RECARE
Preventing and Remediating degradation of soils in Europe through Land Care

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POLICY BRIEF

SUBSOIL COMPACTION – A THREAT TO SUSTAINABLE FOOD PRODUCTION AND SOIL ECOSYSTEM SERVICES

SUMMARY

Compaction of soil affects soil functions and soil ecosystem services, including crop yield. While natural processes and tillage can ameliorate topsoil compaction, compaction of the subsoil, i.e. the layers below normal tillage depth, is persistent and should be prevented. Due to increasing size and weight of field machinery applied in European agriculture, soils are at a growing risk of persistent damage to the subsoil. Between 1960 - 2010, wheel loads from machinery increased by almost 600%. RECARE work indicates that approximately 29% of subsoils across all Europe already are affected by subsoil compaction.

Subsoil compaction results in substantial losses of ecosystem services. The long-term annual loss in agricultural yield has been estimated to six percent or well over a billion Euros a year across Europe.

The threat of subsoil compaction is systemic in nature. Having to balance different considerations including profitability, efficiency, weather, labour and timing when planning their field traffic, farmers rarely prioritize preventing subsoil compaction. The costs of preventive measures are not rewarded by immediate benefits as such measures are costly. It may still be more profitable for farmers to use heavy machinery and compact the subsoil than to adopt preventive measures.

The persistent damaging impacts of subsoil compaction call for policy intervention in order to secure yields and adapt to climate change, as well as to sustain soil ecosystem services for future generations. Policy responses need to address the underlying drivers of farmers' decision-making concerning field traffic through a systematic and coordinated approach for sustainable soil management in Europe. In the short term, policy options include training and risk assessment elements under the Common Agricultural Policy, as well as development support for sustainable technologies.

Fig. 1 | Tractor-trailer machinery used for slurry application in RECARE field experiments

INTRODUCTION

Soil compaction is a major threat to European agriculture, due to the structural and technological developments in agriculture since the WW2, which have led to increasingly large and heavy field machinery. To ensure fieldwork efficiency and remain competitive in food markets farmers have adopted ever-larger machinery. This has resulted in increasing loads on the soil, and since compaction of the subsoil primarily is determined by the wheel load subsoil compaction has grown dramatically in recent years. Based on historical data, it has been estimated that typically used wheel loads increased from around 1.5 to 8.7 Mg in the period 1960 – 2010, or by 600%. As a result, the mechanical stress reaching subsoil layers from typically used machinery has increased by a factor of two for upper subsoil layers to as much as a factor of five for deep subsoil layers in the same period, thereby exceeding soil mechanical strength even at moderately wet soil conditions.[1]

Fig. 2 | The weight of the early Ferguson tractor was less than 1.3 tonnes

Fig. 3 | Modern tractors used, for example, in slurry application have stand-alone weights of about 12 tonnes. With trailer attached, the rear axle alone may carry >14 tonnes.

Soil compaction has a strong negative impact on crop yield and a range of other ecosystem services provided by an uncompacted soil. While topsoil compaction is reversible, compaction of the subsoil, (the layer below normal tillage depth) is effectively persistent, cumulative and invisible on the surface. Therefore, subsoil compaction should be prevented.

Soil compaction implies a reduction in crop yield. Experiments have shown that high-wheel-load traffic in wet conditions inflicts long-term yield penalties in the range 6-12%[2] [3]. In the field this means yield losses of 6% in small grain cereal production or loss in product value of €97 million in Denmark, €487million in Germany and €713 million in France (own calculation based on Bennetzen 2016[2]).

Subsoil compaction also affects a range of other ecosystem services. It reduces the buffer capacity and filter function of the soil, thereby increasing the risk of pollutants leaching to the aquatic environment. It increases the risk of surface runoff and soil loss by erosion, and it may enhance emissions of greenhouse gases. Finally, the soil is a very complex biophysical material performing a range of processes that we are yet not aware of. Hence, subsoil compaction may cause unintended effects that extend beyond the farm gate and into the future.

Subsoil compaction is thus a wicked problem that is not necessarily resolved through market forces. It calls for public intervention in order to secure current soil ecosystem services as well as soil quality for future generations.

RECARE PROJECT

Building on decades of previous research, the aim of RECARE work on subsoil compaction was to identify how the existing knowledge could best be applied to influence farmers' management of their fields. The project used Denmark as the scale for a case study. Researchers from Aarhus University joined forces with scientists at universities in The Netherlands, Sweden and Switzerland. A private company that produces agricultural machinery was also included in the team.

A review of the existing academic literature outlined the process of compaction in physical terms as well as the driving forces, including the specific pressures, the state, and the impact of soil compaction on soil functions. An analysis of existing field experiments quantified the impact of slurry application at different wheel loads on soil properties and crop yields. An existing online decision support tool, Terranimo®, was refined and evaluated by different users.

A nation-wide group of stakeholders with different perspectives on field traffic was formed that included farmers, consultants, external contractors, NGO's, public authorities and university researchers. Two stakeholder workshops revealed different perspectives and perceptions of subsoil compaction in Danish agriculture. Based on these experiences we conducted an on-line survey of farmers' perceptions of soil compaction and preventive measures, with the participation of more than a thousand respondents nation-wide.

PREVENTION RATHER THAN REMEDIATION OF SUBSOIL COMPACTION

Compaction of the **topsoil** (regularly tilled layers, close to soil surface) has a significant impact on crop yield, but this can be ameliorated by tillage and natural processes (biota, dry-wet and freeze-thaw cycles). Topsoil compaction is caused by the stress in the tyre-soil contact area, which is determined by the tyre inflation pressure. The use of wide, low-pressure tyres is the key to minimize compaction of the topsoil.

Compaction of the **subsoil** (the layer below normal tillage depth), on the other hand, is persistent, cumulative and invisible on the surface[4].

There are no effective remediation measures for subsoil compaction. Remediation using mechanical subsoiling is highly problematic because it destroys natural, preferential root channels, and the soil becomes vulnerable to re-compaction[5]. Remediation using 'biological tillage' may modify damages in the subsoil to some extent as root development may loosen the subsoil layers but seems to require decades or more[4]. Confining traffic to certain areas of the field (controlled traffic farming or CTF) is an option that may provide optimal growing conditions for a large part of the field. However, not all field operations can confine wheel passes to the traffic lanes. In order to increase the distance between traffic lanes, the concept of CTF adds to the trend towards larger and heavier machinery. CTF hence is not the optimal strategy to prevent subsoil compaction, especially in the long term.

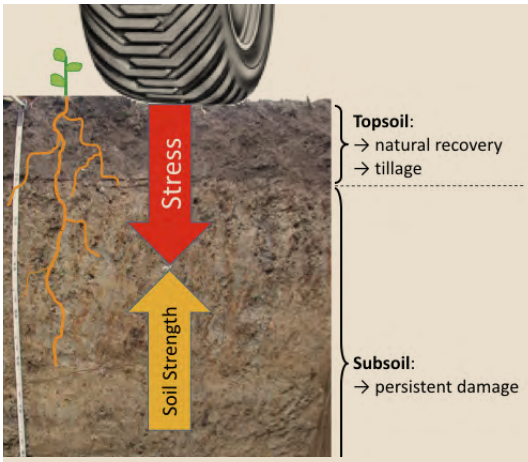


Fig. 4 | Simplified sketch of the interaction between mechanical stress from machinery and soil strength in the soil profile

Soil compaction is a reduction in soil volume and/or a change in soil form with implications for soil pore functions. It occurs when soil is subject to mechanical stresses that exceed its structural strength as a result of traffic with agricultural machinery or the trampling of animals. Stresses in the topsoil are proportional to the tyre-soil contact stress. Stresses in the subsoil are proportional to the wheel load.

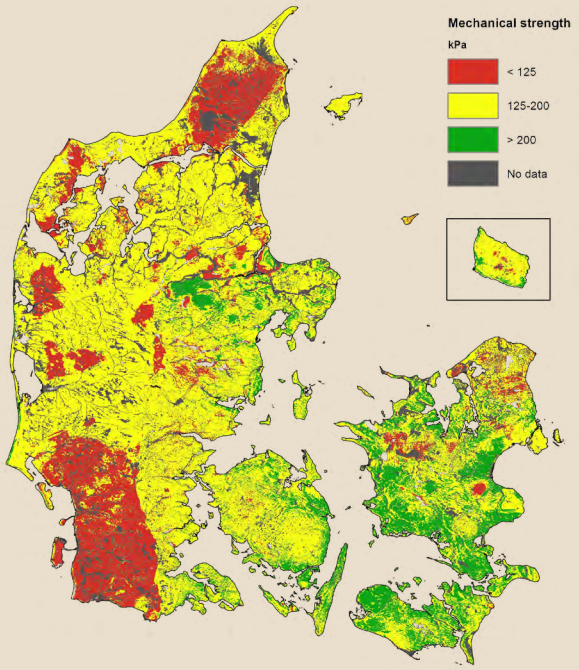
Compaction of the topsoil is ameliorated by natural processes and tillage. Structural damage to the subsoil is effectively permanent.

THE RISK OF SUBSOIL COMPACTION IS SIGNIFICANT UNDER CURRENT FARMING IN EUROPE

In principle, all soils are at risk of subsoil compaction. The risk can be quantified by a comparison of soil mechanical strength to the stresses applied by the machinery. Soil mechanical strength decreases with increasing soil water content and increases with its density.

The map of the case study area, Denmark, shows estimates of subsoil mechanical strength at wet conditions. Comparison to stresses from machinery (see map explanation) indicates that ~18% of the acreage is estimated to be highly vulnerable under wet conditions and only ~14% of the acreage would be able to withstand the stresses from typically used machinery in slurry application and harvest operations (often with >8 Mg wheel loads).

Traffic at wet conditions is mainly a problem of Northern Europe, although it can occur in all regions. It has been estimated that 50% of the most fertile soils of The Netherlands exhibit compacted subsoils[6]. RECARE work indicates that ~29% of subsoils across all Europe are affected by subsoil compaction[7].



Subsoil mechanical strength at wet conditions based on The Danish Soil Database and as predicted from Schjønning and Lamandé (2018)[8].

Acreage with estimated strength:

<125 kPa (red): ~18%
125-200 kPa (yellow): ~68%
>200 kPa (green): ~14%

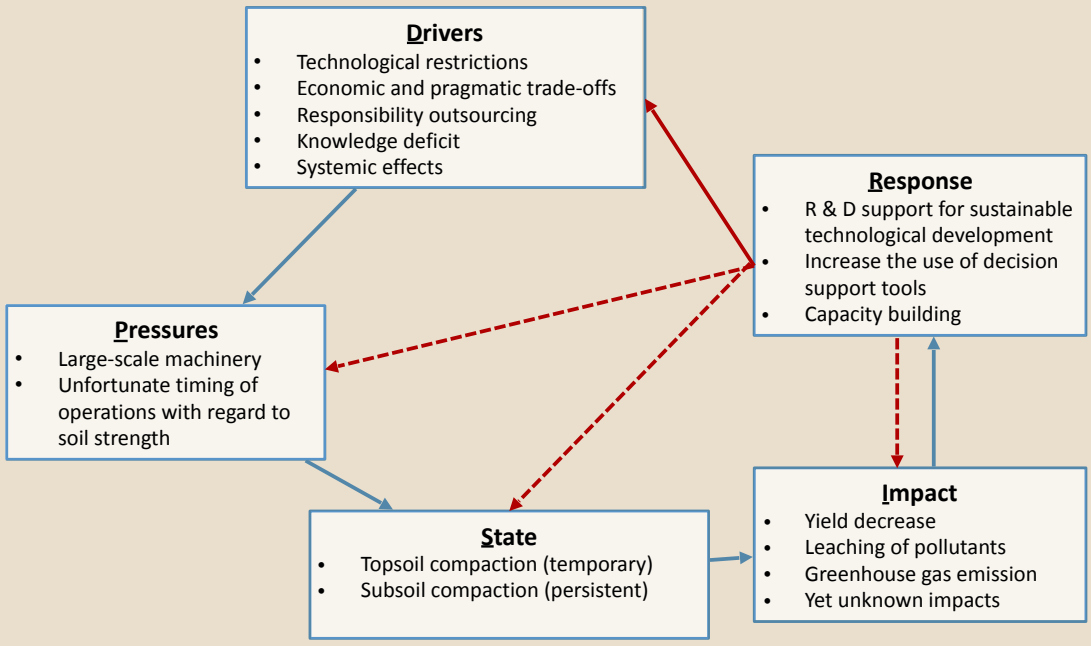
Application of slurry and a range of harvest operations often take place at this water condition and exerts stresses 200-300 kPa to the upper subsoil (e.g. Keller and Arvidsson, 2004[9]; Lamandé and Schjønning, 2018[10]).

Fig. 5 | Model estimate of soil mechanical strength for the 0.3-0.6 m layer of Danish subsoils in early spring water conditions

Even at more dry conditions, the wheel loads currently used may be causing persistent compaction damage of subsoils.. For moderately dry soil, the estimate of Danish acreage that can carry high wheel loads would increase to 33%, still leaving 67% of the area vulnerable or highly vulnerable to compaction (data not shown).

DRIVERS OF SUBSOIL COMPACTION

As mentioned above, remediation of subsoil compaction is problematic. RECARE research shows that policy response is much more likely to be effective if it focuses on prevention by addressing the drivers of subsoil compaction (See DPSIR Framework below).



The DPSIR concept provides the relationship between Drivers, Pressures, State, Impact and Response with respect to soil compaction. 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. Policy ought to focus Response to the drivers (full, red arrow). Temporary solutions in terms of Response to State or Impact should not be considered for a low-resilient damage like subsoil compaction.

Stakeholder interaction in workshops and the web survey documented that farmers are concerned about their soil, which is important, because it also shows that farmers do have the willingness to engage in soil protection, however, not all farmers have the ability to do so. Generally, the extensive **mechanization of fieldwork** following WWII has been driven by an ambition and need to reduce costs and labour.

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 to use heavy machinery and compact the subsoil than to adopt preventive measures. Farmers continuously need to balance different considerations like profitability, capacity, efficiency, weather, labour and timing when planning their field traffic. They rarely prioritize preventing subsoil compaction[11].

Throughout Europe an increasing share of the fieldwork is carried out by an external contractor. This **responsibility outsourcing** implies that many farmers are no longer in control of when the fieldwork is conducted, and which kind of equipment is used.

The web survey from the Danish case study indicates that soil compaction is also driven by **insufficient knowledge** of the compaction process and preventive measures. Without a proper understanding of the issue it is difficult to prioritize and adopt sustainable solutions. Protecting against subsoil compaction is just one among many other legitimate considerations, and many of the factors that drive soil compaction are beyond the reach of the individual farmer. The threat of soil compaction is **systemic**.

POLICY RESPONSE

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 for policy makers 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. But the persistence and the negative impacts on crop yields and soil ecosystem services calls for a policy intervention.

Whereas good management of the topsoil (e.g. through crop rotation and maintaining soil organic matter) can increase resilience of topsoil to compaction damage, subsoil compaction can only be prevented by reducing the stresses (primarily wheel load) from machinery. Policy interventions to prevent subsoil compaction can thus either focus on changing the timing of field operations or ensure that preventive technologies are developed and adopted. While farmers are the actors who carry out the field operations, policy responses to subsoil compaction needs to address the underlying drivers of farmers' decision-making concerning field traffic by adopting a systemic perspective.

Requirements for a general, maximum wheel load would be rigid and limit a range of unproblematic traffic situations. Instead, it is more effective to increase farmers' competences and incentives to adopt sustainable field traffic.

Ideally, a coordinated policy for sustainable soil management should be adopted. Without a coordinating policy on a supranational level it is difficult for companies to coordinate technological development and for governments to prioritize sustainable soil management as other issues gain preference. A new binding legislative initiative has not been proposed by the current European Commission despite the requirement set out in 7th European Action Programme.

The steps that can be taken in the short-term are outlined on the following page.

Fig. 6 | RECARE soil compaction demonstration day (May, 2016)

COMMON AGRICULTURAL POLICY (CAP) POST 2020:

- In general, ensure that the CAP post 2020 earmarks sufficient support and sets out ambitious requirements for the environment and sustainable soil management. The strategic planning at Member State levels needs to clearly identify and address soil management needs and objectives and put in place monitoring to measure the policy impacts.

- Specifically, rephrase GAEC 6 from 'Minimum land management under tillage to reduce risk of soil degradation including on slopes' to 'Sustainable land management to reduce risk of soil degradation including on slopes'. Under currently proposed GAEC 6 definition, subsoil compaction risk is not addressed sufficiently since many risk situations occur on non-tilled soils. The Commission needs to ensure that compaction is sufficiently integrated under GAEC 6 as part of the approval process for Member State definitions of GAEC standards.

- Introduce a compulsory training and risk assessment for compaction under the rephrased GAEC 6. This would require farmers to plan for good soil management and show how they address risk for subsoil compaction. For example, to do this the application of decision-support tools such as, for instance, Terranimo® (www.terranimo.dk) in farmers' planning of field traffic could be considered. The use of such decision-support tools has been shown to increase the awareness of the compaction risk and reduce problematic field traffic.

- Investment funds under Rural Development Programmes for field machinery should be tied to risk assessment for compaction and training on sustainable soil management.

- Broaden capacity building and awareness of subsoil compaction by providing training in agricultural schools and demonstration opportunities for farmers.

R & D SUPPORT FOR TECHNOLOGIES FOR SUSTAINABLE SOIL MANAGEMENT:

Technological innovation may be an important component in preventing soil compaction as the rising threat is largely driven by the structural and technological development in the agricultural sector. The risks of subsoil compaction ought to be included as a priority topic in agricultural European Innovation Partnership (EIP-AGRI) and in the allocations for national research funding in agriculture.

Given the systemic nature of subsoil compaction, these policy recommendations should be viewed as mutually supporting mechanisms to prevent subsoil compaction.

Fig. 7 | The Terranimo decision support tool is freely available on the web (www.terranimo.dk).

Terranimo® (www.terranimo.dk) is an online simulation programme for risk assessment of subsoil compaction. It provides decision support based on machinery and soil characteristics. The model requires inputs of soil and machine characteristics.

A simulation tool similar to Terranimo® was tested as a policy instrument in the Canton of Bern, Switzerland. 420 slurry tankers representing 5% in the Canton participated in a 2009-2015 pilot programme including a payment per ha if the tool documented low mechanical stresses applied to the soil. The 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 (https://www.vol.be.ch/vol/de/index/landwirtschaft/landwirtschaft/bodenschutz/foerderprogramm_bodenkantonbern.assetref/dam/documents/VOL/LANAT/de/Landwirtschaft/Bodenschutz/LANAT_LW_BS_FPB_Schlussbericht_de.pdf).

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AUTHORS

P. Schjønning, M. Lamandé, M.H Thorsøe, A. Frelih-Larsen

Further information about the soil compaction case study: www.recare-hub.eu/case-studies/aarslev

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CONTACT INFORMATION

Project website: www.recare-project.eu
Project dissemination: www.recare-hub.eu
Project coordinator: Prof. Dr. Coen Ritsema, coen.ritsema@wur.nl
Policy Assessment: Ana Frelih-Larsen, ana.frelih-larsen@ecologic.eu

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