SOIL COMPACTION
– DRIVERS, PRESSURES, STATE, IMPACTS AND RESPONSES

PER SCHJØNNING, MATIEU LAMANDÉ AND MARTIN H. THORSØE

DCA REPORT NO. 155 · MAY 2019

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Preface

The Danish Agricultural Agency (Landbrugsstyrelsen) within the Danish Ministry of Environment and Food (in this report MFVM) has requested a report including i) an overview of impact of soil compaction on key soil functions and ecosystem services, ii) an evaluation of the compaction risk in using arable land for storage of crop products, iii) an estimate of the potential in ameliorating existing soil compaction damages, and iv) a list of potential measures to protect the soil from further compaction.

According to the request, the report should facilitate 1) the implementation of the updated EU Common Agricultural Policy, and 2) evaluation of an existing rule for storing crops on arable land.

The present report is based on knowledge gained through decades of research in soil compaction at Department of Agroecology, Aarhus University (AU). This includes field experiments, laboratory studies and non-experimental measurements in arable soil. The research has been supported by national funds (e.g., 'Innovations' projects, 'Promilleafgiftsfonden' and 'Landdistriktsmidlerne', all related to MFVM, and the Danish Council for Independent Research | Technology and Production Sciences). Our research includes a strong cooperation with international partners as witnessed by funding from several international sources. These include the Nordic Joint Committee for Agricultural Research (NKJ) and 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. At present, our research on soil compaction is funded by "Promilleafgiftsfonden" and an ongoing GUDP-project (COMMIT), where AU participate in a consortia with Copenhagen University as well as consultancy agencies (SEGES and SAGRO) and a commercial company (AgroIntelli) providing machine innovation related to mitigation of soil compaction.

We recently participated in an EU-funded research project, RECARE, www.recare-project.eu, addressing a range of threats to a sustained function of European soils. AU was in charge of a case study on soil compaction. During this project, we interacted strongly with Danish stakeholders including farmers, farmers' consultants, contractors, non-governmental organizations (e.g. The Ecological Council), farmers interest organizations (e.g. the Danish Agriculture & Food Council [Landbrug & Fødevarer]), and government officials. An introduction to our activities in the RECARE case study can be found here. As part of the RECARE case study activities, we conducted an online survey about the soil compaction threat among a group of Danish farmers (>1300 respondents). Hence, the suggestions for potential policy measures provided in this report are not only based on research in natural sciences but also include stakeholder opinions and evaluations of the soil compaction threat.

Another result of the RECARE project is a so-called Policy Brief describing the subsoil compaction threat and outlining potential policies to prevent it. The Policy Brief was presented at a policy conference in Bruxelles, September 2018 with Danish participation including MFVM. The AU RECARE group was later (November 2018) invited to present the considerations on how to deal with the soil compaction threat for the EU Commission, for DG-Environment and DG-Agri.

MFVM has requested a report with only a limited number of references to scientific publications. Hence, the cited references are listed in Appendix A together with other key sources of information used in the creation of this document.

A considerable part of the text in this report is based on a recent review published in Advances in Agronomy (Schjønning et al., 2015) and a report from the RECARE project (Schjønning et al., 2016). Another key source of information is a review of the soil compaction threat in a Danish context that was published by AU in 2009 (Schjønning et al., 2009) and can be downloaded from the internet.

The advice provided to the Ministry is comprised by the "Framework agreement between the Ministry of Environment and Food of Denmark and Aarhus University on the provision of research based policy support commissioned by the Ministry of Environment and Food of Denmark and underlying agencies 2019-2022".

The report was reviewed by Senior Scientist Lars J. Munkholm, Department of Agroecology, Aarhus University. We would like to thank a range of experts in the farmer advisory system across Denmark for valuable discussions of potential technologies and measures to mitigate the soil compaction threat.

Foulum, April 2019

Per Schjønning

Senior Scientist, Department of Agroecology, Aarhus University

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Summary

Traffic-induced soil compaction occurs when mechanical stresses from machinery exceeds the mechanical strength of the soil. During field traffic, significant stresses are transmitted to the subsoil. Soil mechanical strength is low at high water contents and high at drier conditions. The wheel load, the tyre inflation pressure and traction from wheels are key drivers of soil compaction. In this report, we define subsoil as the layers below tillage depth,- for ploughed soil typically ~0.25 m. Danish arable fields are generally very dense in the subsoil. Based on soil data collected primarily in the 1970s and 1980s, a considerable part of Danish subsoils (39%, most likely higher today) display densities critically high thereby affecting important soil functions.

Compaction significantly affects soil biota. Root growth in the soil matrix of compacted subsoil layers is restricted with influence on the crops' ability to utilize soil water and nutrients. Subsoil compaction induces a long-term reduction in crop production. The effect is likely most significant in very wet as well as in very dry growing seasons. Compaction may reduce the number of workable days in the field, which in turn may complicate the conditions for establishing the crop. Poor conditions for field traffic because of reduced drainage may increase the risk of total loss of the crop. Compaction-induced reduction in soil water conductivity may increase surface runoff and loss of nutrients and soil sediments to the aquatic environment. Soil compaction has been shown to increase the emission of greenhouse gases to the atmosphere. Compaction of the subsoil may increase the risk of by-pass water flow, hence decreasing soils' filter function for contaminants.

Subsoil compaction is long-term or effectively permanent. Mechanical loosening of subsoils is very problematic, primarily due to a high risk of soil recompaction. Plants are able to modify the structure of dense soil by creating biopores and cracks ('biological tillage'). There is lack of knowledge on biological tillage as an effective mitigation measure for severely compacted subsoils. Root growth tends to facilitate an increase in the pore volume of compacted soil. The results though indicate only minor effects. The time span needed to induce a significant effect is probably very long.

The static mechanical stress from stacks of agricultural products is low and not expected to induce soil compaction. In contrast, the stresses from agricultural machinery involved in managing the stacks are high. Traffic typically takes place at wet soil conditions, where the soil is vulnerable to compaction. Hence, stacks of agricultural products should preferably not be moved from one growing season to the next, but rather restricted to a designated part of the field to reduce the extent of damage.

The subsoil is increasingly at risk of compaction. Modern farming includes a range of field operations with a high risk of (further) deformation of the subsoil. Subsoil compaction is accumulating, persistent, not directly visible. In addition, short-term cost-benefit analyses do not provide an incentive for management changes, and poorly quantified effects on soil ecosystem services related to the environment imply that it is challenging to internalize the costs of compaction. Furthermore, the increasing mechanization in combination with climate change and use of contractors for fieldwork add significantly to the problem. This calls for public intervention.

We recommend consideration of a general requirement for EU-support. Farmers should report their planned field traffic one year in advance. Based on simplified algorithms also implemented in a state-of-the-art decision support tool (www.terranimo.dk) developed by Aarhus University, each planned traffic event should be evaluated for the risk of soil compaction. In order to increase farmers' focus on the compaction threat, we recommend as a first step only a documented planning, while a later step might include a request of modifying the planned traffic in case the evaluation indicates significant compaction damage.

We further recommend eleven potential measures that could be used for voluntary action (eco-schemes) to prevent soil compaction.

Soil compaction – introduction

Terms and definitions

Soil compaction is defined as: "The densification and distortion of soil by which total and air-filled porosity are reduced, causing deterioration or loss of one or more soil functions". The definition clearly emphasizes that compaction is a process, while the term compactness is sometimes used for the resulting density state of the soil following compaction. Compaction takes place when soils are subjected to stresses that exceed the elastic range, i.e., the soil strength.

Compactness is defined as "the state which indicates the extent to which compaction processes have influenced the packing of the constituent solid parts of the soil fabric". It denotes the residual or lasting properties and functions of a soil subjected to compaction that are of relevance for the farmer as well as for society.

Resilience is defined as "the capacity of a system to return to an equilibrium following displacement in response to a perturbation". Only fully elastic materials will return completely to their original state following release of a mechanical stress.

Subsoil is (in this report) defined as soil below tillage depth, which for mouldboard-ploughed soils is often around 0.25 m. For soils subject to continuous ploughless tillage, the subsoil layer should be defined from the alternative tillage depth. Compaction of the subsoil below tillage depth has proven very persistent, as will be documented later in this report. Therefore, the focus of this text is on subsoil compaction.

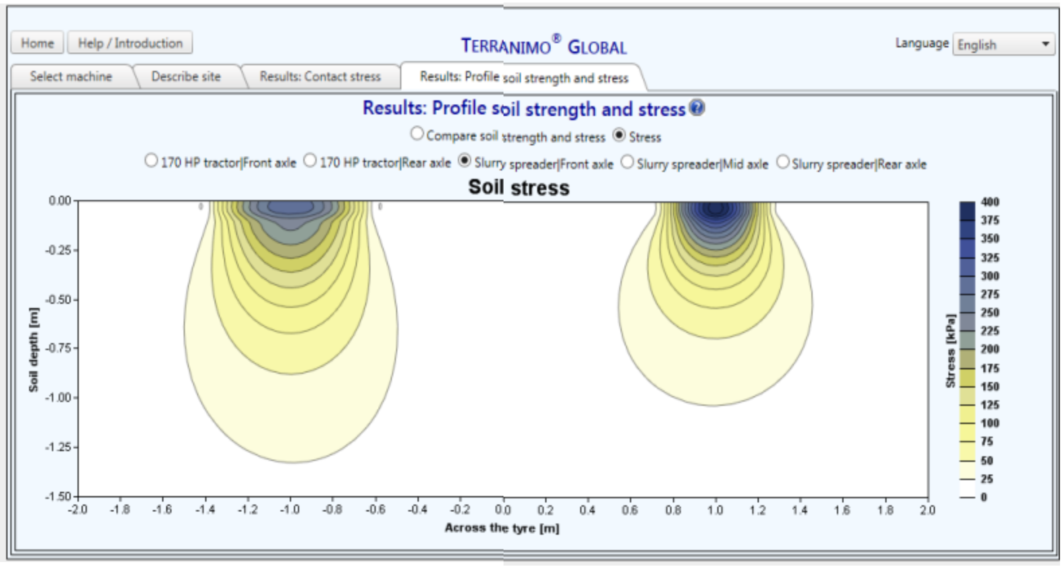
Understanding and quantifying soil compaction

Field traffic-induced soil compaction takes place when the mechanical stresses from machinery exceed soil mechanical strength. When a wheel (or a track) is passing the surface of a soil, mechanical stresses are transmitted down in the soil profile (Figure 1). The stresses reduce with depth, but with modern (heavy) machinery significant stresses may reach deep soil layers, and soil deformation has been documented to at least 0.7 m. When stresses exceed soil strength, soil is deformed. Soil deformation may include a simple reduction of the pore volume in the profile. In addition, distortion of the soil due to shear stresses may add significantly to the damage. This is because soil pores become disconnected, thereby affecting important processes like gas and water transport, root growth, and living conditions for soil biota. Shear stresses are in play especially for machinery, where the required traction to drive the wheels over the field is transferred to the soil by a single or two axles (e.g., a tractor pulling a slurry or harvest trailer).

Soil strength is strongly dependent on soil moisture. Generally, the mechanical strength increases when soil becomes dryer. The soil water content also affects the contact area between tyre and soil and the transmission to deeper soil layers (Figure 1). Hence, the risk of soil compaction is a complicated issue affected by both machinery and soil characteristics. Terranimo® is a mechanistic model that combines the relevant driver variables and predicts the risk of (sub)soil compaction for a given traffic situation based on users' choice

(Lassen et al., 2012). It is available online at www.terranimo.dk and may be used free of charge by farmers, consultants, researchers and other users.

Terranimo® integrates current state of the art knowledge of the soil compaction process. The algorithms implemented in the model includes the most recent quantitative studies listed in Appendix A. The algorithms may also be used in simple tools for evaluating the risk of soil compaction as suggested in the section "Potential measures to minimize the risk of further subsoil compaction" of this report.



○ Compare soil strength and stress ● Stress

○ 170 HP tractor|Front axle ○ 170 HP tractor|Rear axle ● Slurry spreader|Front axle ○ Slurry spreader|Mid axle ○ Slurry spreader|Rear axle

Figure 1. Predicted stress distribution in the soil profile below a similarly loaded and inflated implement tyre for a moist soil (left) and a dry soil (right). Please see text for explanation of the simulation tool, Terranimo®.

Degree of subsoil compactness for Danish soils

One parameter expressing soils' degree of compactness is its bulk density, *Db*. I.e., the mass per unit of soil, typically expressed in g/cm^3. For Danish (non-organic) subsoils, *Db* may range as wide as ~1.2-2.0 g/cm^3. The 'natural' *Db* for a given soil is, however, dependent on soil texture (the size distribution of mineral particles,- usually into classes clay, silt and sand). In order to evaluate, whether *Db* is affected by compaction, we need to look at a texture-dependent expression. The Relative Normalized Density (RND) takes into account the soils' content of clay (particle diameter less than 0.002 mm) and simultaneous relates the density to soil functions (Schjønning et al., 2016):

Clay content <16.7%w/w: $RND = Db/Db(critical) = Db/1.6$ [1a]

Clay content >=16.7%w/w: $RND = Db/Db(critical) = Db/(1.75\text{-}0.0009 \times Clay)$ [1b]

where *Db(critical)* is the *Db* critical to soil functions and *Clay* is soil content of clay (%w/w).

Schjønning et al. (2016) analysed >4800 soil horizons deriving from 1292 soil profiles in the Danish Soil Database. If excluding organic soils (organic matter >10%) and considering only subsoil horizons (including depths 0.25 – 0.7 m), it was found that ~39% of the profiles in the database had critically high densities ($RND>1$) in all geo-regions of Denmark. Importantly, a major part of the data was collected in the 1970s and 1980s. The cumulative traffic-induced compaction since then is likely to have further densified the subsoil. The data thus indicate that at least 39% of the Danish agricultural soils have critically high densities in the upper subsoil. Please consult Schjønning et al. (2016) for details including necessary precautions in the use of this simple index.

An alternative way of evaluating soil compactness is through a comparison of neighbouring fields, i.e., by comparing virgin conditions (soil never or seldom trafficked) with arable agriculture (soil subjected to frequent traffic over a long period). In a previous report (Schjønning et al., 2009), we presented measurements of soil penetration resistance for differently managed soils. Penetration resistance is simply the mechanical resistance against pressing a metal cone vertically through the soil profile. It relates to the density of soil. We compared three different areas at the Barritskov manor in Jutland: i) the park close to the building (never had any traffic), ii) a forest area only occasionally trafficked, and iii) an arable field managed as most agricultural fields in Denmark. The forest soil exhibited higher penetration resistance than the non-trafficked park area serving as a virgin control (Figure 2). The accumulated effects from traffic in the arable field were very clear and especially high at a depth of about 0.3 m, where the penetration resistance in the arable soil was about twice that of the park soil. However, higher values were observed in arable soil for all subsoil layers studied, i.e., to 0.6 m depth. The Barritskov data in Figure 2 in principle may relate to random variability, the arable field just by chance displaying higher values than virgin soil. However, similar measurements in Sweden included a range of cases, and statistical tests supported the results observed at Barritskov (Håkansson et al., 1996). The results in Figure 2 thus clearly indicate that field traffic in arable soil has densified the upper subsoil compared to the virgin condition with no traffic.

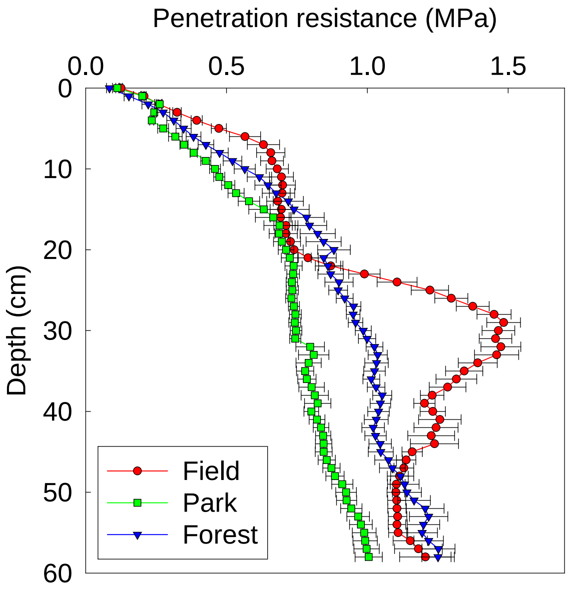


Figure 2. Cone penetration resistance measured at Barritskov Manor (loamy soil) in a non-trafficked park, a forest and in an agricultural field. Bars denote standard deviation (n=40) (Schjønning et al., 2009).

Compaction impacts on soil functions and ecosystem services

Soil pores are strongly affected by compaction. The properties of soil pores are thus key indicators of the compaction effect on processes in and functions related to soil pores. Compaction influences the total volume as well as the volumetric size distribution of pores. Very importantly, also the form (morphology) and connectivity of the pore system is affected, especially due to shear stresses as already mentioned. Both aspects should be addressed in order to understand the effects of compaction on the processes in soil pores. Please consult Schjønning et al. (2015) for a review.

Soil biota

Biotic activity, including root growth, takes place in the soil pore system. Hence, compaction-inflicted modifications of the soil pore system have crucial impact on soil biota. A reduction of the soil pore volume impairs the living conditions of macro-fauna including collembola (Larsen et al., 2004) and earthworms (e.g., Whalley et al. 1995). Root distributions in heavily compacted soil horizons are quite different from those in uncompacted soil horizons. Studies have shown that the total biomass of roots may be retained in compacted soil but that uncompacted soil has a greater proportion of deep roots. Visual evaluation of Danish soil profiles indicate that roots may by-pass compacted soil layers by following vertical earthworm channels (Figure 3). The restricted intensity of rooting in the soil matrix between such macropores of compacted layers may have significant effects on crops' ability to extract water as well as nutrients from the soil profile (Whalley et al., 1995). In one study, subsoil compaction reduced the soil water available in the root zone by up to approximately 90 mm of water (Andersen et al., 2013). Compacted subsoils may create anoxic soil conditions in wet growing seasons. A compacted soil may therefore suffer during a drought (poor rooting conditions) as well as in periods with surplus water.

Figure 3. Photo of roots using an earthworm channel to by-pass the compacted upper subsoil layer (reproduced from Munkholm, 2000).

Soil productivity

Ecosystem services is defined as "*...the aspects of ecosystems utilized (actively or passively) to produce human well-being*" (Fisher et al., 2009). In this section, we will constrain our discussion of soil ecosystem services to crop production (this sub-section) and some functions and services related to the soil environment (following sub-sections).

Soil compaction affects crop yields negatively. For the topsoil, tillage may loosen the soil to a level of compactness not optimal for plant growth. This is counteracted by different management options like furrow packing not to be considered in this report. For the subsoil, the natural density for a given soil is the base point for its support of plant growth. As documented (Figure 2), arable soils are generally compacted in the subsoil. As described in a later section, subsoil compaction is effectively permanent. Public interest in compaction impacts should hence primarily address the yield penalty for subsoil compaction, which is the focus of the following short overview.

A series of long-term field experiments with a single-event traffic treatment with heavy vehicles was carried out in an international collaboration ~1982-1993 between seven countries in Northern Europe and North America (Håkansson and Reeder, 1994). The number of experiments varied during the trial period, from 24 in the beginning to 14 in year 8. For all experiments, the treatments were 0, 1, and 4 passes track-by-track by vehicles carrying loads of 10 tonnes on single-axle or 16 tonnes on tandem-axle units. The average compaction-induced yield reduction for the whole group of experiments from year 4 onward (2.5%) was statistically significant. For the same period, the effect of one pass was about 20% of that after four passes. The 4-5 tonnes wheel loads used in these old experiments are far exceeded for much machinery used today (e.g. combine harvester front axles ~24 tonnes, i.e. ~12 tonnes wheel load). Only a few studies have quantified the effects of such high wheel loads. Voorhees (2000) summarized a range of compaction experiments with high wheel loads in maize production. Wheel loads of ~9 tonnes gave dramatic effects on the yield of maize in the first year after compaction. The residual effects interpreted as being due to persistent subsoil compaction were found to be 6% over an 11-year period for a clay loam in Minnesota, USA, and 12% for a clay soil in Quebec, Canada. In contrast, only minor effects on crop yield were observed in six long-term experiments carried out in Southern Sweden with a self-propelled six-row sugar beet harvester loading ~35 tonnes on four wheels (Arvidsson, 2001). Hanse et al. (2011) compared soil conditions on sugar beet yields for top and average growers, top and average performance being based on past yield data with average growers. Top growers had 20% ($P < 0.001$) higher sugar yields compared with their neighboring farmers, who were average growers. The yield difference was interpreted as being due to the water conductivity of the most dense 5-cm thick subsoil layer (within the 0.25-0.45 m depth range), which was significantly higher for the top growers' fields than for those of the average growers.

Compaction effects on crop yields are generally considered much affected by the weather conditions. This may mean low yields at very wet conditions especially for clayey soils (e.g. Alakukku, 2000) or at very dry conditions for other soils (e.g. Alblas et al., 1994).

Ongoing experiments on compaction in Denmark have shown blurred results. In 2010-2013, experimental plots at three sandy loams in eastern Denmark were trafficked annually with machinery for slurry application. The most common in practical agriculture is tractor-trailer combinations (typically with two tractor wheels followed by three trailer wheels in the same track). As an average of 2014-2018 (five years following stop of experimental compaction), a tractor-trailer treatment with wheel loads around 6 tonnes (most common practice) reduced the yield of winter wheat with 1.5-5.3% compared to control plots (averaged for three locations: 3.4%) (Vestergaard, 2018; Lars J. Munkholm, personal communication). An experimental treatment with an increase in trailer wheel loads to 8 tonnes (only two locations) increased the yield loss to 4.4%. The results from the individual years of experimentation indicated that weather effects on compaction impacts are very complex (data not shown).

For one of the Danish experiments a self-propelled machine with wheel loads up to 12 tonnes – but with no wheels running after each other and with traction on all wheels – was also tested. This treatment did not induce yield reduction (actually, the average 2014-2018 period yield was 2.5% higher than for control plots). Although tested at only one location, the latter calls for an increased focus on shear failure effects from traction (in tractor-trailer systems).

Assuming an acreage of 1.44 Mha of small grain cereals, an average 65 hkg/ha grain yield and 130 kr/hkg product price (www.statistikbanken.dk), the 3.4% compaction-induced long-term yield decrease related to subsoil compaction represents a revenue loss of 414 million kr. each year only for cereals production in Denmark. Assuming the same effect for agricultural areas cultivated with rapeseed (0.16 Mha), a loss of 58 million kr. per year is expected. Cereals and rapeseed represent 63% of the total agricultural area in Denmark.

The potential impact of subsoil compaction on crop yield may be much more severe than deduced from average results of even long-term field trials, where some factors may have less impact on the yields than in practice. For instance, compaction-induced poor drainage may reduce the number of workable days in the field, which, in turn, may affect the conditions for establishing the crop (delay seeding). Poor drainage may also cause problems for crop harvests in periods with much rain. Hence, the possibility of total loss of a year's crop is much more serious to the farmer than the average effect of compaction. Increasing precipitation in Northern Europe due to climate change may thus significantly worsen the compaction problem for Denmark.

Greenhouse gas emission

Compaction of subsoil layers tends to decrease the diameter of – but not close – vertical biopores, while considerably reducing the volume of minor pores branching from the vertical pores. This increases the risk of anaerobic conditions. Denitrification of nitrate is one of the potential undesirable side effects, since it removes plant-available nitrogen from the soil and potentially adds to the atmospheric concentration of the potent greenhouse gas nitrous oxide (N_2O). Soils are mostly sinks of methane (CH_4). However, anaerobic conditions promote the fermentation of organic matter, and the decomposed C may be released as methane. Some studies have indicated that compaction may turn soils into an emission source, but this effect is poorly quantified (see references in Schjønning et al., 2015).

Water flow and the soil filter function

A reduction in the volume of marginal pores in between vertical subsoil biopores decreases the pathway for water in unsaturated conditions (i.e. part of the total porosity is air-filled) and hence the unsaturated hydraulic conductivity. The saturated hydraulic conductivity is also reduced by compaction (Schjønning et al., 2017). So, saturated as well as unsaturated hydraulic conductivity will be reduced by compaction. The net effect of compaction may therefore become an increase in the risk of water saturation and potentially by-pass (preferential) flow through the macropore system (Schjønning et al., 2019). In field experiments, by-pass flow in vertical macropores is actually observed more frequently in compacted than in uncompacted control soil (e.g., Etana et al., 2013). Compaction thus affects the rate and flow paths of water in the soil profile and hence the soil filtering function. This – in turn – may increase the risk of loss of contaminants to the groundwater and aquatic environment.

Nitrogen surplus and leaching potential

The abovementioned compaction-inflicted modification of root proliferation in the subsoil may affect the crops' ability to extract nutrients including nitrogen (N) from the soil profile. One effect is a reduction in crop yield. Studies have shown that subsoil compaction affects crop N uptake more than the dry matter yield (e.g., Alakukku, 2000). A poor uptake of N from the soil profile implies a higher risk of leaching of N to the aquatic environment.

Surface runoff and water erosion

Compaction will decrease soils' ability to infiltrate and transport excess water from precipitation and thaw events. Measurements in ongoing Danish soil compaction experiments indicated critical conditions for the percolation of excess rainwater for severely compacted soil at one of three locations (Schjønning et al., 2017). When water is not taken up at the rate of precipitation, surface runoff of water will take place. For sloping areas, this may transport nutrients in solution as well as soil sediments to the aquatic environment. This – in turn – may cause eutrophication but also adds to an increased risk of flooding. Also the loss of soil from the soil is a problem in itself as it decreases soil fertility. Please consult Schjønning et al. (2009) for a review of erosion for Danish soils.

Resilience and remediation / restoration possibilities

Persistence of soil compaction

The topsoil will always be affected by traffic. However, tillage and natural processes (wetting-drying circles, freeze-thaw events and soil biota) are rather quickly able to ameliorate the damage caused. In contrast, the subsoil seems to have a very poor resilience with respect to compaction damages. Håkansson and Reeder (1994) concluded – based on crop yields for a range of field experiments – that compaction inflicted on soil layers deeper than 0.4 m depth may be regarded as effectively permanent. The effects of frost and drying have often been claimed to alleviate compaction effects. However, many of the experimental locations with persistent compaction effects mentioned previously in this report are subject to either annual or frequent frost-thaw cycles as well as wet-dry cycles that reach deep into the soil.

It is difficult to extrapolate the observations to periods beyond the approximately three decades relevant for the studies discussed. However, the historical Wadsworth Trail in Minnesota, USA, was intensively travelled by immigrants to the US more than a century ago. Supposedly, only quite light traffic was used at that time. Nevertheless, a study of soil characteristics across this trail demonstrated that the detrimental effects of mechanical stresses may last for more than a century (Sharratt et al., 1998). We thus consider that subsoils exhibit a very low resilience to compaction.

Mechanical loosening of the subsoil

One potential response to subsoil compaction might be mechanical loosening of the soil by specially designed tillage tools. However, a range of studies has clearly shown that this is a very problematic solution. An efficient subsoiling operation has to take place at water contents where the soil is friable, leading to a real breakup and fragmentation of the soil rather than smearing. However, even in such cases, the immediate effect may be detrimental to the crops. Munkholm et al. (2005) showed that root growth of winter wheat was delayed in a mechanically loosened subsoil compared with a reference (dense) soil. Generally, roots tend to follow existing macropores. When their continuity is reduced due to subsoiling, roots need to establish new routes. In addition, mechanical loosening reduces soil strength. When re-trafficked, the soil is recompacted. A range of studies has clearly indicated that for fields with continued high-load wheel traffic, severe recompaction will take place following mechanical subsoiling (see Schjønning et al., 2015 for references).

Amelioration by root growth

'Bio-drilling' is a term reflecting the action of crop roots on the pore system (Cresswell and Kirkegaard, 1995). An effect of plants may also be shrinkage and crack-formation related to increased drying-out of the soil profile. The latter process is though limited for typical Danish soil types showing limited shrink-swell ability (e.g. graded morainic or very sandy soils; Schjønning and Thomsen, 2013). Chen and Weil (2010) found that two taprooted cover crop species (both Brassicas) had more roots at the 0.15-0.5 m depth of an experimentally compacted soil than a fibrous-rooted species (cereal rye). Very importantly, in uncompacted soil there was very little difference in the vertical penetration of the roots of these three cover crops. This indicates that taprooted species may have the potential to “open up” compacted soil by creating or perhaps by enlarging existing vertical biopores.

Abdollahi et al. (2014) showed that a Brassica cover crop may also alleviate tillage pan compaction under Danish conditions. Facilitation of “preferential” growth of roots in vertical biopores may be an advantage for a succeeding crop with respect to its ability to reach deep(er) soil layers but has been shown also to decrease the root-length density of the upper subsoil layers (Perkons et al., 2014; also see Figure 3). In this context, it is encouraging that results indicate the potential of a perennial, taproot-multibranch species like alfalfa to also affect the pore system between the large biopores (Uteau et al., 2013). Former Swedish and ongoing Danish studies indicate that perennial species like chicory and alfalfa are more effective than annuals and perennial grasses in alleviating upper subsoil compaction (Lofkvist, 2005; Lars J. Munkholm, personal information).

Storage of agricultural products on arable soil

Quantification of mechanical stresses from static loading

There are generally four types of agricultural products stored in the field: potatoes, carrots, sugar beets, silage. We chose silage for the calculation of the mechanical stresses applied by the weight of the agricultural product, as it presents the largest density. Given a stack of 10x50x1.5 m of silage with a density of 1500 kg m^{-3}, the mean ground pressure was model-predicted to 22 kPa, i.e. 0.225 kg cm^{-2}, which is low in a soil compaction context. No subsoil compaction due to the weight of the silage is to be expected. The mean vertical stress in the subsoil deriving from the weight of the stack would then be almost ten times lower than the maximum vertical stress of 200 kPa beneath the rear tyre of a 330 hp tractor equipped with wide, low pressure tyres (650/85R38; rated inflation pressure; 7 tons wheel load). Even higher stresses are expected beneath the high-pressure tyres often used on tractors taking the agricultural products to the storage area (see below).

Storage duration effects

Potatoes, carrots, and sugar beets are stored on the headland of agricultural fields during the autumn, waiting to be transported to the factory. Silage may be stored for a longer time. Even with the application of the pressure due to the weight of the agricultural product for several months or even more, no subsoil compaction is to be expected from the low level of stress applied by the stored agricultural products.

Mechanical stresses from machinery during storage-related traffic

Soil compaction due to storage of agricultural products originate from the traffic to and from the storage area. Transport of agricultural products and establishment of stacks usually imply vehicles equipped with high pressure tyres dedicated to construction sites (bulldozer, excavator) and not to traffic in agricultural fields. In addition, as the storage usually takes place in the autumn, the soil around the stack is typically wet, therefore less resistant to compaction (see section ‘Understanding and quantifying soil compaction’). The number of passes around the stack is high, which will expose the soil to high stresses in a period with low soil strength. The repeated loading will generate a significant risk of subsoil compaction. As subsoil compaction is effectively persistent (see previous section), the storage area should not be moved from one field to another but rather kept on one specific spot on the farm. This in order to minimize the area exposed to the high risk of permanent damage.

Subsoil compaction as a public concern

Drivers, Pressures, State, Impact and Response (DPSIR) for soil compaction

The DPSIR concept provides an illustration of the relationship between Drivers, Pressures, State, Impact and Response with respect to soil compaction (Figure 4). Generally, the Drivers are the overall framework for farming, Pressures are the specific causes of compaction, State is the degree of damage (compaction) of the soil, Impact includes the compaction effects on soil processes, functions and ecosystem services, and Response is action taken to interfere with the problem. Potential policy regulation ought to focus Response to the drivers (full, red arrow). Temporary solutions in terms of Response to State or Impact is not considered relevant for a persistent damage like subsoil compaction.

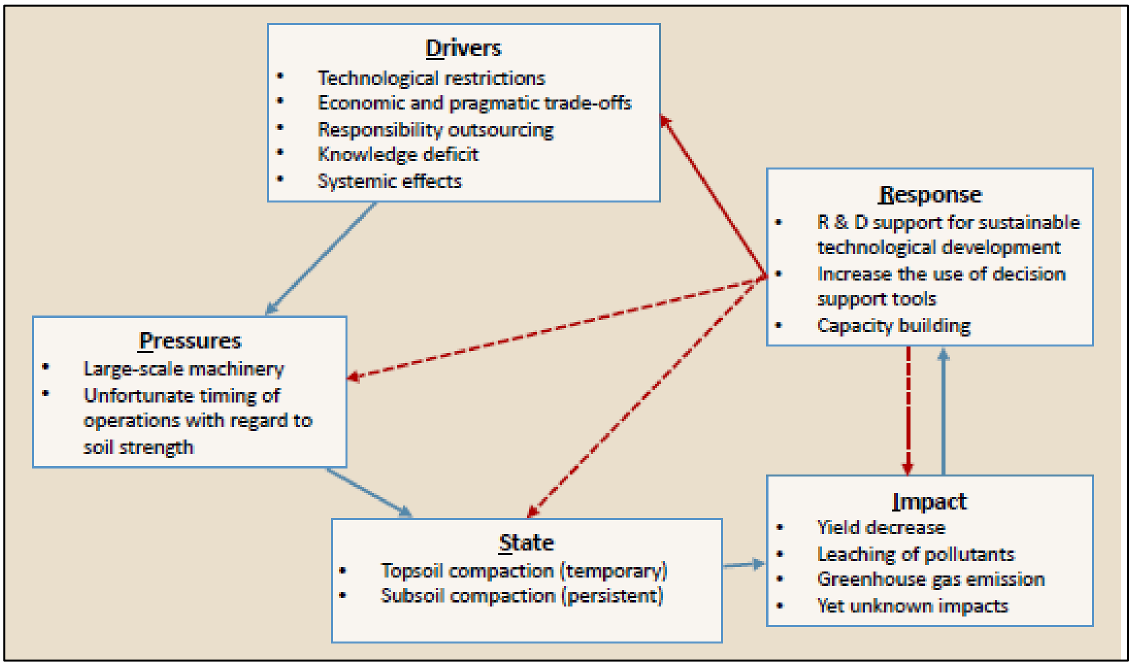


Figure 4. The Driver-Pressure-State-Impact-Response (DPSIR) concept for (sub)soil compaction. The boxes list selected characteristics discussed to some extent by Thorsøe et al. (2019).

The main Pressure: Machinery used in the field

Field operations have been increasingly mechanized since the World War II. An important side effect of this development is a significant increase in the weight of the machines. In the period 1958-2009, the wheel load of tyres on fully loaded Dronningborg combine harvesters has increased by a factor of 6 (Figure 5, left). We note that the development has further increased since 2009, modern combines with full tanks exerting wheel loads of ~12 tonnes to the soil (Henning S. Lyngvig, personal information). However, the increase in the tyre-soil contact area has not kept up with the increase in load (a factor of only 3.5 in the 1958-2009 period). As a result, the average stress at the tyre-soil contact area increased by approximately 43% from 1958 to 2009 (not shown). Simulations with the Terranimo® tool indicate that the net effect is significant increases in stresses reaching the subsoil (Figure 5, right). The vertical stress increased by a factor of 1.9, 3.0, 3.9, and 4.6, for soil depths 0.25, 0.5, 0.75 and 1.0 m, respectively (Schjønning et al., 2015).

These data document that the vertical soil stresses from commonly used machinery have increased for all depths of the soil profile during the 50-year period considered. This is despite the use of much wider and more voluminous tyres for the heavy modern machines than those mounted on older machinery.

Mechanization is driven by an ambition and need to reduce costs and labour. The larger and hence heavier machines are much more efficient in terms of minimizing labour use and therefore farmers have an incentive to apply large-scale machinery that imply a larger risk of subsoil compaction. The increase in tyre size, the use of rubber tracks, and increase in tractor power enable field operations under wet conditions, implying transmission of higher stresses to a weaker subsoil than decades ago.

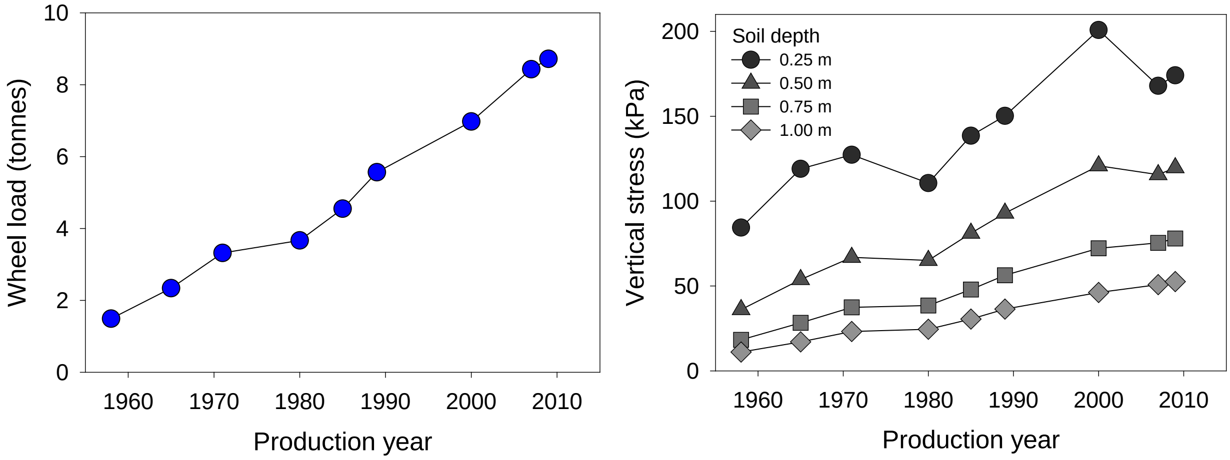


Figure 5. Development with time of wheel load (left) and model-predicted mechanical stress transmitted to the soil profile (right) for typically used combine harvester wheels in the period 1958-2009 (based on Schjønning et al., 2015).

As part of the EU-project RECARE (see Preface) the field traffic at eleven Danish farms was monitored for two years (2014 and 2015; Carstensen, 2016). At each farm the investigation included two fields, and all traffic around the year was tabulated including information on machinery as well as data on soil and cropping. The risk of soil compaction was estimated by the Terranimo® (www.terranimo.dk) decision support tool. A total of 612 traffic events was evaluated.

For 48% of the investigated wheel passes, no risk of subsoil compaction was found. For 14% there was a moderate compaction risk, while 38% included a high compaction risk. The risk was assessed in terms of the compaction at 50 cm depth of the soil profile. Four parameters were found to be especially important for the compaction risk: soil water content, tyre inflation pressure, size of tyre, and the wheel load. The investigation was presented as part of the RECARE Case Study Soil Compaction Stakeholder Workshop II.

Subsoil compaction is a systemic problem

The increasing machinery size is an attribute of a farming system which is challenged by poor adaptive capacity and the highly wicked nature of subsoil compaction. Our research documents that farmers are concerned about their soil. This is important, as it also shows that farmers do have the willingness to engage in soil protection. However, not all farmers have the ability to do so (Mills et al., 2013; Thorsøe et al., 2019). Generally, a number of factors imply that it is difficult for farmers to ascertain and address subsoil compaction:

- It is increasingly difficult for farmers to recognize the risk of subsoil compaction because it occurs underground, hence changes are gradual and cumulative and therefore, subsoil compaction is invisible to the naked eye. Furthermore, modern machinery allow farmers to perform field operations under much wetter conditions. Hence, the technological development has decoupled what takes place above ground from what happens underground, which was previously not the case. Our analysis also indicate that insufficient knowledge of subsoil compaction and preventive measures are an important explanation for the difficulty of preventing subsoil compaction.
- For farmers the costs of preventive measures are not rewarded by immediate benefits, as preventive measures are costly. It may still be more economically viable (at least in a short-term perspective) to use heavy machinery and compact the subsoil than to adopt preventive measures. Farmers continuously need to balance different considerations like profitability, the need to fulfil delivery contracts, capacity, efficiency, weather, labour and timing when planning their field traffic. In relation to some of these immediate concerns, farmers are often unable to prioritize preventing subsoil compaction.
- Contractualization of field work also partly explains the high risk of subsoil compaction in Denmark, where up to 70% of certain field operations, e.g harvesting and manure distribution, is carried out by external contractors (Thorsøe et al., 2019). Hence, the farmer is no longer entirely in control of what takes place on his fields and when activities are carried out.

Many of the abovementioned drivers are highly interrelated. Therefore, the threat of subsoil compaction is a systemic effect of a production system that afford short-term decisions, and which consequently lead to a long-term production of externalities.

As outlined in previous sections, subsoil compaction is persistent. The very poor resilience (the natural capacity of the soil to return to a pre-compacted state) imply the need for a policy response, furthermore although a number of effects are documented, these effects are poorly quantified, (see section 'Compaction impacts on soil functions and ecosystem services'). There is an increasing focus on non-recognized soil ecosystem services or non-use values of soil. Non-recognized ecosystem services can also be expressed as option values: the value we place on keeping the option open to use yet unknown ecosystem services in the future. All in all this imply the need to activate the precautionary principle to prevent further ecosystem degradation.

Figure 6 lists four soil ecosystem services that are affected by subsoil compaction (i: crop production, ii: influence on the aquatic environment, iii: soil buffering of greenhouse emissions, and iv: non-recognized ecosystem services). The effect of subsoil compaction on crop yields will not necessarily imply farmers to change to sustainable management due to short-term cost-benefit considerations. Even if some of the effects are poorly quantified, the persistent nature of the damage calls for precaution and hence public intervention.

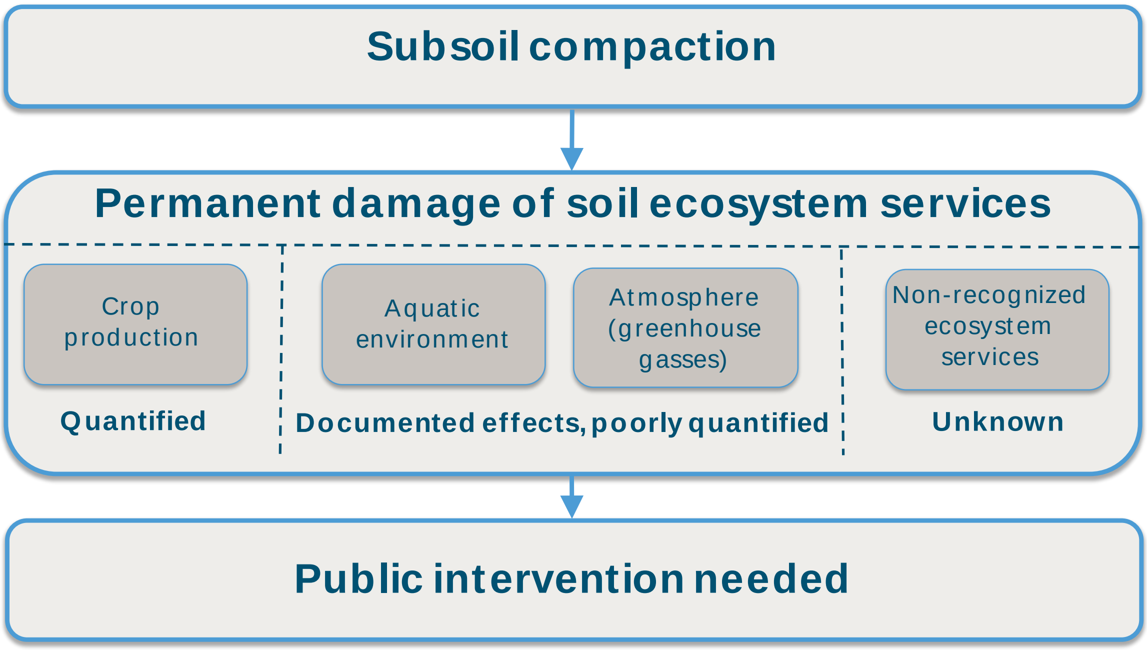


Figure 6. The persistent nature of the subsoil compaction threat combined with our (poor) knowledge of effects on soil ecosystem services calls for public intervention.

Potential measures to minimize the risk of further subsoil compaction

General rule

Reporting planned field traffic and assessing sustainability

Currently, farmers have no prior knowledge of the damage inflicted by their field traffic. One way of addressing this issue would be to set requirements for reporting planned field traffic prior to commencing field work in line with requirements for development of a nutrient plan (gødningsplan) and chemical crop protection (sprøjteplan). Reporting requirements should include: Timing of operations, machinery used, wheel load, tyre types and inflation pressures. Based on such a field traffic plan it is possible to assess the risk of subsoil compaction using the algorithms implemented in the Terranimo® risk assessment tool: mechanical stress from machinery can be compared to mechanical strength of the soil (a general description of the Terranimo® tool can be accessed here).

For the time being (2019), we find it most realistic to prepare simple tools for this exercise. This might include typical categories of machinery combined with climate-scenario-based estimates of soil strength for different combinations of soil types, geographical location and crops. Later, more detailed evaluations may be taken into use by user-friendly versions of the full Terranimo® decision support system (a sample report from the Terranimo® tool is found at the end of the note linked to in the former paragraph).

We suggest that a first step includes only documentation of planned traffic around the year. This should include an evaluation of the sustainability in performing the traffic at the scheduled time and with the intended machinery. This awareness-rising about the risk of subsoil compaction is crucial.

We note that existing decision support tools already widely used among farmers (MarkOnline/Cropmanager related to 'Dansk Markdatabase' [SEGES]) may facilitate our suggested documentation and evaluation of field traffic.

Our suggestion is based on experiences gathered in Switzerland. A simulation tool similar to Terranimo® was tested as a policy measure in the Canton of Bern. Farmers were generally satisfied with this option, which as a spin-off stimulated producers of slurry application machinery to meet the demands required in their production of new machinery (RECARE Policy Brief). We note that – in line with the Swiss experiences – the suggested assessment of sustainability of field traffic as a general requirement may alternatively be considered as a potential voluntary measure (Eco-schemes).

Eco-schemes measures

There are several opportunities to reduce the risk of subsoil compaction by use of already available technologies. The high degree of outsourcing of field work to contractors imply the need to reflect on the role of these actors in a policy intervention to prevent an ineffective outcome. We reiterate that up to 70% of high-wheel-load field traffic like slurry application is outsourced (Thorsøe et al., 2019). Policy intervention should aim at securing the application of the technologies outlined below. This should be kept in mind when designing a model for the financial support of new technologies. Below we list eleven technologies (measures) that may be used in reducing the compaction damage.

Central Tyre Inflation System (CTIS) (automatisk dæktryksregulering) (measure 1)

The use of wide, low-pressure tyres reduces the mechanical stress exerted to the soil,- primarily to the topsoil but also to some degree to the subsoil. However, the factory-recommended tyre inflation pressure for traffic at low speed (10 km/h) should be used. Often, higher pneumatic pressures are used in order to allow for traffic at higher speed on roads to and from the field. A CTIS allows the driver to inflate/deflate tyres while the vehicle is in motion thereby ensuring that farm equipment may continuously be adapted to the specific task. This is particularly relevant for machinery transporting slurry, chalk, fertilizers, etc., to the field or crop products from the field (e.g. grass, maize, small-grain cereals). The system not only allows the tractor driver to change from a low pressure in the field to a higher one for road driving. It includes the potential also of a continuous regulation taking into account the load on the wheels at any given point in the field. See note #1 on anticipated impact below. Eco-schemes supporting the use of CTIS are recommended.

Separate machinery in the field and on the road (measure 2)

An alternative way of always driving with the recommended low inflation pressures in the field is the use of a combination of different machinery on the road and in the field. Transport of products to and from the field (same materials as mentioned for measure 1 above) should then take place with machinery fitted to high load and driving speed on roads. Exemplified for slurry application, a buffer tank will then be located at the edge of the field, where the slurry spreader can load the slurry that is continuously refilled using lorries for transport from the farm. See note #1 on anticipated impact below. Eco-schemes supporting the use of separate machines in the field and on the road are recommended.

Umbilical Slurry Spreading (USS) (gyllepumpning) (measure 3)

The umbilical method of slurry handling involves pumping slurry from the tank using a high-pressure pump unit, via a pipeline, to a tractor mounted applicator unit. As no heavy tanker is taken over the fields this drastically reduces the wheel loads applied as well as the number of repeated wheel passes. Hence, the compaction damage to the subsoil is significantly reduced. The combined effect is difficult to quantify. However, if assuming the wheel load and inflation pressure of the tractor driving the fields would be 4 tonnes and the inflation pressure 1 bar, the stresses mentioned in note #2 below will give an indication. Eco-schemes supporting the use of USS systems are recommended.

Reduction of traction (measure 4)

Damaging effects to soil pores from shearing are often not taken into account in risk assessment of soil compaction. The rolling resistance of heavily loaded implement wheels on soft soil is very high. It is overcome by the pulling force of the tractive wheels. For traditional tractor-trailer systems, all traction forces are transferred to the soil by the four tractor wheels. Traction forces may induce significant soil pore distortion in the plough layer as well as the subsoil, which implies deleterious effects on soil functions. Self-propelled machinery often has traction on all wheels, which distributes traction forces at each individual wheel. A few trailers (e.g. slurry wagons) are equipped with traction at (typically) one of the trailer axles, hence reducing the traction demanded at the tractor wheels. Unfortunately, it is not yet possible to provide quantitative estimates of the reduction in stresses from traction. Nevertheless, eco-schemes supporting the use of machinery with many tractive wheels are recommended.

Reduction of wheel loads on slurry tankers (measure 5)

In Denmark, fully loaded slurry wagons mounted to tractors typically puts wheel loads about 6 tonnes to the soil. One way of reducing the wheel load is to install rubber tracks underneath the tank that can carry some of the weight of the machine. The effect of reducing the wheel load has been documented (Lamandé and Schjønning, 2017) and is especially relevant if combined with the abovementioned reduction in traction. This can be obtained in case the rubber tracks provide traction. See note #2 on anticipated impact below. Eco-schemes supporting the use of technologies to reduce the wheel load of tyres running in the field are recommended.

Offset steering machinery (measure 6)

Repeated wheeling in the same track increases the compaction damage compared to just one wheel pass. Some machines (self-propelled, as well as implements) allows for offset steering, i.e. for having the wheels running in each their path on the field (also labelled ‘dog-walk’), which will reduce the compaction impact. Unfortunately, it is not yet possible to provide quantitative estimates of the reduction in stresses from repeated wheel passes. Nevertheless, Eco-schemes supporting the offset steering concept are recommended.

Storage capacity for slurry and/or late dates of application (measure 7)

The storage capacity for slurry is often limited, hence forcing the farmer to initiate the application of slurry to the field from the 1st of February,- when it is allowed according to the rules and regulation related to leaching of nutrients. However, soils are generally wetter – hence more vulnerable to compaction – in the winter than in the spring period (Schjønning et al., 2018). We strongly suggest eco-schemes supporting later application of slurry to the fields in the spring.

Slurry application with trailing hoses rather than by injection (measure 8)

The rules and regulations related to reduction of ammonia loss during slurry application have implied more intensive and heavier traffic. This is because trail hose application systems typically demand tram lines only for each 24-36 m distance, while injection systems narrows this to 8-12 m. The increase in load for injection systems is due to the additional weight of the injection gear. We recommend eco-schemes supporting the use of trail hose application systems rather than injection systems. We note that slurry acidification combined with hose application can replace slurry injection having nearly the same risk of ammonia volatilization and hence may be one technology to take into account.

Tile drainage (measure 9)

In Denmark, the yearly precipitation has increased during the last century. It is anticipated that current climate change may further increase the precipitation in Denmark. Soils are vulnerable to compaction when wet.

Hence, an improved drainage would reduce the risk of compaction and/or increase the time window for sustainable field traffic. Eco-schemes supporting tile drainage of relevant fields are recommended.

Automatic weather stations including soil moisture monitoring (measure 10)

As mentioned several times, soils are most vulnerable to soil compaction when wet. Timing of field operations might be optimized by monitoring soils' water content. Commercially available weather stations includes the option of monitoring soil water content. Even if not used directly in planning, the monitoring would add to the important awareness-rising on the compaction risk. Eco-schemes supporting monitoring of soil water content are recommended.

On-land ploughing (measure 11)

Traditional mouldboard ploughing implies two of the tractor wheels driving in the open furrow. Tilting of the tractor exerts more than 50% of the tractor weight on these wheels. Further, the stresses from the wheels are delivered to a deeper soil layer, hence the stresses reaching the subsoil and especially the very upper part are very high. Finally, the high traction demand inflicts significant horizontal stresses leading to shear damage including distorted and disconnected (macro)pores in the subsoil. On-land ploughing is a technology, where all four tractor wheels are driving 'on land', i.e. on the topsoil. The technology is well established. Eco-schemes supporting the use of on-land ploughing are recommended.

Note #1: The effects of reduced inflation pressure (measures 1 and 2)

Assuming, as an example, the widely used Nokian 800/50R34 tyre mounted on a slurry wagon, the maximum stress in the tyre-soil contact area will nearly double (from 155 to ~300 kPa) if using 3 bar rather than the factory-recommended 1 bar tyre inflation pressure. The corresponding vertical stress transmitted to 0.5 m depth will increase from ~90 to ~115 kPa. In comparison, soil mechanical strength for a moist field in the spring is around 80 kPa (calculations based on the Terranimo® decision support tool (www.terranimo.dk)). Thus, the risk of subsoil compaction may be significantly reduced by using the factory-recommended tyre inflation pressures for traffic in the field. An important side-effect of the use of inflation pressures fitted to the traffic situation (low pressures in the field and high pressures on hard surfaces [roads]) is a reduction in fuel consumption. Lyngvig and Højholdt (2017) estimated approximately 8% reduction in fuel consumption in field operations with rated inflation pressures. The same study also documented that – in contrast to the field situation – high inflation pressures optimizes low fuel consumption when driving on roads.

Note #2: The effects of reduced wheel load (measures 3 and 5)

The wheel load is a primary driver for the vertical stress transmitted to the subsoil. Reduction of the load will thus reduce the risk of soil compaction. Assuming as an example the typically used Nokian 800/50R34 tyre mounted on a slurry wagon, the maximum stress in the tyre-soil contact area will reduce from 155 kPa for 6 *tonnes wheel load (rated inflation pressure, 1.0 bar) to ~120 kPa for 4.5 tonnes (rated pressure,- 0.6 bar). The corresponding vertical stress transmitted to 0.5 m depth will decrease from ~90 kPa for 6 tonnes to ~70 kPa for 4.5 tonnes wheel load. Again, soil mechanical strength for a moist field in the spring is around 80 kPa. Thus, the risk of subsoil compaction may be significantly reduced by reducing the wheel load. Calculations based on the Terranimo® decision support tool (www.terranimo.dk).*

Background for suggested eco-schemes measures

The characteristics of the topsoil mean a lot to crop development and the yield. Topsoil compaction will impair crop production the year it is inflicted and has proven to last for 4-5 years for clay-holding soil. It should thus be avoided. However, in the upper soil layers the conditions for natural amelioration through wet-dry and frost-thaw cycles and by biotic activity are ideal. In addition, tillage operations loosen compacted topsoil and may thus initiate a recovery of beneficial soil structural conditions. The public concern regarding the harmful impacts on soil should therefore focus particularly on the harmful management impacts on soil functions from which the soil requires a long time to recover. This has implications for potential measures to be considered for ameliorating the soil compaction threat.

Some management options occasionally suggested for minimizing soil compaction are deliberately not recommended in this report. As an example, Controlled Traffic Farming (CTF) constrains field traffic to fixed tracks in the field for as many field operations as possible. This is beneficial to crop growth in between these tracks, especially because the topsoil is not affected by wheel traffic. However, not all field operations may fit into the CTF concept (e.g., injection of slurry may require more narrow paths than spraying operations). Furthermore, the CTF concept strengthens the trend towards heavy machinery (a high distance between tracks requires powerful and hence heavy machines). The net result of CTF is thus a considerable damage to the subsoil below the tracks. This effectively permanent effect should be avoided and hence CTF should only be promoted in case it in some way solves the problem of very high wheel loads in the permanent tracks.

Another technology often discussed is the use of tracks instead of tyres on tractors as well as self-propelled machinery. Tracks will reduce the average stress in the contact area between machinery and soil. However, measurements have documented that with currently available tracks, the rollers within the track system exert significant peak stresses to the soil (Keller et al., 2002). Further, measurements indicate that tracks may induce shear higher stresses to the soil than tyres (Lamandé et al., 2018).

Subsoil compaction is a very complex issue and a consequence of the overall agri-industrial model, technological developments and market forces. It is challenging to address in policy making due to the highly dynamic nature of the soil threat, the invisibility of the problem, and because the individual yield penalty is not a sufficient incentive for farmers to change their practices. Attempts to ameliorate compacted soil by for example mechanical subsoiling have proven ineffective and even counter-productive. Hence, policy interventions should support prevention of further compaction. Potential measures to prevent subsoil compaction can focus on changing the timing of field operations and/or ensure that preventive technologies are adopted.

A range of management procedures have been significantly regulated in order to minimize leaching of nutrients to the aquatic environments. The rules implemented for that purpose have significant side-effects on soil compaction. For example, farmers are allowed to distribute animal manure and slurry only at given time windows. Also some tillage operations are restricted to certain periods of the year,- dependent on soil type. As an example of these unfortunate interactions, the storage capacity for slurry often does not allow farmers to await reasonable dry conditions in the spring for taking the slurry to their fields. Extremely heavy machinery for slurry application is driving on Danish fields from the 1st of February. At that time of the year, the soil is very wet and hence vulnerable to soil compaction.

General requirements like – for example – maximum wheel loads or ban of traffic in specific, pre-defined time windows would be rigid and limit a range of unproblematic traffic situations. Instead, it is more effective to increase farmers' competences, ability and incentives to adopt sustainable field traffic.

Appendix A, Literature references

The following list of literature includes major sources of information used in compiling this report. References cited in the text are **highlighted**.

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DCA - National Centre for Food and Agriculture is the entrance to research in food and agriculture at Aarhus University (AU). The main tasks of the centre are knowledge exchange, advisory service and interaction with authorities, organisations and businesses.

The centre coordinates knowledge exchange and advice with regard to the departments that are heavily involved in food and agricultural science. They are:

Department of Animal Science
Department of Food Science
Department of Agroecology
Department of Engineering
Department of Molecular Biology and Genetics

DCA can also involve other units at AU that carry out research in the relevant areas.

SUMMARY

Traffic-induced soil compaction occurs when mechanical stresses from machinery exceeds the mechanical strength of the soil. During field traffic, significant stresses are transmitted to the subsoil. Danish arable fields are generally very dense in the subsoil. Compaction significantly affects soil functions and ecosystem services including crop yields. Compaction-induced reduction in soil water conductivity may increase surface runoff and loss of nutrients and soil sediments to the aquatic environment. Compaction of the subsoil may increase the risk of by-pass water flow, hence decreasing soils' filter function for contaminants. Subsoil compaction is long-term or effectively permanent. Mechanical loosening of compacted subsoils is not a solution among others because of a severe risk of soil recompaction. There is lack of knowledge on biological tillage as an effective mitigation measure for severely compacted subsoils. The subsoil is increasingly at risk of compaction because modern farming includes a range of field operations with heavy machinery. Subsoil compaction is accumulating, persistent, and not directly visible. In addition, short-term cost-benefit analyses do not provide an incentive for management changes. This calls for public intervention. We recommend consideration of a general requirement for financial EU-support. Farmers should report their planned field traffic one year in advance. In order to increase farmers' focus on the compaction threat, we recommend as a first step only a documented planning, while a later step might include a request of modifying the planned traffic in case the evaluation indicates significant compaction damage. We further recommend eleven potential measures that could be used for voluntary action (eco-schemes) to minimize soil compaction.

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