011.

Results and discussion

Crop yield of barley as a function of the degree of compactness is shown in Fig. 1. Although yield was lowest at the highest levels, the correlation was week. An example of crop yield of different crops as a function of applied traffic is presented in Fig. 2. Barley and spring wheat was less sensitive to compaction than oats and peas.

Relative yield for shallow tillage compared to mouldboard ploughing is presented in Table 1. Generally the cereal crops had higher relative yields than the dicotyledons.

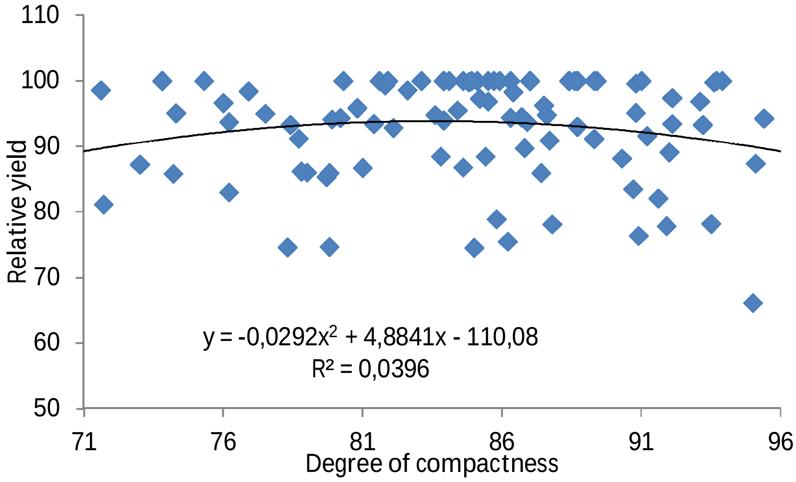

Figure 1. Relative yield of barley in experiments with different levels of compaction. In each individual experiment, relative yield=100 in the treatment with the highest yield.

Conclusions

Cereal crops was relatively insensitive to soil compaction, especially wheat and barley, while oats was slightly more sensitive. Dicotyledons, especially peas, potatoes and winter oilseed rape reacted more negatively to compaction. The results from experiments with application of extra traffic were consistent with results from experiments with shallow tillage.

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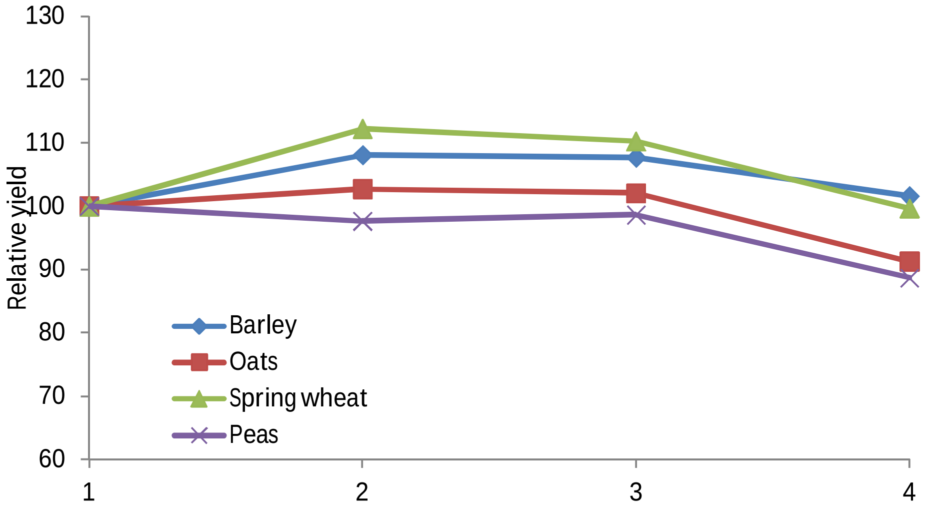

Fig. 2.Relative yield in experiments with different levels of applied traffic. 1=No traffic, 2=1 pass with light tractor, 3=1 pass with medium-sized tractor, 4=3 passes with medium-sized tractor.

Table 1. Relative yield of different crops in ploughless tillage (mouldboardploughing=100). Results from experiments 1986-2011

Crop	Rel. yield (ploughing=100)	Number of experiments
Winter wheat	97	284
Spring wheat	102	44
Barley	100	241
Oats	98	126
Winter oilseed rape	96	47
Spring oilseed rape	100	34
Peas	90	15
Potatoes	95	11
Sugar beet	95	23

Changes of plant growth and some soil properties due to the compaction on grassland

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Identifying the vulnerability of soils to compaction damage is becoming an increasingly important issue when planning and performing farming operations. The grassland is believed to be stable because of the perennial plant cover and to the root reinforcement. Vegetation is able to provide stability or improve the bearing capacity of soils in which they grow (Cofie et al., 2000) and reduce the stress transmitted to deeper depths (Stahl et al., 2009). The strength of rooted soil is higher due to a combination of soil and root strength as well as the interface strength between soil and roots (Mickovski et. al 2009). However, the production of perennial forage crops demands a great intensity of traffic (fertilizer and slurry spreading, rolling, harvesting and transport) especially during crop harvesting operation. Aim of the current study was to investigate the soil compaction effect on some soil physical-mechanical properties and productivity in farm used grassland as well in field experiment.

The field experiment to study the effect of soil compaction on some grassland species have been established on sandy loam Haplic Luvisol (siltic) at the experimental station of the Estonian Agricultural University in Rõhu in year 2007. Trial factors were: 1) plant species; 2) cuts – three cuts per year; 3) soil compaction – after every cut by 3 ton tractor by two tyre-to-tyre passes. Plant biomass samples were collected before every cut. Soil samples to measure soil bulk density, porosity (air filled pores, plant available and unavailable water content) and water permeability were collected after every cut after compaction. Soil samples were taken by 100 cm3 steal cylinders from 0–5 cm and 20–25 cm depth. The collection of the samples from the farm fields followed the same schema as in experiment, but there the samples were collected from tyre tracks and between the tracks.

The results revealed significant changes in soil properties due to the compaction in field experiment and in farm fields. The changes were detectable mainly in the top 5 cm soil after first cuts, but also in 20 cm deep soil after third cut and continues compaction with the years. Compaction had the most negative effect on Phalaris arundinacea and Lolimum perenne root and shoots growth and less effect on Dactylis glomerata and Bromus inermis. Bromus inermis had the highest root volume and under it, the lowest values of penetration resistance and bulk density were detected in compacted and un-compacted soil compared to the other investigated species. From legumineous compaction had less effect on Medicago sativa than Trifolium pratense as Medicago roots penetrated compacted layers. The soil precompression stress and cohesion was lower on the un-compacted area than on the compacted one. Significant decrease of air and water permeability was detected after third cut in all investigated depths in field experiment and in farm field soils. Average reduction of shoot mass due to the compaction was 20% in dry years and up to 50% in rainy years. However, on gravel rich sandy soil the increase of shoot mass was detected due to the moderate compaction in dry year as the amount of macropores decreased and amount of medium and small pores increased and with that the plant available water in the soil.

The study was supported by Estonian Scientific Foundation grant No 7622.

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Effects of harvest time (early winter or spring) of reed canary grass on track depth, penetration resistance and plant growth and development

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Reed canary grass grown for fuel is most often harvested in spring, when substances causing corrosion and sintering of ash have been leached from the biomass during winter.At the experimental farm of Röbäcksdalen, SLU Umeå, several fields of reed canary grass were established in the late 1990's. After some years with good harvests the yields declined2004-2007. The reason for this is not known and one reason could be harvest damages.Harvest of reed canary grass on silty soil, as atRöbäcksdalen, can often damage the sward causing deep tracks. The harvest has to be conducted before the new crop has grown too much and on silty soils that have been frozen in winter the growth sometimes starts before the soil is really dry enough for tractor traffic. We hypothesized that, if the harvest was made in early winter instead, when the soil had started to freeze, there would be less tractor damage and higher yield the following season.

An experiment was conducted in a reed canary grass field at Röbäcksdalen experimental station, SLU Umeå 2008-2009. The crop was established 1998 so the crop was 10 years old at the start of the experiment. Two 25 m wide strips were harvested with a mower on November 19 2008 when the top soil was frozen. The harvested material was chopped and removed from the field the following day. The following spring, May 19 2009, the remaining reed canary grass on the field (also on two 25 m wide strips) was cut with a mower and harvested with a square baler weighing 7.5 tons. The amount and depth of the tractor tracks, penetrometer measurements (Eikelkamppenetrologger) and small plot harvests were assessed along two lines 150 m apart, across the field. The harvested biomass from both cutting of 50 x 50 cm plots along two lines in the field and the two field harvests are shown in Fig. 2. Equal amounts of dry matter per hectare were harvested with late autumn harvest and spring harvest. However in November the water content of the biomass was 72% compared to 20% in May. The energy value of the biomass harvested in autumn thus was very low. There were more tractor tracks in the spring harvested area, and the tracks were also deeper. In the spring harvested area 58% of the surface was tracks, with a mean depth of 5.2 cm compared to 44% tracks, 2.3 cm deep in the autumn harvested area.

There were no differences in penetration resistance in tracks compared to between tracks (Fig. 1). However, significantly more pressure was needed to push down the penetrometer into the soil in the autumn harvested area compared to the spring harvested area. This was probably due to a faster drying of the soil in the autumn harvested area because of lack of biomass cover and an earlier growth of the reed canary grass. When small plots were harvested after the growing season 2009 there were no significant differences in biomass dry matter between the two harvesting strategies. However, there was more biomass between tracks than in tracks, and also more straw biomass even though the straw percentage in the biomass was not different in tracks and between tracks (Fig. 2).

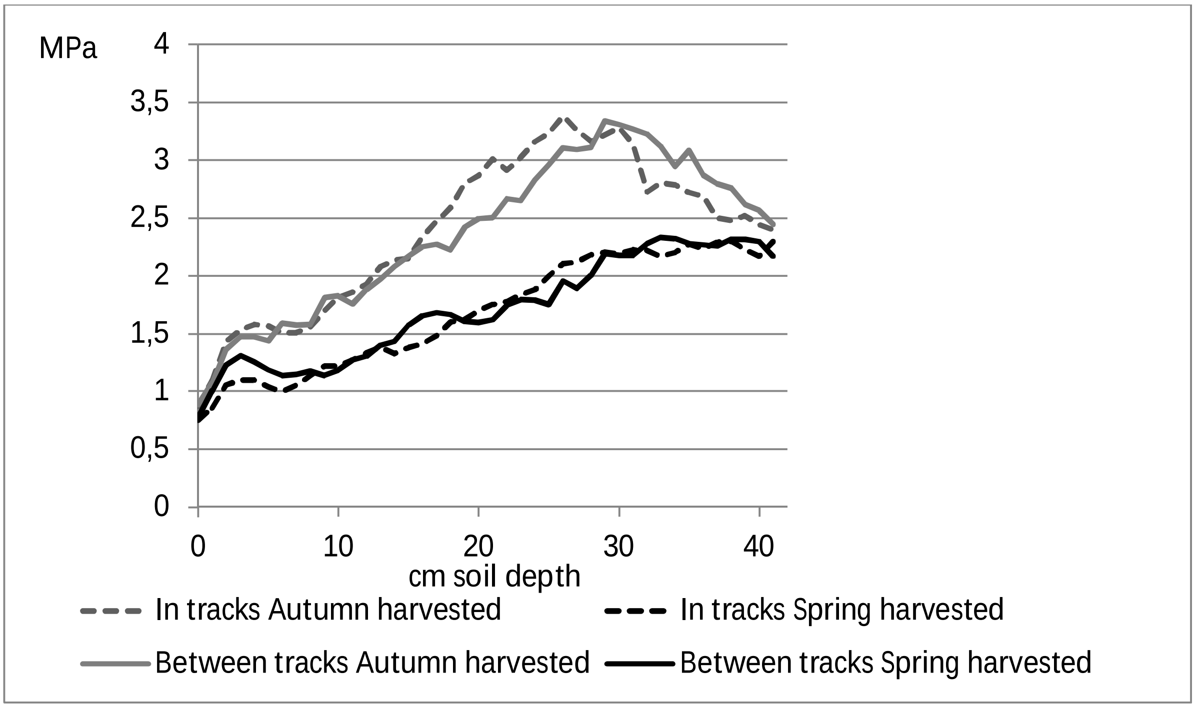

Figure 1. Penetration resistance in spring 2011

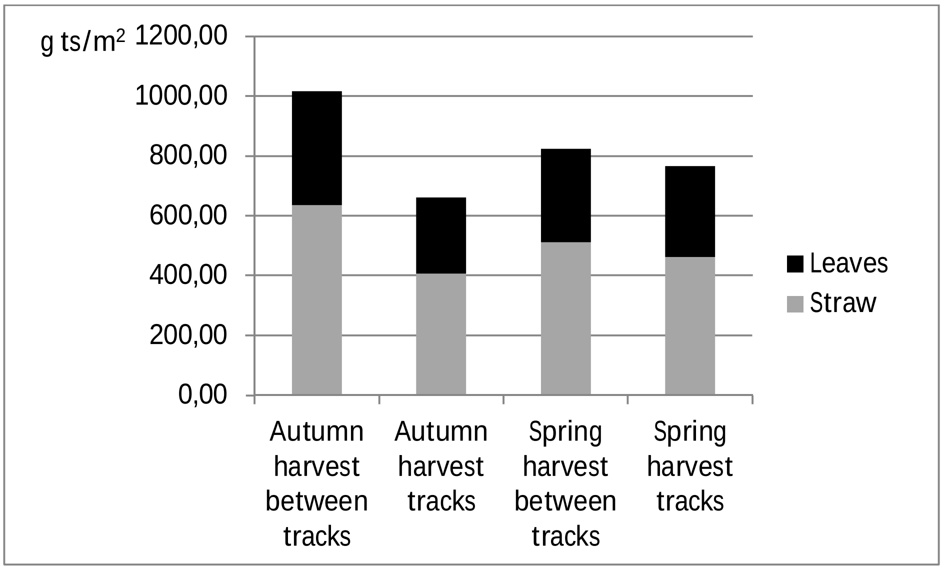

Figure 2. Average yield of aboveground biomass from sampling of 50 x 50 cm plots along two lines across the field.

Although we could not show any yield benefit of the autumn harvest method it was obvious that spring harvest with heavy equipment caused deep tractor tracks. In later years a modification of the spring harvest method has been developed: The biomass is cut in the autumn and put in strings. These strings are then harvested in spring. Our study confirms that avoiding extensive tractor traffic in spring by this method is a good strategy.

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Soil compaction and preferential solute transport

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The effects of compaction on soil water balance, root zone aeration, drainage and crop growth are well documented and well understood. In contrast, much less is known of the effects of compaction on transport processes in soil, and in particular how it affects leaching of agricultural pollutants such as phosphorus and pesticides to groundwater and surface waters (via subsurface drainage systems). Preferential transport in soil macropores dominates leaching of such reactive solutes (Jarvis, 2007) and compaction is known to primarily reduce macroporosity in soil. However, the effects of compaction on leaching in macroporous soils have not yet been investigated.

Based on some simple theoretical considerations the hypothesis is put forward that, depending on initial and boundary conditions, moderate compaction should increase preferential solute leaching, since near-saturated hydraulic conductivity is reduced. More severe compaction will tend to reduce leaching due to restrictions in macropore continuity, but surface runoff will then negate any benefits.

We are testing this hypothesis in the Nordic project POSEIDON. Some preliminary results are presented for a field experiment at Brahmehem in the south of Sweden that show that persistent subsoil compaction reduced saturated and near-saturated hydraulic conductivity and increased the deep penetration of brilliant blue dye.

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Subsoil compaction of a clay soil persists three decades after heavy wheel traffic

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Introduction

Detrimental consequences of compaction in the topsoil – defined as the frequently tilled soil layer – can usually be counteracted by tillage operations. Compaction in the subsoil can only be alleviated by natural processes: drying and wetting (including shrinking and swelling), freezing and thawing, macrofauna activity, root growth. These processes are slow, and evaluation of the persistence of subsoil compaction requires long-term experiments. In the present contribution, we evaluated the persistence of compaction at 0.5 m depth in a Finnish agricultural soil, for which natural recovery after a traffic event with heavy machinery should be possible due to its textural composition and the prevailing climate at that location.

Materials and methods

The Jokioinen compaction experiment (60º 49 N, 23º 23’ E) was established in 1980 (Alakukku, 1996) on a clay soil (Vertic Cambisol according to the WRB (FAO) system). The textural composition of the soil is given in Table 1.

Table 1. Textural composition of the soil at 0.5 m depth

Clay <2 µm	Silt 2–60 µm	Sand 60–2000 µm	Organic matter	Particle density
	(g g^{-1} soil)			(g cm^{-3})
0.635	0.233	0.132	0.007	2.79

The experiment had a randomized block design with four replicate plots. The plots were 4.5 m × 20 m. Compacted plots were subjected to four repeated wheelings (track-by-track to cover 100% of the area in the plots). The machinery used in the compacted plots was a a combination of a tractor and a trailer, which showed a maximum wheel load of 79.3 kN on tandem wheels and a maximum tyre inflation pressure of 700 kPa. Control plots were not compacted. After the compaction event until sampling date (June 2010), the plots have been managed in an arable crop rotation (spring cereals) with ploughing to 0.2 m depth until 2001, and then conservation tillage methods have been used. A total of 16 intact vertical soil cores (8 cm high and 9.65 cm inner diameter in aluminium cylinders) were sampled at 50 cm depth (2 cores by treatment in each block). At the time of sampling, the soil water potential was close to -100 hPa at 50 cm depth.

The samples were first saturated then sequentially drained at -100, -300 and -1000 hPa matric potentials. Air-filled porosity, ε_a, and air permeability (as described by Iversen et al., 2001), k_a, were measured at each water potential. When drained at -100 hPa the samples were scanned with a medical CT scanner (SIEMENS Biograph 16) at 120 kV. The resolution was 300 µm in the diametric dimensions and 600 µm in the vertical dimension. Intensity histograms were analysed to perform the segmentation of the pore space and the solid phase. The CT air-filled porosity, ε_{aCT} (m^3 m^{-3}), was derived from the air-filled pore volume and the total volume of the scanned soil column used for the analysis.

Treatment effects were analysed by a mixed model taking into account the fixed effect of treatment and the random effect of block.

Results and discussion

The single heavy compaction event 30 years prior to our investigation still affected significantly the air-filled porosity and air permeability measured at 0.5 m depth (Table 2). Air-filled porosity was reduced at the three matric potentials, indicating a reduction of the macroporosity (> 30 µm equivalent diameter) as well as of the microporosity (< 30 µm equivalent diameter). The air-filled porosity derived from CT images represents the largest pores (> 300 µm diameter), and was also significantly affected by compaction (Table 2). The pores of this size were mainly related to the activity of the ecosystems engineers present in the field (macrofauna and roots), as shown by the CT images (Fig. 1). It raises the hypothesis of better living conditions in the control plots as compared to the compacted plots. Even for a heavy clay soil subjected to shrinking and swelling, compaction under the maximum tillage depth seems to be persistent. Air permeability measured at -100 and -300 hPa matric potential was very low for both treatments (Table 2).

Table 2. Average air-filled porosity, ε_a, air permeability, k_a, at -100, -300 and -1000 hPa matric potentials and average CT-derived air-filled porosity, ε_{aCT}, at -100 hPa matric potential for the two treatments at 0.5 m depth. Figures in brackets denote standard error. Different letters indicate significant differences between treatments (P = 0.05).

Matric	ε_a ($m^3\ m^{-3}$)		ε_{aCT} ($m^3\ m^{-3}$)		k_a (μm^2)	
Potential	*Control*	*Compacted*	*Control*	*Compacted*	*Control*	*Compacted*
-100 hPa	0.042a	0.019b	0.026a	0.010b	0.80a	0.02b
-300 hPa	0.053a	0.028b			1.19a	0.07a
-1000 hPa	0.077a	0.051b			84.9a	16.0b

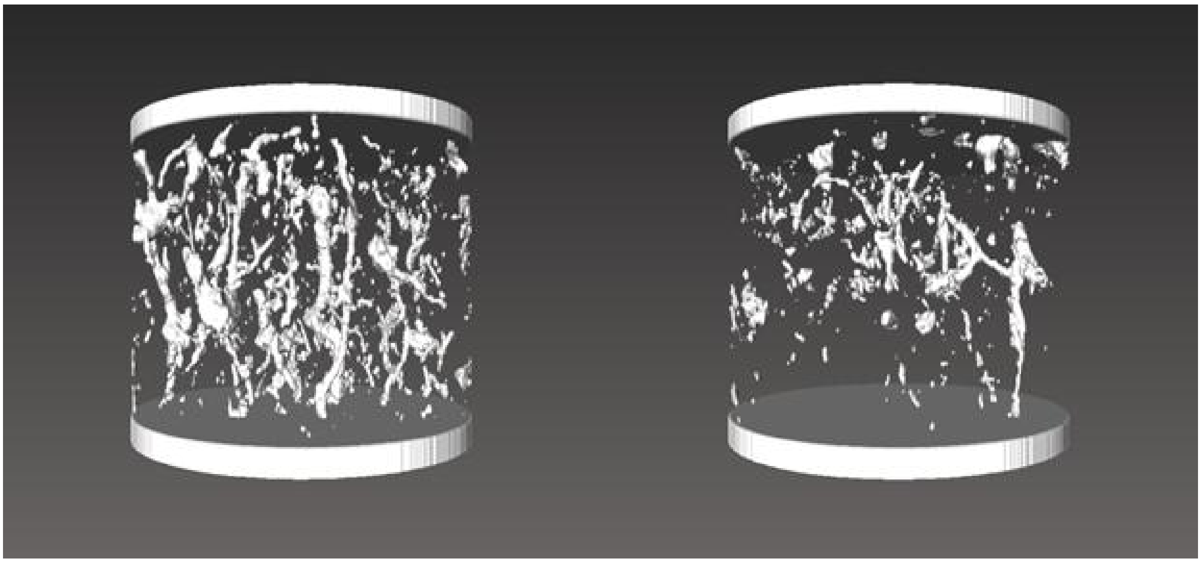

Figure 1. Example of air-filled macroporosity detectable on CT images (resolution: 300×300×600 µm) for both treatments (Left: control; Right: compacted). The two soil columns selected here showed the closest ε_{aCT} to the means presented in Table 2 for each treatment (for control and compacted: 0.0260 and 0.0095 $mm^3\ mm^{-3}$ respectively).

Conclusions

We investigated the persistence of soil compaction at 0.5 m depth in a Finnish clay soil 30 years after the experiment was established. A lower macroporosity as derived from images obtained by X-ray CT scanning, a lower air-filled porosity derived from total porosity and volumetric water content at three matric potentials from -100 to -1000 hPa, and a lower air permeability measured at the same three matric potentials indicated a persistence of subsoil compaction since 1980. The direct compaction effect on the soil physical properties seemed to influence the biological activity in the long term, as shown by the type of macropores detectable on the CT images, when the soil was used for spring cereals production using conservation tillage methods.

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Compaction along tramlines of winter cereals generates soil erosion on sloping land

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Introduction

The research is in response to the need for practical, affordable and targeted management of fields with combinable crops to help decrease the risk of losses of soil and nutrients. Silgram et al (2010) have demonstrated that for winter cereals on moderately sloping land (3–7°) compacted un-vegetated tramline wheelings account for 80% of surface run-off, suspended sediment and phosphorus losses. The aim of this work is to investigate the most cost effective and practical ways of managing tramlines to decrease the risk and amount of surface run-off and sediment transport.

Methodology

Surface run-off is monitored in replicated large hill-slope sections 100 m long by 3 m wide (Fig. 1). The research focuses on the over-winter period when soils are wet and physical protection of the soil surface from the growing crop is limited. Experimental treatments include the use of low pressure tyres and deploying a sprayer-trailed spiked-harrow. Soil physical measurements including shear strength, penetrometer resistance and water retention characteristics are determined when the treatments are applied. Run-off volume is recorded and flow proportional samples are analysed for suspended sediment and total and dissolved phosphorus and nitrogen.

Figure 1 shows a gutter buried in the soil and the tramlines leading up-hill from it. Water and sediment flowing down the tramlines is directed along the gutter to collection tanks.

Results and Discussion

From the site at the James Hutton Institute there are now one and a half winter's data. Differences exist in the soil properties between wheeled and un-wheeled areas and between soil under the tyre cleat vs the tyre casing. Run-off from the wheeled tramlines is decreased by the use of a spiked harrow resulting in decreased sediment and nutrient loss. Differences between run-off under different tyre types is less clear, but monitoring is on-going. Run-off from snow melt produced different sediment yields than run-off from rainfall. The merits of the various methods to minimise or alleviate surface compaction and the related environmental consequences will be discussed.

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Persistence of subsoil compaction and its effects on pore characteristics and gas transport

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Introduction

Subsoil compaction is recognized as an important problem in the field of agriculture and at policy level due to its persistence. However experimental data on persistency of subsoil compaction are scarce. This study examines the persistency of subsoil compaction and its effect on soil pore structure and gas transport processes. For this purpose we selected two existing field experiments with contrasting texture.

Materials and methods

The soil samples were collected from one long-term compaction experiment in Finland (Jokioinen; 60º 49' N, 23º 23' E) in June 2010 and one in Sweden (Brahmehem farm; 55º 49' N, 13º 11' E) in May 2009. The Jokioinen compaction experiment was established in 1980 (Alakukku, 1996). Compaction at Brahmehem was inflicted in 1995 (Arvidsson, 2001). The Jokioinen soil is a Vertic Cambisol, with 64% clay, 23% silt and 13% sand. The Brahmehem soil is a Mollic Endogleyic Luvisol, with 23% clay, 28% silt and 49% sand.

Both experiments had a randomized block design with 2 treatments (control and compacted) x 4 plots. Compacted plots were subjected to four repeated wheelings (track-by-track to cover 100% of the area in the plots) with machinery as indicated in Table 1. The Jokioinen plots have been managed in an arable crop rotation with ploughing to 0.2 m depth until 2001, and then with conservation tillage. The plots at the Brahmehem were managed in an arable crop rotation with ploughing to 0.25 m.

Table 1. Machinery used during the compaction event

Location	Type of machinery	Wheel	Wheel load (kN)	Tyre width (mm)	Inflation pressure (kPa)
Brahmehem	six-row sugarbeet harvester	Front	102	800 – 1050	200-240
		Rear	67.2	-	-
Jokioinen	tractor-trailer combination	Front	7.4	320	150
		Rear	27	429	250
	trailer	tandem	79.3	254	700

Intact cores of 100 cm^3 were collected at 0.3, 0.5, 0.7 and 0.9 m depths (the two lower depths only in Sweden). The cores were used to measure water retention, air permeability (k_a) and gas diffusivity (D_s/D_0) at -100 hPa matric potential. Air-filled porosity, ε_a, at -100 hPa was calculated from water retention characteristics of the soil. Treatment effects were analysed by a mixed procedure, which takes into account the fixed effect of treatment and the random effect of block.

Results and discussion

The compaction inflicted 14 and 30 years prior to sampling at the Brahmehem and Jokioinen soils, respectively, reduced air-filled porosity at -100 hPa in all depths (significant at 0.3 m at Brahmehem and at 0.5 m at Jokioinen soil; Fig. 1a and 1d). This reduction in air-filled pore space had also a considerable effect on soil gas transport function. We found a significant reduction in D_s/D_o at Brahmehem at 0.3 and 0.9 m depths, and Jokioinen at 0.5 m depth (Fig. 1b and 1e).

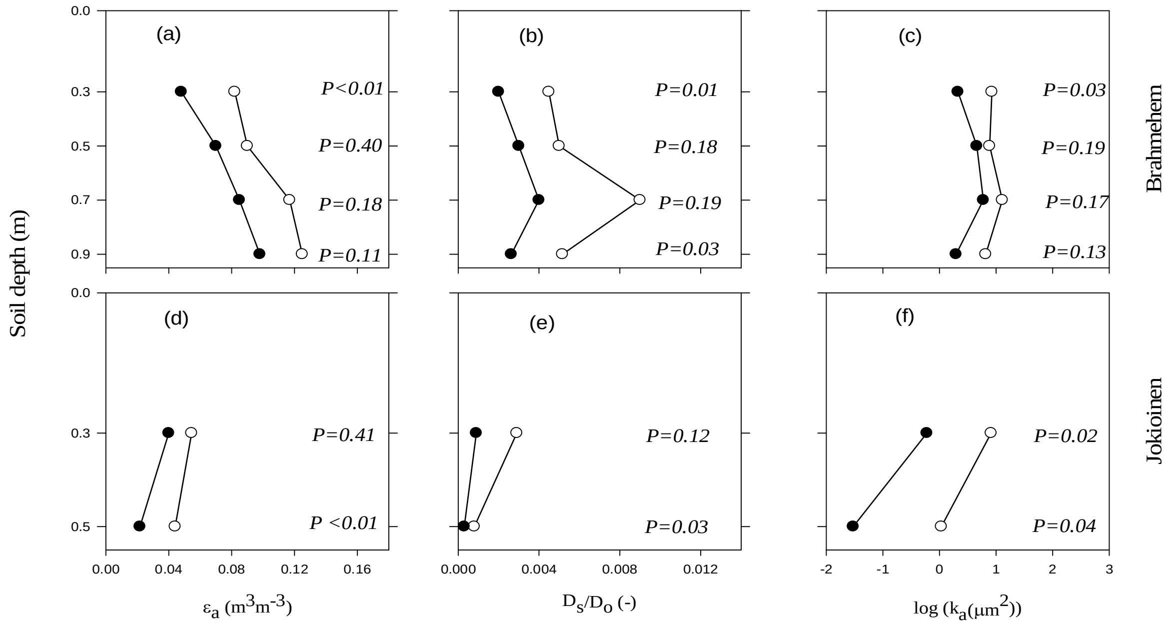

Figure 1. Air-filled porosity, ε_a (a, d), relative diffusivity, D_s/D_o (b, e) and air permeability, k_a (c, f) at -100 hPa for compacted (shaded) and control (open) soils. The values are least squares means of medians observed in four replicate blocks. P-values show results of MIXED procedure test for the differences between control and compacted treatments.

We note that the values for D_s/D_o of both soils were smaller than the lower limit for aerobic microbial activity, D_s/D_o=0.005, as proposed by Stepniewski (1980). For the loamy soil at Brahmehem, we measured consistently lower values of k_a in the compacted than in control soils at all depths, although the differences were not always statistically significant (except at 0.3 m). For the clayey soil at Jokioinen, the compaction event resulted in a considerable and significant reduction in k_a at 0.3 and 0.5 m depth. We also note that the k_a values in compacted plots were lower than 1 μm^2 ($\log(k_a)=0$), a value which reflects an effectively impermeable soil (Ball et al., 1988).

Conclusions

Compaction events 14 and 30 years prior to sampling at Brahmehem and Jokioinen, respectively, reduced ε_a, thereby affecting the soils' ability to conduct gases. This may increase the risk of anoxic conditions. Air permeability is known to be correlated to the saturated hydraulic conductivity, and our results hence also indicate that subsoil compaction may decrease drainage of water.

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Effects of persistent subsoil compaction on soil air composition and nitrous oxide emission from arable soils

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Introduction

Compaction by heavy machinery commonly impairs important functions of agricultural soils by increasing the water retention and mechanical impedance as well as slowing down the movements of water and gases in soil. As soil tillage and natural processes of soil structural development are mostly limited to topsoil, the compaction of subsoil may impair plant growth for decades (e.g. Alakukku, 1999). Concurrently, the impaired soil aeration may increase greenhouse gas emissions from soil, such as those of N_2O produced in soil by nitrification and denitrification. Soil compaction may enhance these processes by increasing the water-filled soil volume available for microbes, restricting soil aeration and impairing nitrogen uptake by plants. This study reports results on nitrous oxide (N_2O) emissions and soil air composition in two field experiments in southern Sweden and Finland, where persistent compaction effects were still found in the subsoil after 28 or 14 years after heavy wheeling.

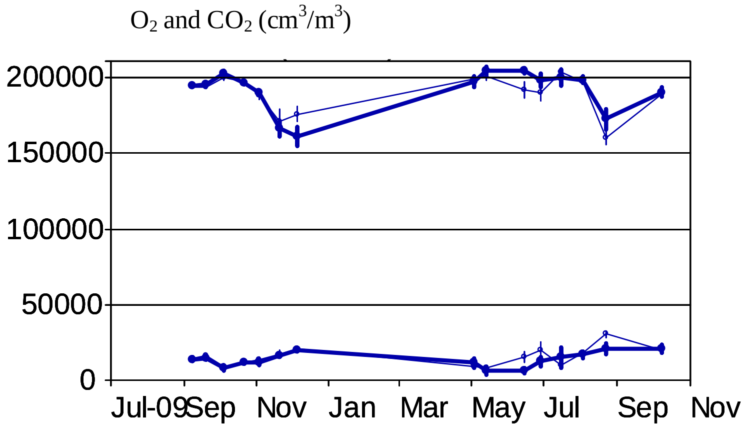
Methods

This study was carried as part of a Nordic joint research project POSEIDON (https://djfextranet.agrsci.dk/sites/poseidon-nordic/offentligt/Sider/front.aspx). The Swedish site was located at the Brahmehem Farm in Kävlinge on a sandy clay loam field with half of the plots compacted by 4 passes track-by-track with a 35-Mg six row sugar beet harvester in 1995. After compaction, the field had been managed according to the local farming practice with a 7-yr crop rotation (2009 winter wheat, 2010 sugar beet), mouldboard ploughing (c. 25 cm depth) and occasional reduced tillage (c. 10 cm depth). The Finnish site was in Jokioinen on a clay soil compacted with 4 passes track-by-track with a 19 Mg on a tandem-axle unit in 1981. After compaction, the plots selected for the present study had been under cereal cultivation. Increased penetration resistance was observed in the subsoil of both fields in spring 2009.

Samples of N_2O emissions and soil air were taken at approx. biweekly in 2009-2010 both with static chambers on the soil surface and gas samplers in the soil profile, and analysed by gas chromatography. Both fields had four replicate blocks of compacted and control treatments. Two sets of soil air samplers were installed at 15, 30, 50 and 70 cm depths in each plot, and one or two emission chambers per plot in Finland and Sweden, respectively. Soil air could not be sampled during winter. The annual emissions were calculated for the period Oct 2009 – Sep 2010. Soil moisture and temperature were monitored (5TE, Em50, Decagon Devices, Inc.) at 15 and 30 cm depths in selected plots. Weather data were taken from nearby weather stations.

Results and discussion

Compaction occasionally increased N_2O in soil air, but generally no large differences in soil water content, air composition or N_2O emissions were observed between the compacted and control treatments. In both fields, the highest water contents in spring 2009 corresponded to less than 10 vol-% air, commonly taken to indicate deficient soil aeration. Soil air data indicated better soil aeration of the sandy clay loam in Sweden than the clay in Finland. Even the lowest soil O_2 concentrations at 70 cm depth in Sweden were above 15% compared with 6-7% in Finland (Fig. 1). Deep in the subsoil, soil compaction tended to slow down the return of aerated conditions on soil drying after a period of low O_2 concentrations at the Finnish site. A somewhat similar pattern was observed in the same field in 1988 (Simojoki et al., 1991).



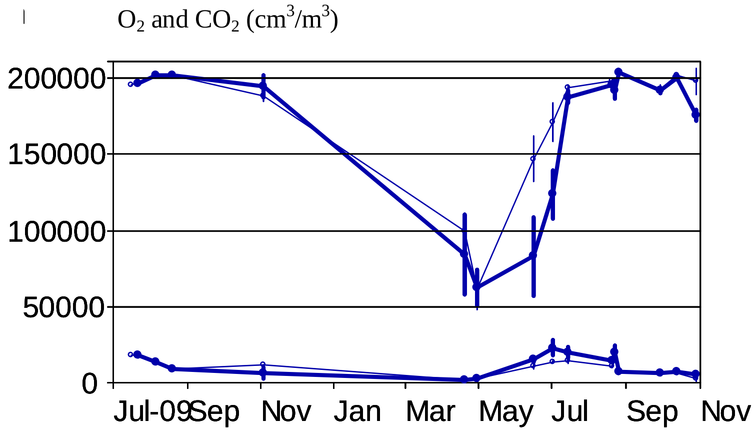


Figure 1. Concentrations of O_2 and CO_2 in soil air at 70 cm depth at the Swedish (upper) and Finnish (lower) site (thick line: compacted, thin line: control).

The annual fluxes of N_2O (mean ± standard deviation) during Oct 2009 - Sep 2010 in the control and compacted treatments, respectively, were 8.6 ± 3.7 and 9.4 ± 1.0 kg N ha^{-1} in Finland, and 10.0 ± 4.1 and 8.3 ± 3.8 kg N ha^{-1} in Sweden, with no significant differences between the treatments. The concentrations of N_2O at the depths of 15, 30, 50 and 70 cm correlated positively with the emission of N_2O from the soil in both fields (r = 0.4-0.7***). Compaction tended to increase N_2O in soil air. The oxygen concentrations in the subsoil correlated negatively with the N_2O emission, but only at the Finnish site. The results suggest that despite periods of impaired subsoil aeration and higher concentrations of N_2O in soil air, subsoil compaction does not significantly increase N_2O emissions from these soils to the atmosphere 15-30 years after compaction. This may indicate a minor role of subsoil in the production of N_2O compared with topsoil.

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Subsoil compaction effects on N_2O emissions – *In situ* manipulation experiments

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Introduction

Two *in situ* manipulation experiments were conducted to assess the impact of subsoil compaction on N_2O emission. “Fertigation” (irrigation + fertilization) was used to create optimal conditions for N transformations and denitrification in soils below the plough layer in two long-term POSEIDON experimental sites which showed persistent compaction in the subsoil <10 years after compaction treatment. The sites we irrigated with nitrogen solution in order to provoke ideal conditions fordenitrification along the entire soil column. Thereafter N_2O emissions and ancillary variables were measured at a high frequency.

Materials and methods

The experiment at Kävlinge (Southern Sweden) was conducted in 18-22 October 2010, shortly before harvest of sugar beets,the aboveground parts of which were removed priorto irrigation. 1 m^2 microplots for flux and soil sampling (8 compacted, 8 non-compacted) were fertigated with 40 mm water containing NPK fertiliser (NH_4NO_3) equivalent to a fertilisation rate of 100 kg N ha^{-1}. N_2O and CO_2emissions were measured four times per day with static chambers and soil air concentrations of N_2O and CO_2were determined daily from samples drawn from preinstalled soil air samplers at 15, 30, 50 and 70 cm soil depth. Soil $NH_4^+$and NO_3^- contents were determined in the beginning and at the end of the campaign from 0-20, 20-40, 40-60 and 60-80 cm depth. The samples for the initial values were collected nearby the microplots (in order to prevent disturbing the soil inside the frames). The campaign at Jokioinen (Southern Finland) was conducted 6-15 July 2011. The site had been used for cereal cultivation in previous years, but was unvegetatedin 2011.1 m^2 microplots (four in compacted and four in the non-compacted treatment) werefertigated with 80 mm water containing KNO_3equivalent to 100 kg N ha^{-1}. Measurements were carried out similarly to the Kävlinge campaign. In addition, identically treated areas closeby the microplots were established for daily measurements of soil NH_4^+ and NO_3^-content.

Results and discussion

In both campaigns, fertigation resulted in clearly higher NO_3^- concentrations throughout the soil profile, showing that the added fertilizer had entered the subsoil. In the Kävlinge campaign (where NH_4NO_3 was added), NH_4^+ concentrations increased substantially only in the topsoil of both compacted and non-compacted sites. In the Jokioinen campaign, the average NO_3^- concentrations were slightly higher in the compacted than in non-compacted subsoil.

The average N_2O emission was slightly higher in the non-compacted than the compacted soil in the Kävlinge experiment, whereas no differenceswas seen in the Jokioinen experiment. Additional flux measurements were carried out at the Jokioinen site 4 days after fertigation when rain events led to increasing water table. At this point, N_2O emissions were 10 times higher than the average flux measured after fertigation and slightly higher in the non-compated than the compacted site.

In the Kävlinge campaign, the soil air N_2O concentrations increased towards the end of the experiment, showing highest values in the topsoil of the non-compacted treatment. During the Jokioinen campaign,soil air N_2O concentrations increased after the fertigation in both compacted and non-compacted soils, however there was no increase in the lowest soil layer (80 cm). N_2O concentrations dropped sharply after six days, when the weather turned colder and rain events occured.

In both experiments, N_2O flux and soil air concentrations showed high variability within treatments, rendering observed differences between compacted and non-compacted sitesinto statistically insignificant. This is in line with the reported annual N_2O emissions in the same sites which were statistically indistinguishable, too. It has to be stated that the weather during the Kävlinge campaing was colder and during the Jokioinen warmer and drier than normal for the season. This may explain observed low N_2O emission rates despite of fertilizer addition.

Soil physical properties under different cropping systems in Estonia

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Introduction

Regarding a soil compaction survey carried out at the end of 2008 by the Estonian University of Life Sciences in collaboration with the Agricultural Research Centre, soil compaction was define as one of the currently bigger problems in Estonian soils (Reintam et al., 2010). Soil compaction reduces porosity, permeability and therefore water flow through the soil is blocked, increasing the soil erosion and creating anoxic conditions in the bulk which causes denitrification, and therefore the uptake of nutrients is reduced (Bakken et al., 1987). In conclusion soil compaction affects directly to the plant root development and crop yield.

Organic farming, which avoids or largely excludes the use of synthetically compounded fertilizers and pesticides, is presented nowadays as a sustainable alternative to conventional agriculture and as a practice that promotes the conservation of physical and chemical properties of soil. Despite of the increasing popularity of organic farming during the last decade, there is a lack of comparative research into the physical properties of soil between organic and conventional management (Stolze et al.. 2000).The aim of this research is to contribute to this field of study by assessing the effects on soil physical properties, focusing on penetrability and water retention capacity under organic and conventional farming systems in Estonia.

Materials and methods

Five-year crop rotation system (pea, potato, barley, red clover and winter wheat), based on 80 plots, was conducted on sandy loam *Stagnic Luvisol* at the experimental station of Estonian University of Life Sciences in Eerika, Tartu (Estonia) since 2008. From those plots, 40 were cultivated under conventional farming systems with different concentrations of mineral fertilizers. The remaining 40 plots were cultivated under organic farming conditions with the same rotation but having winter oil-rape after pea, winter rye after potato and ryegrass after winter wheat as cover crops. In addition 20 of them (organic II) receive yearly 40 t ha^{-1} of manure in those plots were pea is cultivated.

The present research is based on a total of 320 samples from the 80 plots (4 replications per plot), taken in October 2010 and 320 samples taken in October 2011, after harvest and before soil tillage. From these plots penetration resistance by cone penetrometer (Eijkelkamp Penetrologger with 60 degree 1 cm^2 cones) down to 80 cm depth and bulk density, total porosity, air filled pores, water permeability and plant available water by steal cylinders (57 mm diameter and 40 mm height) at 5 to 10 cm depth were studied. Currently, samples of the second year of experiment are being analyzed and comparison between these first two years of experiment is performed. For testing significant differences between cropping systems and among crops, one-factor ANOVA test was used.

Results and discussion

The distribution of penetration resistance with depth was uniform in the first year of study and very similar for every cropping system, but results from 2011 reveal an increase of resistance; especially in the conventional plots where pressure was almost double than in the previous year of experiment along the first 20-25 cm.

The water content at the moment of sampling varied between 16-17% under both cropping systems and did not cause differences in penetration resistance. However, in 2011, the diagram of pressure with depth shows a possible existence of plough pan at 30 cm probably caused by tillage at that depth, reaching values higher than 3 MPa.

Significant differences ($p<0.05$) were found among the different cropping systems for the rest of the physical properties analyzed. Conventional plots showed a lower bulk density and higher percentage of total porosity, air filled pores and plant available water in comparison with the organic ones. No significant differences were found between organic plots, therefore no manure influence was blatant in organic II plots, since at the time of sampling the rotation was not completed and consequently not all they had the addition of it.

Conclusions

Significant differences ($p<0.05$) have been observed in the data of the first year of experiment (2010) at the time of comparing both systems, showing a slightly better quality of the conventional soils. However, first analyses of the second year samples show a higher compaction of the conventional plots in comparison with the organic ones. Due to the early state of the experiment (rotation has not be completed yet) data from more years seem necessary for drawing further conclusions.

Acknowledgments

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Tillage and traffic impacts on soil bulk density and on the stratification of carbon and phosphorus

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Tillage modifies soil structure through the applied stress (compaction) and through the tilling implements (loosening). Compaction and loosening take place sometimes simultaneously and sometimes consecutively depending on the purpose of the machinery traffic. The structure of arable topsoil is more dynamic due to frequent tillage or weather conditions than the structure of underlying subsoil, which is not commonly loosened. Another aspect of tillage is its mixing or stratifying effects on organic matter and nutrients. The purpose of this article is to shortly summarize the status of soil bulk density, organic carbon and phosphorus in a 35-year old tillage experiment on a clay soil in Uppsala (Sweden).

The investigation was conducted in April, 2009 in two treatments, i) mouldbordploughing to 22-24 cm (MP) and shallow tillage to 10-12 cm (ST). The main investigations were: soil dry bulk density, organic carbon content and phosphorus. Dry bulk density of the lower topsoil (12-25) was significantly higher for ST than for MP but the reverse was observed in the subsoil (25-50 cm). The difference should be the results of different tillage depths and compaction effects between the treatments. Omitted loosening but continuous traffic for different field works led to the increase of bulk density in the lower layer in ST. This consolidated layer has a better bearing capacity than the continuously loosened soil so the dry bulk density of the subsoil ST was significantly lower than the corresponding layer of MP. However, the main reason for higher bulk density in MP should be the driving in the furrow, which is commonly wet during autumn ploughing.

As several other investigations showed, organic carbon content (gkg^{-1} soil) was greater in the upper topsoil (0-12 cm) for ST than for MP. In the lower layers (12-50 cm), organic carbon was slightly greater for MP than for ST but the difference was not statistically significant. The abundance of organic carbon in the whole soil profile (Mg ha^{-1}) was slightly greater for MP than for ST. Phosphorus distribution in the soilprofile was similar to that of organic carbon.

Danish field trials with soil compaction

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Introduction

Does heavy traffic in the field influence the yield? New field trials with soil compaction are started in Denmark in spring 2010. These trials are conducted in cooperation between Aarhus University, University of Copenhagen and Knowledge Centre for Agriculture. Aarhus University is responsible for all measures on soil physics. University of Copenhagen is responsible for all measurements on plant physiology. The Knowledge Centre for Agriculture is the project leader and responsible for the treatments in the trials. The trials are placed on three locations in Denmark with the following soil types: 1. Loamy sand (10-12% loam), location “Aarslev”, 2) Sandy loam (13-17% loam) location “Flakkebjerg” and 3) Loam (15-18% loam) location “Taastrup”.

Materials and methods

The treatments are carried out in early spring under wet conditions. A slurry trailer, Samson PG 25 has been used for treatment 2-5, and a Vervaet slurry tanker has been used for treatment 6. The plan is to stop the annual treatments after the first 3-4 years, but continue measurements – both on soil physics and on plant physiology.
The treatments are:
Treatment 1: No compaction
Treatment 2: Slurry trailer. 8-9 tons wheel load once (first year)
Treatment 3: Slurry trailer. 3 tons wheel loadonce a year for 3-4 years
Treatment 4: Slurry trailer. 6 tons wheel load once a year for 3-4 years
Treatment 5: Slurry trailer. 8-9 tons wheel loadonce a year for 3-4 years
Treatment 6 (only atone location): 11-12 tons wheel load (Vervaet slurry tanker) once a year for 3-4 years
The trial design is randomized block design with 4 replicate blocks.

Besides registration of crop yields a range of different measurements on soil physics and plant physiology has been conducted.

Results and discussion

The trials have now been carried out for two growing seasons, and the results given are the results from these two years. These results will be followed by more results in the next years.

Therefore the results should be regarded as preliminary results. In general the trials shows that traffic with heavy loaded wheels gives a decrease in the yield. Probably this decrease is caused by compaction and pugging of the surface soil in the first years of treatments.

Results on soil physics found in the first year (Schjønning et al., 2010):

- The peak load in the contact area between wheel and soil was one bar higher than the tyre pressure.
- The high peak loads in the contact area reachedthe depth of 30 cm's with nearly no attenuation.
- Vertical stresses of up to 100 kPa were measured at 90 cm depth below the slurry tanker wheels loaded with 6 tons.
- The repeated traffic with three tanker wheels following two tractor wheels deformed the soil consistently in the plough layer.

Results on plant physiology found in the first year (Petersen et al., 2010):

- There was a decrease in the amount of the plant parts above soil surface.
- There wasa tendency of less evaporation in leafs from the plots with high wheel loads.

Results on soil physics found in the second year (Schjønning et al., 2011). Measurements only in "Flakkebjerg":

- Asignificantreduction in soil porosityat30 cm depthwas observed for the treatment with 8 tons compared to no compaction and 3 tons load.
- The reduced porosity in treatments with 6 and 8 tons wheel loads significantly reduced theair permeability in the soil- when drained to field capacity – as compared to no compaction and 3 tons load.
- Measurements of soil macropore volume and air permeability at 30 and 60 cm depths and across the width of a wheel track indicated that the compaction effect on

macropores was most severe at the center of the track, while soil functions - here in terms of air permeability - were most affected at the periphery of the track.

Results on plant physiology found in the second year (Petersen et al., 2010). Measurements only in "Taastrup":

- No continuing impacts of compaction with 8 tons wheel loads in 2010 on the yields in 2011 were found. This result was supported by the fact that there was no effect (except in one occasion under earing) on the amount of green parts of the plant or on the concentration of abscisic acid (ABA) in the xylem sap.
- Water balance and productivity calculations with the "Daisy-model" indicated effective root development down to at least 100 cm soil depth in the treatment with 8 tons wheelload in 2010.
- Traffic with heavy loaded machines in 2011 resulted in a decrease in the yield and the amount of green leaf parts, which were probably a result of structural damages in the plough layer and, as a result of that, a poorer establishment of the crop.

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Applications of Visual Soil Evaluation for subsoil structural quality assessment

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“Applications of Visual Soil Evaluation” was the title of a meeting held by ISTRO Working Group F, 16th-18th May at the Aarhus University Flakkebjerg Research Centre, Denmark. The objectives were to continue and further cooperation in the development and use of field methods of visual soil examination and evaluation (VSEE). Papers were presented and methods were demonstrated in the field. The papers will be published in a special issue of Soil and Tillage Research in 2012. There was special focus on subsoil compaction and papers were given dealing with the development of methods for assessing subsoil structure and relating structure to other soil physical properties. Five of the principal methods for evaluating topsoil and subsoil structure were able to demonstrate their techniques in the field. Six trenches had been dug in a long-term soil compaction experiment where different wheel loadings and number of passes had been applied to a sandy loam soil containing 12-17% clay. There were clear visual signs of compaction below the depth of ploughing. Examples using different methods will be presented at the seminar.

There was considerable enthusiasm for the wider promotion of field techniques using numeric classes at the meeting. Those to assess topsoil structure are now well established and are being used in several countries (Ball et al, 2007; Shepherd, 2009). Although there was also agreement that numeric methods for evaluation of subsoil structure were desirable, there were a number of difficulties to be overcome.

At the moment we are examining the possibilities – and some of the difficulties – in developing a numeric assessment of subsoil structural quality in relation to soil as a plant growth medium. At the outset, we recognize that there is a need to take into account the interaction between subsoil quality and climate. Furthermore, it should be possible, within the overall system of evaluation, to identify criteria for specific types of soil. We are designing a test for use by non-specialists as a tool of soil management to evaluate both land capability, soil damage and the response to remedial work. More detailed methods for the comprehensive examination of the physical properties of subsoils are used in formal surveys of soils in many countries and also for specific purposes such SoilPAK for cotton growers (McKenzie, 2001).

When assessing the quality of subsoil, there are two distinct aspects to consider. The first is to assess those properties that determine the inherent capability of the soil as a whole. These would include an examination of the whole of the rooting depth for the range of crops to be grown and to assess its value as a rooting medium. The depth to be assessed would depend on the climate and the expected maximum soil water deficit. The second is to look at the 'transition zone', a critical zone lying just below the topsoil, which may have been compacted or smeared by machinery during tillage, planting or harvest. This may be a few cm thick or may extend to 30 cm or more. In the evaluation we are focussing on cracks and macropores, roots and soil compaction and soil strength. An outline of the method and examples of the use of the method will be presented at the meeting.

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Strategies to prevent soil compaction and a possible application in Switzerland

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Principles

Two basic ideas are governing physical soil protection regarding soil structure: 1) Maintaining a good soil structure has to be based on preventive measures and not on remedial actions, because this would be time consuming, costly and not really effective; 2) Impacts on subsoils have to be avoided first and foremost, because alleviation of subsoil compactions may be extraordinarily time consuming, costly and unfruitfully – in contrast it is assumed that impacts on topsoils can be alleviated in short term (although topsoil compaction may influence subsoil functions).

Another basic decision is whether the compaction process shall be prevented in any case, i.e. for every structural state, or whether only compaction events leading to deformations beyond given critical values for certain physical soil parameters ("harmful compactions") shall be avoided.

Compaction process

The formation (and degradation) of soil structure is a complex interaction of many different factors related to site properties and agricultural soil management. This complexity with a multitude of influencing factors (often with non-linear relationships between factors, difficult quantification of parameter values, and diverse time scales of processes) is complicating problem analysis and decision making. Therefore, the use of IT-based utilities offers a possibility for non-experts to make assessments in this confusing situation a little bit easier.
The interaction between site properties and agricultural soil management determining compaction risk may conceptually be described by two basic parameters. These can be used to assess the compaction risk by wheeling in a simplified way and to indicate which risk factors are relevant in a given situation. These two parameters are 1) the soil stress caused by wheels (rubber belts, …) or by tillage implements in a given soil

depth, which in turn is depending on the soil strength in the layer above the given depth; 2) the strength of the soil in a given depth, which is depending on soil properties changing in different time scales (seconds to centuries).

Whether the loaded soil volume will be deformed (compacted or sheared) and to which degree depends principally on the relation between soil strength and soil stress; the exact value for soil strength still remains to be determined, however.

The assessment of impacts by soil tillage is currently not described in such a detailed way as the effect of wheeling.

Assessment of compaction risk

Practical recommendations to reduce compaction risk, which are based on single target values related to vehicle or soil properties (e.g. total vehicle weight, axle or wheel load, mean stress in the tyre-soil contact area, moisture content) are more or less easy to check in practice. However, in a given situation they may turn out to be suboptimal in its efficiency either for physical soil protection or for the planning of field operations, because they may lead to decisions which are either too restrictive or too tolerant. The reason for this is that procedures based on single target values do not consider the interactions between soil and vehicle properties defining strength and stress. Therefore, a procedure to assess the compaction risk should take both of the main parameters soil strength and vehicle-induced soil stress into consideration.

A reliable quantification of these two basic parameters governing the compaction process, is crucial for the assessment of the compaction risk. Because methods for determining soil strength in the lab or in the field are normally too expensive, laborious and time-consuming, procedures to derive strength from site characteristics, easily measurable soil properties or simulation models by the use of pedotransfer functions are required for practical decision situations. Quantification of soil stress depends both on the availability and quality of the data describing the vehicle properties as well as on the accuracy of the modelled stress propagation in soil. For the former, models have been developed to calculate stress-distribution in the contact area between tyre and soil, which is important for the quality of stress distribution modelling. For the latter several methods differing in the amount and quality of the necessary input data as well as in the detailedness of the results are available.

The requirements and restrictions of practically applicable tools will normally lead to the choice of elementary solutions to quantify soil stress.

Although the prevailing strategy of most utilities to quantify the compaction risk is to concentrate on risk estimation in the wheel rut area, the proper reference would in fact be the total field area. Therefore risk assessment tools should be able to consider both the compaction risk in the wheel rut and the percentage of wheeled area in a field in order to deliver the necessary information for optimizing mechanisation regarding its effects on the whole field area. This also means that not only vehicle properties are relevant for assessing the compaction risk, but also working techniques and field traffic organisation.

Preventive actions

Preventive actions against soil compaction are covering a broad range of agricultural management options and necessitate a well-considered prioritization, coordination and adjustment in order to reduce compaction risk effectively and efficiently. In principle they are aimed at three pivotal missions: 1) increase soil strength, 2) promote soil structure formation and regeneration, and 3) reduce soil stress.

Preventive actions to fulfill these missions may be grouped according to the velocity with which they influence the basic parameters strength and stress:
1) Improving soil strength is usually possible only in longer periods of weeks to years: Several measures dealing with agricultural management practices (crop rotation, fertilization, tillage, ...) or investments in land development (drainage) are potentially helpful to reduce compaction risks resulting from limitations by low soil strength. Normally they are effective only in the long run, meaning that they are rather a general investment in soil quality than a specific preventive action, because additional organic carbon, more intense soil cover and rooting or reduced loosening intensity are improving soil structure – together with natural alleviation processes – only slowly over time. To find an effective prioritization among feasible measures as well as the optimum characteristics and an adequate combination of preventive measures at acceptable costs, a thorough knowledge both of the risk situation and the farm situation is necessary, together with sound practical experiences.
2) In contrast reducing soil stress is feasible almost immediately: If soil moisture is the crucial reason for low soil strength and a high compaction risk, organizational measures to stop and postpone field traffic are the only possible options. If the reduction of soil stress

could diminish compaction risk to an acceptable level, then technical and organisational adaptations may offer possible solutions (adaptation of a given vehicle, e.g. by increasing the soil-tyre contact area using twin tyres or lowering tyre inflation pressure, by reducing wheel load through limiting vehicle payload; selection of an alternative vehicle, e.g. of smaller size, better running gear design or tyre equipment, installed regulation system for tyre inflation pressure; use of alternative working techniques, e.g. regarding fertilization equipment, tillage systems, tillage-seeding combinations; improvement of field traffic organisation, e.g. by optimizing transport chains).

Decision making tools

IT-utilities will be the tools of choice to make the complexity of a compaction assessment open to public. Depending on the objective and time horizon of a compaction risk assessment, decision making tools may offer different information or are implemented differently. Whereas the typical average risk assessment needed for long-term decisions like machinery investments or the improvement of a crop rotation may be presented in tabulated form on paper, the situative risk assessment needed for short term decisions like “go/no go” or the adaptation of vehicle properties has to be offered as interactive IT tool or even as part of the vehicle information system (in the best case coupled with sensors and actuators on the vehicle to directly control total weight, tyre inflation pressure and possibly weight distribution). The input information for decision making tools may be of different quality and resolution in space and time, depending on information type (estimated value, standard value, measured value) and source (personal estimations, databases, measuring networks, local sensors). Typically, a decision making tool should be able to handle different qualities and sources of input data, adapting the detailedness of its assessment to the availabla data quality.

Possible application of a prevention strategy

In Switzerland a scheme for the practical prevention of soil compaction in agriculture is currently under discussion. The aim is to combine a) recommendations of soil protection offices regarding actual soil strength, based on soil moisture measurements, and b) advices of agricultural advisory services regarding the soil stresses caused by field operations in order to c) implement preventive measures against long-lasting soil compaction (especially subsoil compaction) as required by the Swiss soil protection law.

For this purpose information on matric tension (or soil strength) shall be made available for the farmers by the soil protection offices of the Cantons, ideally by a tensiometer network in typical soils. The farmer himself/herself shall have access to simplified information sources regarding soil strength and soil stress (e.g. tables with classified data and diagrams with continuous data). Based on information from the tensiometer-networks, the farmer can in turn roughly estimate a) the expected present soil strength, and b) the expected maximum soil stress in the reference depth caused by a vehicle typically used for the scheduled work. 35 cm have been chosen as reference depth for determining soil strength and soil stress because this depth is considered to be the typical upper boundary of a subsoil. Comparing soil strength and soil stress values in a so called “decision diagram”, the farmer then decides whether the compaction risk is low (“go!”) or whether it is elevated or high (“check or no-go!”). According to the Swiss soil protection law, farmers have the responsibility to avoid long-lasting soil compaction. Therefore, if for a planned task the rough estimates for the soil strength and the expected maximum stress for a typical vehicle are leading to a “check or no-go”-recommendation, the farmer has to postpone this task. However, if he/she can prove to the soil protection office that in the particular situation soil strength is higher and/or soil stress is lower as assumed for the general case (due to different soil properties and/or better vehicle properties), which is resulting in a low compaction risk (“go”), then the field operation can be carried out as planned. This situation-specific assessment can be done by the farmer using an IT decision making tool such as Terranimo (Stettler et al., 2012).

Reference

Stettler, M., Keller, T., Schjønning, P., Lamandé, M., Lassen, P., Pedersen, J., Weisskopf, P., 2012. Terranimo® - a web-based tool for evaluating soil compaction: Machinery-induced stresses versus soil strength. Proceedings of the NJF seminar 448, 6–8 March 2012, Helsinki, Finland.

Terranimo® - a web based tool for evaluating soil compaction: Model design and user interface

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Introduction

ICT (Information and Communication Technology) is an umbrella term that includes technologies for processing, exchanging and managing data, information and knowledge. Data on soil characteristics and climatic conditions across large areas are now available in digital form, which creates great potentials for optimizing a range of processes and procedures in agriculture. Among these is evaluation of the risk of soil compaction for any planned traffic on agricultural land. An international group funded by the European Commission's ERA-NET "Coordination of European Research within ICT and Robotics in Agriculture and Related Environmental Issues" (ICT-AGRI) under the 7th Framework Programme for Research is currently preparing a web-based tool named Terranimo (Terramechanical model) for this purpose ('PredICTor' project). The PredICTor project outcome is seen as a precondition and a first step along a line towards internet-based systems for 'on-site' decisions on traffic in order to avoid compaction. The tool Terranimo is designed with 3 separate components (Fig. 1): Database, Model and User interface. Each component can be implemented on different servers.

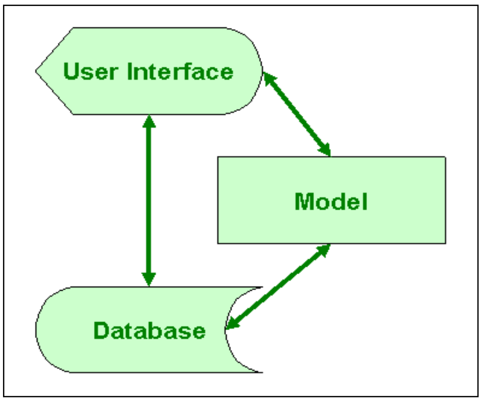

Figure 1. Diagram showing the 3 Terranimo system components and the interactions between them.

1 Database

The Terranimo database is implemented as a relational database on a Microsoft SQL Server. Tables are configured for holding machinery data, tyre data, soil data and scenario data for registered users. The machinery and soil data are identified by a country code in order to be able to use the system in several countries with different setup. The machineries are divided into three categories: Tractors, self-propelled vehicles and implements and trailers, and all are characterized by axles and wheels. Soil data comprises both texture data and water data. The tyre database is common for all participating countries and currently holds data of more than 700 tyres together with related tyre load and tyre pressure combinations. Registered users can save their setup data as "scenarios", which is a specific combination of machinery and soil conditions.

2 Model

The Terranimo model is implemented as two object-oriented classes: One for calculating contact stress and one for calculating soil stress. The model can be directly linked to the user interface, but can also be implemented as a web service and hence be used by other extern applications.

2.1 Contact stress

The methods for calculating contact stress takes several tyre parameters as input and returns a two-dimensional array as result, which represents the stress executed by a tyre on a soil surface. The resolution of the array can be set in order to optimize calculation time against precision of the result. Calculations are implemented as described by Stettler et al. (2012).

2.2 Soil stress

The calculation of soil stress uses the array from the contact stress calculations as input together with a calculation of a concentration factor. The method returns a two-dimensional array, which represents a vertical soil slice below a tyre. Calculations are implemented as described by Stettler et al. (2012).

3 User interface

The Terranimo user interface on www.soilcompaction.eu is programmed in ASP.NET using Microsoft Visual Studio 2010. It consists of two pages: A welcome page and an input/output page.

On the welcome page the user can select language for the user interface and the user can also choose to use the public part of the system with a standard scenario with default setting. In that user mode, the user can select tyres and regulate load and pressure, but the results cannot be stored. For storing scenarios the user can register and then configure his/her own machinery with specific tyres, and save the settings for machinery and soil for future use.

The input/output page is divided into four tab pages: Two for input of machinery and soil and two for output with results for contact stress and soil stress.

3.1 Input

3.1.1 Machinery

On the tab page for input of machinery the user can select from a list of icons of machinery a tractor with or without an implement or a self-propelled machine. The selected machinery is then represented by a larger icon on a graphic representation, where it is also possible to select a specific axle or wheel. By selecting an axle or a wheel, a panel with information of the selected item is shown, and tyre type, wheel load and inflation pressure can be changed by the user.

3.1.2 Soil

On the tab page for soil data the user can select different ways of soil data input. The default setup is to use a soil type with predefined texture divided into predefined soil horizons and a water regime from a predefined list. The user can then select another soil type and water regime in order to use another set of predefined data.

If the user has detailed data from a soil, it is possible to enter texture data and/or water content data manually into soil layers defined by the user.

The system can also retrieve soil texture data from national soil databases. By supplying a field position by latitude/longitude, a data structure of soil texture can automatically be uploaded to the system.

The system is currently being prepared for automatic soil water data access through model calculations on soil, crop and weather data from a specific field position.

3.2 Output

3.2.1 Contact stress

The tab page for contact stress shows graphic presentations of the results from the model calculation of the stress on the soil surface. The user can select between two different views: One in three dimensions, where the stress from the tyres are shown as cones and another as a two-dimensional contour chart.

3.2.2 Soil stress

The tab page for soil stress shows graphic presentations of the results from the model calculation of the vertical stress as well as for soil strength. One chart shows the stress from the tyres as isobars below the tyres into the soil. Another chart shows the strength of the soil calculated for layers of a height of 10 cm. A third chart shows the difference between soil strength and soil stress. This chart represents the final result for the user, where it is possible to evaluate if it is safe to drive with the selected machinery configuration for the given soil conditions in order to prevent permanent damage to the soil. Recommendations for the calculated results are given below the chart.

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Stettler, M., Keller, T., Schjønning, P. Lamandé, M., Lassen, P., Pedersen, J., Weisskopf, P., 2012. Terranimo® - a web-based tool for evaluating soil compaction: Machinery-induced stresses versus soil strength. NJF-seminar 488: Soil compaction – effects on soil functions and strategies for prevention. Helsinki, Finland, March 6-8, 2012.

Terranimo® - a web-based tool for evaluating soil compaction: Machinery-induced stresses versus soil strength

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Introduction

Soil compaction due to heavy agricultural machinery has been shown to negatively affect important soil functions such as productivity, leaching of nutrients, and emission of greenhouse gases, and to be effectively persistent in soil layers deeper than approximately 0.4 m (Håkansson, 2005). Based on experimental data from wheeling experiments, we are developing a web-based terramechanical model for the simulation of stress and strain in soil under agricultural machinery named Terranimo®.

Description of the model

The model is simulating the effects of wheeling in three steps:

1. Calculation of the contact area and the stress distribution at the tyre-soil interface. This depends on wheel load, tyre characteristics (tyre dimensions, inflation pressure) and topsoil conditions (texture, tillage, soil water).
2. Analytical calculation of the stress propagation in the soil profile, depending on soil properties and water content.
3. Calculation of the soil deformation risks by comparing soil stress and soil strength, using the concept of precompression stress.

The methods used in each step are described in the following.

Contact area and stress distribution at the tyre-soil interface

In order to be able to predict stresses in the soil due to agricultural machinery, one has to be able to predict the stress at the tyre-soil interface. It is important to know not only the area of contact, but also the stress distribution over the contact area, which together form the upper boundary conditions.

Terranimo® incorporates FRIDA (Schjønning et al., 2008), a model for prediction of the contact area and the stress distribution between tyre and soil that is based on the original work of Keller (2005). The periphery of the contact area is described by a super ellipse, and the stress distribution is modelled with a power-law function in the driving direction and an exponential function perpendicular to the driving direction.

The model has demonstrated to give good descriptions of measured footprints and the stress distribution at the tyre-soil interface (Fig. 1).

Terranimo® includes 'pedo-tyre-transfer functions' for the prediction of the necessary model parameters to allow a direct estimate of contact area, shape and stress distribution in the tyre-soil interface from wheel load and readily-available tyre parameters (tyre dimensions and tyre inflation pressure) and the topsoil conditions (texture, tillage and matric potential).

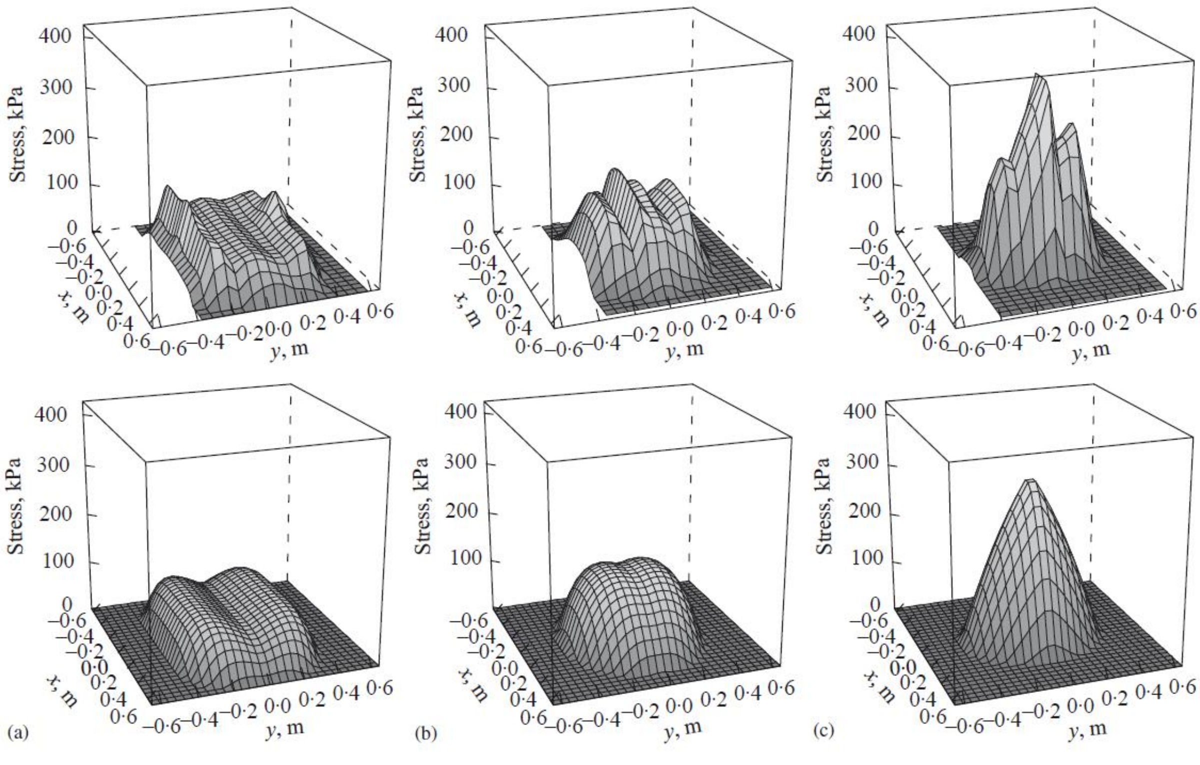

Figure 1. Examples of measured (top) and model-fitted (bottom) stress distribution across the contact area with three inflation pressures (a: 50 kPa; b: 100 kPa; c: 240 kPa) for a Nokian ELS 800/50R34 implement tyre at a wheel load of 60.3 kN. Driving direction is along the x-axis. (From Schjønning et al., 2008)

Stress propagation in the soil profile

Stress propagation in the soil profile is simulated using the analytical approach based on the work of Boussinesq (1885), Fröhlich (1934) and Söhne (1953). This approach has shown to be accurate enough while saving a lot of computational power and input data for soil characteristics compared to finite element models (Keller et al., 2007).

To account for different propagation characteristics, the necessary concentration factors are derived from soil conditions (texture, precompression stress), based on recent work in Sweden and Denmark.

Evaluation of the risk of soil compaction

In Terranimo® the concept of precompression stress is applied. Principally, by limiting the imposed stress to below precompression stress (σ_{pc}), the risk of soil compaction (i.e. plastic deformation) and undesirable changes of soil structure – and hence soil functions – can be minimized. Pedotransfer-functions have been established to estimate σ_{pc} from readily-available soil attributes (texture and matric potential, Schjønning, 2011, unpublished).

User interface

Terranimo® can be accessed for free at www.soilcompaction.eu/. Please contact us if you would like to use the current test version, and we will deliver the necessary login information.

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Tracks instead of tyres to avoid compaction

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Introduction

Tracks generally gives a large contact area which is beneficial in terms of soil compaction. Traditionally, tracks have mainly been used on large tractors with one long track on each side of the tractor. Today, there are tracks also for small tractors as well as for combines and sugarbeet harvesters. Also, instead of two tracks, the vehicles may be equipped with four or two shorter tracks mounted on the wheel axle. Thus, at least for European conditions, tracks instead of tyres have become a more realistic alternative for many farmers. The objective of the present paper was to discuss possible advantages of tracks compared to tyres to avoid soil compaction.

Material and methods

Measurements were made on a clay soil in Sweden in 2009, using an 85 kW tractor with a total weight of 7700 kgequipped with tracks, single and dual wheels (Arvidsson et al., 2009). The rubber track system consisted of four tracks mounted on the conventional wheel axles of the tractor. Soil stress and soil physical properties were measured at different depths in the soil profile. In 2011, a pilot investigation was carried out to measure soil stress for a combine harvester with tracks or wheels. Model calculations of soil stresses were also made to estimate the compaction risk of different vehicle types.

Results

The measured stresses were similar for the tracks and dual wheels at all depths studied (15, 30 and 50 cm), but were considerably higher for the single wheels at all depths (Fig. 1). Simulations of soil stresses correlated closely to measured values for the tracks and the dual wheels, but underestimated soil stresses in the topsoil compared to measured values for the single wheel. Bulk density and penetration resistance were consistently highest and saturated hydraulic conductivity lowest after wheeling with single wheels, while there were no statistically significant differences between tracks and dual wheels. The use of four tracks resulted in a more even stressdistribution than is normally obtained with two long tracks.

Also the pilot investigation with a combine harvester showed clearly lower stresses for tracks compared to single tyres.

Discussion and conclusions

Tracks will generally decrease compaction compared to single wheels when mounted on the same vehicle. In contrast, differences in stresses and compaction between tracks and dual mounted wheels may be small, which was shown in measurements as well as in model calculations.A track mounting which allows the track undercarriage to be rotated around each axle can have a more even stress distribution compared to single tracks that are fitted on fixed bearing wheels, which are much more sensitive to how the weight is distributed along the tractor. However, there will always be an uneven longitudinal stress distribution along the track, which can be seen as local stress peaks under the bearing wheels and support rollers, also in the subsoil. A disadvantage of tracked tractors isalso that they often have a low power/weight ratio, meaning they are more heavy than necessary for traction. Thus, tracks are most beneficial for vehicles which cannot be used with dual wheels, such as combines and sugarbeet harvesters, or when tractors cannot be equipped with dual tyres. This also means they are suitable in controlled traffic systems, when the area covered by wheels or tracks should be kept as low as possible.

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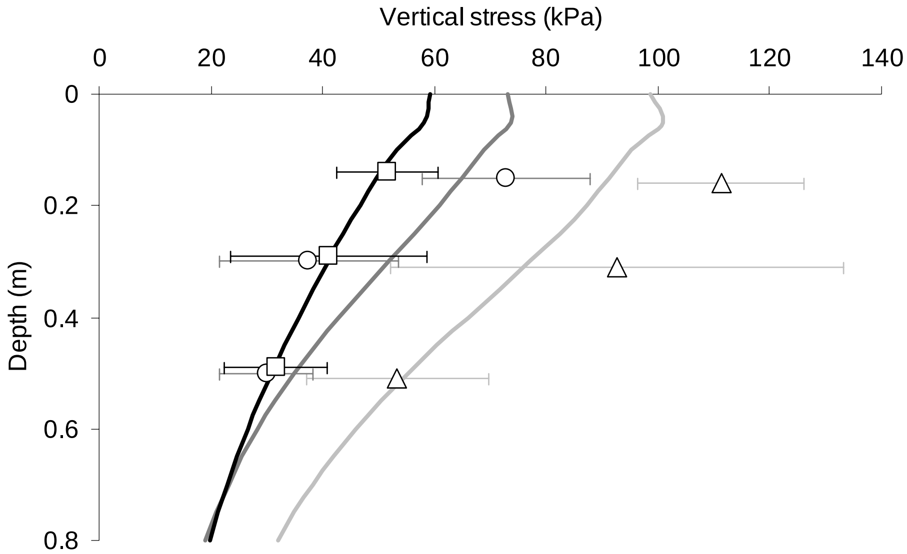

Figure 1. Measured (symbols) and simulated vertical stress (curves) under the rear track of the tracked tractor (measured: squares; simulated: black curve), under the rear wheel of the tractor equipped with dual tyres (measured: circles; simulated: dark grey curve) and single tyres (measured: triangles; simulated: light grey curve). Error bars indicate ± standard error of the mean.

Performances of different type of tractors in forestry soil conservation tillage

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Introduction

Conservation tillage is defined by the Conservation Technology Information Center (CTIC, 1992) as “any tillage and planting system that maintains at least 30% of the soil surface covered by residue after planting to reduce water erosion”. Conservation tillage involves the planting, growing and harvesting of crops with minimal disturbance to the soil surface avoiding inversion tillage method. Advantages of conservation tillage include soil erosion control, water conservation, less use of fossil fuels normally associated with land preparation, reduced labour requirements, more timeliness of operations of greater flexibility in planting and harvesting operations that may facilitate double cropping, more intensive use of sloping soils, and less risk of environmental pollution (Blevins and Frye, 1993).

Materials and methods

In this research field tests on machinery carrying out tillage operations for reforestation were carried out on a silt clay soil seeded with alfa-alfa (*Medicago sativa*) in Central Italy. Field condition during the tests are shown in Table 1.

Machinery used during field tests was a mounted rotary plough driven by the tractor p.t.o. composed by a fixed frame provided of two metal wheels and by 12 anchors (4 for disk) set on horizontal rotary shaft.

The above mentioned machinery was mounted on four different tractors with different running gear and power transmission systems with the aim of finding the optimal coupling between tractor and machinery and to assess soil workability: 1) a medium power metal tracked (13000 kg of mass and 114 kW of engine power) coded MMT; 2) a high power rubber tracked (11895 kg of mass with ballast and 179 kW of engine power) coded HRT; 3) a high power wheeled tractor (10100 kg of mass with ballast and 191 kW of engine power) with hydro-mechanics power transmission coded HWT; 4) a medium power wheeled tractor (6420 kg of mass with ballast and 81 kW of engine power) with power-shift transmission coded MWT.

During the tillage operation the tractor-machinery performances, the quality and quantity of the work were quantified through the following parameters: forward speed, work width, work depth, slip, fuel consumption, global energy employed, average energy employed for volume of shifted soil and the degree of crushing of the soil as a result of the operation (clodness).

Results and discussion

Due to the push of the rotary plough in forward direction of the tractors, the slip values during field tests were of 0% for all treatments as shown in Table 2. From comparison of the unitary fuel consumption and time of unitary work it emerged that treatments regarding the wheeled tractors showed better performances with respect to the treatments regarding the tracked tractors. Particularly for global energy employed results showed for HWT and MWT treatments values of 159 and 160 kWh ha^{-1} respectively while for MMT and HRT treatments values of 377 and 415 kWh ha^{-1} respectively.

Between the two wheeled tractors, HWT registered lower values of unitary fuel consumption but higher values of time of unitary work than MWT (Table 2). Equal values of global energy employed among wheeled tractors were recorded but HWT showed lower value than MWT in terms of average energy employed for volume of shifted soil [38 and 53 kWh $(1000\ m^3)^{-1}$ respectively].

Results of clodness measured after the tillage operations are shown in table 3. It emerged that for all treatments there were a good degree of crushing of the soil, and this avoided a supplementary tillage operation for seedbed preparation. High power tractors (HRT and HWT) created more than 50% of clods smaller than 50 mm highlighting an optimal degree of crushing of the soil, furthermore treatment HRT does not created clods bigger than 200 mm.

Conclusions

From the analysis of results it emerged that the choice of the machinery used for field tests represents a useful tool for conservative soil tillage and reforestation. The tractor mounted machinery tested allows cultivation only of the strip that will be planted with tree species, maintaining at least 30 % of soil cover. Concerning tractors performances, time of unitary work and unitary fuel consumption and global energy employed the best coupling between tractor and machinery was founded with wheeled tractors particularly regarding fuel consumption and average energy employed for volume of shifted soil.

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Table 1. Field test conditions

Particle size distribution (%)	Sand (> 50 μm)		7.5	
	Silt (50 - 2 μm)		67.5	
	Clay (< 2 μm)		25.0	
Field capacity (%)	25			
	MMT	HRT	MWT	HWT
Water content (%): (0.15-0.20 m depth)	26	29	25	24
Bulk density (Mg m^{-3}): (0.15-0.20 m depth)	1.2	1.4	1.2	1.2
Cone index (MPa): (0.15-0.40 m depth)	1.7	2.3	1.6	1.6

Table 2. Average tests results for different treatments

	MMT	HRT	MWT	HWT
Forward speed (m s^{-1})	0.75	1.0	1.1	1.0
Measured work width (m)	1.00	1.00	1.00	1.00
Work depth (m)	0.45	0.45	0.45	0.45
Real work capacity (ha h^{-1})	0.27	0.36	0.46	0.36
Time of unitary work (h ha^{-1})	3.7	2.7	2.2	2.7
Slip (%)	0	0	0	0
Fuel consumption (kg h^{-1})	23.7	40	17.6	12.1
Unitary fuel consumption (kg ha^{-1})	87.8	100	38.5	33.3
Global energy employed (kWh ha^{-1})	377	415	160	159
Average energy employed for volume of shifted soil [kWh (1000 $m^3)^{-1}$]	90.0	98.8	53.3	38.0

Table 3. Subdivision of the clods in size classes (mm) produced by the rotary plough

Clodness (%)	MMT	HRT	MWT	HWT
>200	15	0	8	11
200-100	28	11	41	15
100-50	28	30	27	24
50-25	13	21	14	16
<25	16	38	10	34

Leaching of nutrients arising from subsoiling

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Introduction

Subsoiling may be applied to break compacted layers in the soil. The results are not always satisfactory, but subsoiling may be a good first aid. Subsoiling breaks the soil mechanically, creates hollows, and reveales new surfaces open to the influence of water. It also makes new transport routes which extend into deeper soil layers than before. These probably affect water flow in the soil, as well as nutrient transport in the water. This article represents some observations about the effect of subsoiling on the leaching of nutrients. It also discusses other consequences of subsoiling.

Methods

The effect of subsoiling on the leaching of nutrients was studied on a drainage experimental field on a clay soil. There were four plots on the field. In plot A, plastic pipes with a thin cloth as an envelope material were installed by a drainage plough at intervals of 6 m. The plot was also subsoiled to the depth of 50 cm a year later. In plot C, plastic pipes with gravel as an envelope material were installed by a chain trencher between the old drains, so that the drain spacing became 8 m. Plot B and D were left undisturbed as control plots. Drain spacing was 16 m in B and 32 m in D.

The experimental field was equipped with a drainage water collector system. The amount, as well as the nutrient content of the drainage water could be determined from every plot. The measurements were conducted in three periods: 1) before the installation of the drains into plots A and C (in 2007-2008), 2) after the installation of the drains but before the subsoiling of the plot A (in 2008-2009), and 3) after the subsoiling of the plot A (in 2009-2011). There was variation in the circumstances between the plots (i.e. water discharge, groundwater level, malfunctioning of the instruments). Therefore, only periods when the circumstances were about equal in all plots were included in this study. Groundwater level and soil moisture were also measured, and the amount and quality of the yield were determined.

Results and discussion

Subsoiling did not have much effect on the amount of discharge. However, subsoiling seemed to keep groundwater at a lower level; groundwater probably filled the hollows thus reducing the rise in wet conditions.

Subsoiling, as well as installation of the drains by a drainage plough (which "subsoils" a strip around the pipe line), increased the nitrogen-N, and total-N contents in the drainage water. The average of the nitrate-N content could be as high as 16 mg/l in the subsoiled plot, whereas it was maximum 6 mg/l in the other plots. Ammonium-N content was low in every plot and every period unless slurry was used as a fertilizer. On the other hand, subsoiling decreased the contents of total-P, and solid material in the drainage water. This may be a result of drier conditions on the soil surface, following that less erosion material was released. Soil particles may also be sieved into deep soil layers. Subsoiling did not affect soluble-P content.

Subsoiling didn't increase yield nor improve yield quality.

Conclusion

Subsoiling is a harsh treatment, and changes soil properties at least temporarily. According to the first observations, the environmental effects seem to be the increase of nitrate-N content, and the decrease of total-P content in the drainage water.

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The effects of organic matter application and intensive tillage and traffic on some soil structural properties

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Introduction

Modern mechanized agriculture is characterized by large inputs of mechanical energy to soil from traffic and tillage operations. When applied as kinetic energy by power-harrows, mechanical energy fractures the soil structural elements and in addition disperses soil colloids (e.g. Watts et al., 1996). Dispersed clay may cement on soil surfaces (on the topsoil or on inner surfaces of aggregates) and hence affect soil friability (e.g. Schjønning et al., 2012). Traffic by heavy machinery will induce vertical as well as shear strain. The reaction of soil to compaction is known to be influenced by organic carbon (OC). Soane et al. (1981) reviewed results indicating that OC decreased the maximum impact of compaction at the most sensitive water content. More recently, Schjønning et al. (2007) showed that management-derived increases in OC boosted the resilience of soil to compaction. The purpose of this study is to evaluate the effects of mechanical inputs to soil with different levels of OC.

Materials and Methods

The field experiment was carried out in Denmark at Research Centre Foulum. The soil is a coarse sandy loam (Typic Hapludult) with 82 g clay (<2 µm), 116 g silt (2–20 µm) and 776 g sand (20 µm – 2 mm) / kg soil. The basic field experiment, initiated 13 years prior to sampling, includes four adjoining fields in a cash-crop rotation including winter wheat (*Triticum aestivum L.*). Different organic matter management strategies were applied: fertilization with slurried manure, mineral fertilizer and straw incorporation (treatment ORG), or fertilization with only mineral fertilizers and with all crop residues removed (treatment MIN). The main plots with MIN and ORG treatments were replicated three times in a randomized block design. The soil was rotovated (treatment ROT), compacted (treatment PAC) or left undisturbed (treatment REF) as split-plot treatments in the main plots with organic matter management. The mechanical treatments took place immediately after each mouldboard ploughing operation in a two-year period prior to sampling. Treatment PAC included wheel-by-wheel traffic by a small tractor with narrow tyres, while treatment ROT involved a Howard RotoLabour tine cultivator that operated to a depth of ca.

0.1 m in the soil and with a high ratio between rotovation speed and tractor driving speed. The six combinations of treatments are labelled MIN-REF, MIN-ROT, MIN-PAC, ORG-REF, ORG-ROT and ORG-PAC.

In the spring of two consecutive years 13-14 years after start of the experiment, we sampled cubes of soil from the 6-13 cm layer in the field grown with winter wheat. The cubes were taken to the laboratory and stored at 2^{o}C until analyses could take place. In the field, a drop-shatter test was performed as described by Schjønning et al. (2002), and soil fragmentation quantified as the mean weight diameter (MWD) of the aggregate size distribution. In the laboratory, subsamples from the soil cubes were taken to a Yoder-type measurement of wet aggregate stability and a measurement of clay dispersibility as described by Schjønning et al. (2002)

Results and discussion

The organic treatment with no mechanical energy input (ORG-REF) gave rise to the highest friability (least MWD; Fig. 1). Soil compaction (PAC) reduced soil friability in the MIN as well as in the ORG treatments, but most pronounced for the MIN soil. Rotovation (ROT) increased the MWD and hence decreased soil friability for the MIN as well as the ORG soil but significantly only for the latter.

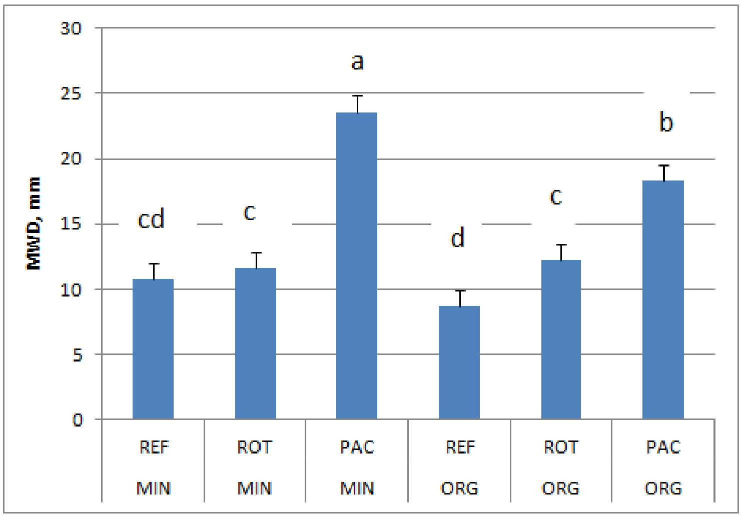

Figure 1. Effects of different management systems on the Mean Weight Diameter (MWD) determined from the size distribution of aggregates following a drop shatter test. Bars labeled by identical letters are not significantly different (P=0.05).

Thirteen years of amendment with animal slurry and plant residues (ORG) increased aggregate stability (trend with P~0.12) and decreased clay dispersion compared to non-organic soil (MIN) (Table 1). Both mechanical treatments (PAC and ROT) increased significantly the clay dispersion as compared to the REF treatment, meaning that clay dispersibility is highly sensitive to mechanical energy input, which is in accordance with Watts et al. (1996). Also the stability of macroaggregates to mechanical breakdown was reduced by the mechanical treatments, but only significant for the ROT treatment. We interpret this as a puddling effect of the kinetic energy applied in the rotovation process; appa-rently this kind of energy is more injurious for soil aggregate stability.

Table 1. Treatment effects on water stable aggregates and clay dispersion. Numbers followed by identical letters are not significantly different (P=0.05).

	Organic Treatments		Mechanical Treatments		
	MIN	ORG	REF	ROT	PAC
Water stable aggregates *mg aggr. g*$^{-1}$ *soil*	538^{a}	593^{a}	589^{a}	541^{b}	566^{ab}
Clay Dispersion *mg clay g*$^{-1}$ *soil*	5.27^{a}	4.40^{b}	4.55^{b}	4.90^{a}	5.06^{a}

Conclusions

- The friability of the organic soil was less affected by soil compaction than the soil dressed only with mineral fertilizers
- Thirteen-fourteen years of amendment with organic manure and incorporation of straw increased macro-aggregate stability and decreased clay dispersion
- Soil compaction and rotovation decreased macro-aggregate stability and increased clay dispersion
- Our results indicate that soil organic matter may help soils cope with the detrimental effects of traffic and tillage

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Soil hydraulic properties and preferential flow in relation to basic soil properties and soil compaction

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Introduction

Soil compaction is a major threat to a sustained soil quality and is increasing since agricultural machinery is becoming heavier and is used more intensively. Compaction may reduce pore size as well as having an impact on the pore morphology thereby affecting the hydraulic properties of the soil. Preferential flow through the macropore system is linked to abundance of macropores and the hydraulic conductivity of the soil matrix. A change of the hydraulic conductivity may lead to an increased risk of preferential flow in the soil macropores and thereby an increased risk of leaching of contaminants out of the root zone. In this study we aim at investigating the effect of soil compaction on the soil physical and hydraulic properties of the soil and the resulting effects on preferential flow.

Materials and methods

A total of 64 undisturbed soil columns (6280 cm^3, $\varnothing$ = 20 cm, L = 20 cm) were sampled in an agricultural soil (glacial till deposits; clay: 23%, silt: 28%, sand: 49%) at the Brahmehem farm in southern Sweden (55° 49' N, 13° 11' E). Sampling depths were 0.3 and 0.7 m (corresponding to the middle of the soil column). Our sampling took place in the spring 2009 fourteen years after operation with a heavy sugar beet harvester. Soil cores were sampled both from uncompacted control blocks and from compacted blocks. In the laboratory the saturated (K_s) and unsaturated hydraulic conductivity ($k[h]$) was measured. In addition, air permeability (k_{air}) at a matric potential –10 hPa was measured on the same columns. A leaching experiment was performed where free drainage was used as lower boundary. As upper boundary, artificial rain water was supplied homogenous at specific applications rates. At steady outflow, a tritium pulse was applied during a period of two hours. Effluent was collected at regularly intervals during the experiment and the tritium activity was determined using liquid scintillation counting. Macropores in the large soil cores were made visible by CT scans performed at a water content at field capacity.

Table 1. Transport parameters measured in the laboratory on soil columns (6280 cm^3) sampled in control and compacted plots at the Brahmehem farm.

Soil depth (m)	Treatment	K_s (cm/d)†	$k[-10]$ (cm/d)†	k_{air} (μm^2)†
0.3	Control	102	0.16	4.5
	Compacted	25	0.21	3.3
	p value	*0.03*	0.76	*0.04*
0.7	Control	123	0.32	10.3
	Compacted	138	1.20	5.3
	p value	0.90	0.30	0.30

† geometric means

Results and discussion

For the 0.3 m depth our results indicate a significant decrease in K_s for the compacted treatment whereas $k[-10]$ did not show any significant difference between treatment (Table 1). Also k_{air} showed significantly lower values for the compacted treatments at this depth. At the same depth, a visual interpretation of the CT images showed signs of a lower macroporosity. For the 0.7 m depth we did not observe any significant differences for the measured values in relation to treatment (Table 1). This lack of significance was probably related to a large variation in the soil texture at that depth (data not shown). Our results therefore indicate that the soil compaction had an effect on the transport parameters for the upper part of the subsoil. Fig. 1 shows two examples from the leaching experiment at two different columns sampled at 0.3 m. Despite significant differences in the hydraulic properties no clear trends in the leaching pattern were discovered in relation to soil treatment (analysis not shown). The results indicate that differences in the leaching patterns probably are more related to the high variability in soil texture and bulk density across the field.

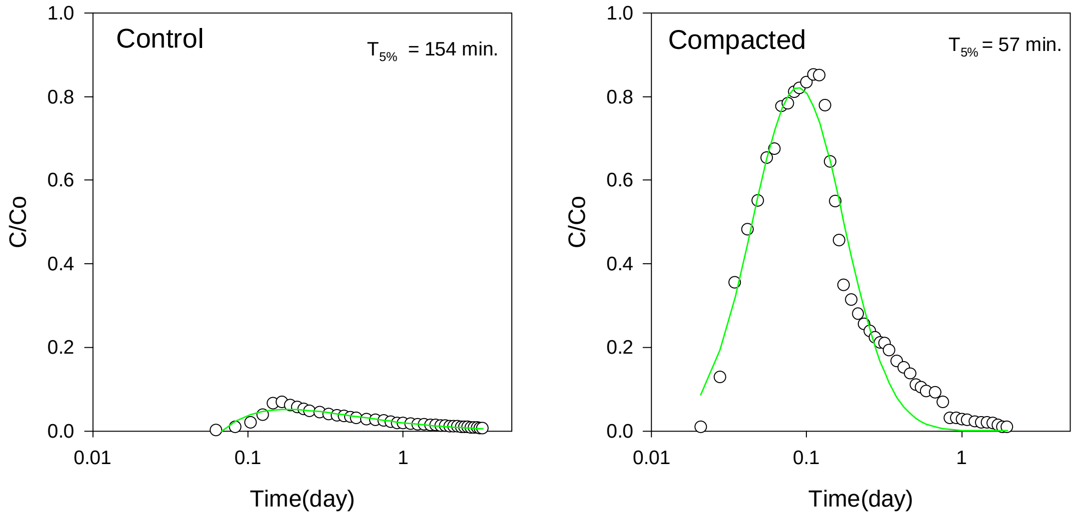

Figure 1. Example of breakthrough curves for the 0.3 m depth. Solid line shows a fit using a double-log normal equation from where the 5% arrival time ($T_{5\%}$) of the tracer was calculated.

Conclusions

We conclude that despite a high variability in soil texture among our replicates, the measured changes in the analyzed transport parameters support our hypothesis that the colloid-facilitated transport of agrochemicals in spatially connected macropores leads to a higher risk of leaching of contaminants out of the root zone. However, results from a leaching experiment on soil columns from the same experiment indicate that further analysis taking into account the high variability of the soil is needed.

Moiré as a novel approach to quantify soil compaction

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Introduction

The extent and severity of compaction depends on the soil (water content, strength, and existing aggregation) and on properties of the machine involved (axle load and tyre pressure). The resulting deformation or compaction of the soil is also influenced by shear stresses associated with the speed of travel and the patterns or lugs on the tyres. With so many factors involved the nature of the deformation is also difficult to quantify.

Several methods have been tried to quantify the impact of tyres on the soil surface by constructing profiles or topographic contours. Methods include moulding the indentations with plaster or other material and using pin meters to measure the depth of any indentation. Laser scanning of the surface of the indentations left by vehicles has also been used (e.g. Huang et al., 1988). Each method has problems including the expense of the measurement either as equipment or cost of labour involved, the resolution of the measurement or that the measurement introduces material into the indentation. For some methods the data obtained may need considerable processing to provide useful information. There is clearly a need for a relatively low-cost, easy to use, precision method that can take repeated measures of multiple vehicle passes and that provides the data into an accessible quantitative form. The need is to both quantify the extent of the compaction and to compare vehicles, tyres, speeds of travel etc.

The need to analyse (without contact) biological surface profiles, and to reproduce a range of irregularities requires similar solutions to quantifying soil compaction. The moiré technique is an alternative for constructing profiles, topographical contours, and shape and deformation values and has been used for biological material (e.g. Costa et al., 2008). The moiré technique can be used to produce a digital map of a surface by comparing two periodic structures. One structure follows the behaviour of the object surface and the other one is kept constant without deformation, working as a reference plane. The composition of the two grids using the projection approach results in moiré fringes that are related to the surface level of an object and that can be used to create 3-dimensional maps. The aim of the current work described was to test the application of the projection moiré technique using simple commonly available equipment to quantify soil compaction.

Methodology

After laboratory trials we ran tests using a standard data projector to project a grid onto the soil surface. The soil was a Stagnic Cambisol in the FAO classification (6% clay in the Ap horizon) that had been ploughed and cultivated to produce a seedbed. The soil was near to field capacity. The grid was photographed before and after the passing of a Massey Ferguson MF 5460 tractor (vehicle mass 6340 kg) travelling at 2 km/h. The tractor was fitted with Michelin tyres (front 320/85R32 at 190 kPa; rear 340/85R46 at 200 kPa). Images of the grids were captured on a digital camera (Fig. 1).

Figure 1. Image of grid projected onto the wheel track.

The images were processed using freely available software and digital maps produced.

Results and Discussion

The moiré technique allowed the production of digital maps and example of which is presented in Fig. 2. The merits of the technique, its sensitivity and comparison with alternatives will be discussed.

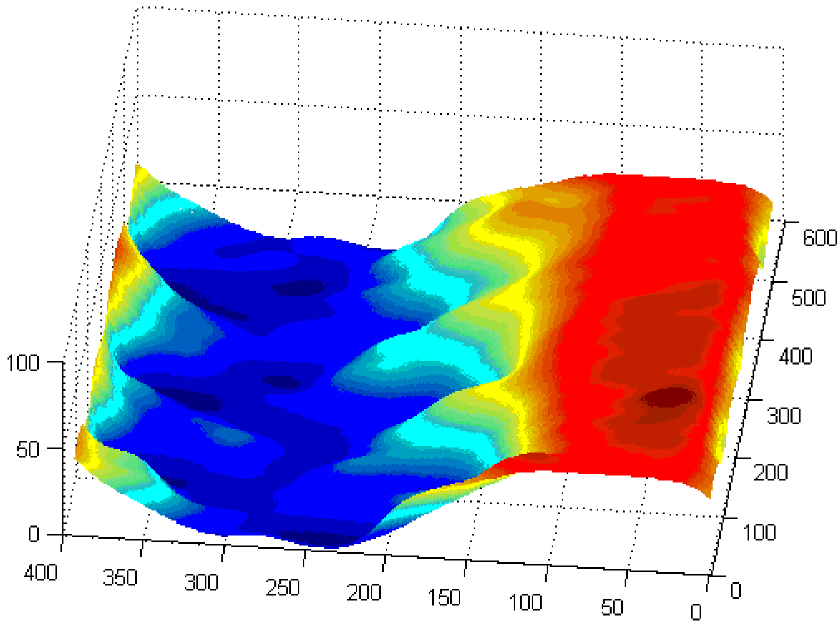

Figure 2. Digital map of the wheel track photographed in Figure 1 with all axes in mm.

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How does compaction influence preferential flow in soil?

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Soil compaction by vehicular traffic modifies the pore structure and soil hydraulic properties. These changes potentially influence the frequency of preferential flow events in macro pores especially in well-structured clay soils. However, this has been little studiedso far.Our aim was to study the effectof compaction on saturated hydraulic conductivity and preferential flow.We conducted a randomized block design trial in two well-structured clay soils mainly different in the level of groundwater. The treatments included two level ofcompaction referred to as compactedand control. The compactedtreatment was created by repeated passes with a 5-ton wheel load. After one year, undisturbed soil columns (20 cm height × 20 cm diameter) from both compacted and control plots at a depth of 30-50 cm were sampled. We observed that compaction decreased the air permeability of soil. The porosity from CT-images was also smaller in compacted than in control columns.To study the presence of preferential flow we also look at the shape of bromide breakthrough curves (these measurements are carried out at present). We hypothesizethat although compaction may decreasethe saturated hydraulic conductivity of the soils,its influence on the pore structure may alsoincrease the risk of preferential flowevents.

Soil compaction by slurry tankers at high wheel loads on a clay loam soil in Norway

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In modern agriculture increasing economic pressure leads to use of more effective and heavier machinery, even on smaller farms. Increasing cost for mineral fertilizer and the aim of accumulation of organic material in soils leads to a growing interest in use of slurry. Liquid manure is often transported over long distances between farm and field, resulting in a conflict of adapting machinery to use on arable soil.

To satisfy nutritional need of plants, slurry is often used in periods (spring) when the soil is rather wet. In combination with high machinery weight the risk for severe soil impaction therefor increases.

Soil compaction is known to reduce the production capacity of a soil and can have severe negative ecological and economical impacts. Heavy loads can enhance subsoil compaction which is considered to be irreversible.

The effect of different long term tillage practices (ploughing, direct drilling) on the bearing capacity of a clay loam soil is studied in a recently established cooperation project between Bioforsk (Norway), Christian- Albrecht- Universität Kiel (Germany) and University of Life Sciences (Norway). Furthermore it is examining the influence of the use of two different slurry tankers (4.1Mg; 6.6Mg wheel load) and contrasting wheeling frequency on soil parameters under the climatic conditions of SE Norway.

Field measurements and sampling took place at Øsaker, Sarpsborg (59° 23´ N and 11° 02´ E, 40 m above sea level) in southern Norway in spring 2011. The soil is characterized as clay loam with 34-40% clay and 40-50% silt in the topsoil, overlying clay (52%).

Soil tillage on the field site had been the same since year 2000, giving the possibility to investigate longterm tillage effects on soil structure. There were investigated two different tillage regimes, direct drilling and autumn ploughing. In both cases single (1x) and multiple (10x) passes with two different tractor slurry tank combinations were simulated.

Unloaded reference plots and loaded wheel tracks were sampled by taking undisturbed and disturbed soil samples (20, 40, 60 cm depth) to determine soil physical parameters. Stress propagation during wheeling was measured with a stress state transducer (SST). Yields of barley were measured in autumn 2011.

Preliminary results will be presented. These results show that:

- Direct drilled soils can have a higher bearing capacity compared to conventional tilled soils
- Enlarged soil-tire contact area can reduce soil compaction in the topsoil
- The first pass of a wheel can cause the greatest damage
- Soil water content is an important factor influencing bearing capacity

The results of this field trial will be part in adaption of existing guidelines and recommendations to farmers on how to avoid soil compaction under northern European conditions.

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