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Reducing soil compaction[1]

1 Measure definition

Soil compaction due to vehicular traffic constitutes a major threat to agricultural soils by adversely affecting key soil functions for agricultural productivity and gas exchange. Furthermore, it may lead to a cascade of physical feedbacks by increasing runoff and the risk of soil erosion by water and wind (Horn et al. 1995). In combination with N fertilisation soil compaction leads to enhanced N_2O release because of favoured denitrification processes in compacted soils in zones of pronounced anaerobic conditions (e.g., Oenema et al. 1997; Schmeer et al. 2014).

The increasing size and weight of agricultural machinery in Europe has led to an increase in wheel loads from machinery from 1.5 to 8.7 Mg or by almost 600% between 1960 - 2010 (Schjoning et al. 2018). Since contemporary arable farming requires some type of vehicular traffic on agricultural land, zero soil compaction seems to be impossible. Manure distribution and harvesting have the highest impact on soil compaction (Thorsoe et al. 2019). Here we focus on the so-called harmful soil compaction ("Schadverdichtung" in German). Two types of soil compaction can be distinguished: topsoil compaction and subsoil compaction, i.e., compaction occurring in the layers below the tillage depth. Research from the RECARE project indicates that approximately 29% of subsoils across all Europe already are affected by subsoil compaction. Topsoils are similarly affected (Keller et al. 2019), but due to regular loosening with ploughing and other tillage operations, topsoil compactions and their implications are prevalent for shorter periods only. The economic costs of soil compaction are significant, with research in England and Wales indicating that harmful soil compaction (topsoil and subsoil) leads to total costs of 56.4 € ha^{-1} yr^{-1} (Keller et al. 2019; Graves et al. 2015). Long-term yield penalties from high-wheel load traffic in wet conditions are estimated to be from 6 – 12% (Schjønning et al. 2018). Hence reducing soil compaction has not only agronomic but also societal impact.

Three overall approaches need to be combined to reduce the risk of soil compaction: 1) improve overall soil management by improved crop rotations and maintaining good soil health/soil structure to increase resilience of topsoils; 2) increase awareness and knowledge about soil compaction, and support capacity building for farmers; 3) reduce wheel loads and develop preventive technologies. For the latter, three important measures are available: i) reducing vehicle mass, ii) increasing bearing surface of tyres and iii) controlled traffic farming. For reducing vehicle mass, there are novel strategies in progress such as using small robots operating in swarms and performing those jobs for which no traction for soil working devices is needed and which weigh only a portion of the 4 tonnes of an average tractor (Keller et al. 2019). The bearing surface of tyres can be increased through reduced tyre pressure. Controlled traffic farming often draws on GIS-based controlling systems to confine field traffic to specific or permanent tracks leaving about 85% of the field area with no traffic (Blanco-Canqui and Wortmann 2020). With this measure, farmers can reduce soil compaction by confining traffic to inter-rows that has already been trafficked, thus, limiting the amount of soil driven over (Crozia and Heitman 2014).

[1] This factsheet was developed as part of the research project "Naturbasierte Lösungen (NbS) im Klimaschutz: Marktanreize zur Förderung klimaschonender Bodennutzung" (FKZ 3721 42 502 0) and is also published as part of the Annex to the UBA report "Role of soils in climate change mitigation", see www.umweltbundesamt.de/publikationen/Role-of-soils-in-climate-change-mitigation.

This factsheet focuses on the third approach of reducing wheel loads and developing preventive technologies on agricultural soils. Although harvesting machinery also has adverse impact on forest soils, this will not be addressed here.

Geographical and biophysical applicability

- **Suitability to different biophysical conditions** Reducing soil compaction can be applied anywhere and should be of highest priority at sites/regions with high proportion of soils prone to compaction (e.g. hydromorphic soils with high clay content or organic soils), and in particular with specific activities which result in the highest weight bearing of machinery (e.g. harvest of maize, tube crops in the fall, and application of slurry).

- **Suitability in EU/German conditions:** Because of the high mechanization in EU/German agriculture, the topic is of high relevance. Reducing soil compactions by means of controlled traffic farming is locally appropriate to a wide range of commercial farms in temperate regions (Crozia and Heitman 2014; Antille et al. 2016) including different European regions (Lamers et al. 1986; Chamen et al. 1992; Vermeulen and Mosquera 2009).

Fit with NbS definition

Reducing compaction is an effective means to maintain and enhance soil health, soil biodiversity, as well as soil regulating and productivity functions (Hagedorn et al. 2018). The reduced use of machinery in itself is not an NbS, however reducing compaction is in line with the definition of nature-based solutions for this research project set out in Reise et al. (2022), provided that the measures put in place are of sufficient ambition to actually result in significant reduced risk and deliver benefits to soil health and functions.

2 Mitigation Potential

2.1 Carbon sequestration

Up to now, there are no robust estimates on the carbon sequestration potential due to adoption of measures reducing soil compaction. It can be assumed, however, that reducing compaction by introducing measures such as controlled traffic farming more SOC will be built up (Antille et al. 2015). Soil compaction affects plant growth in various ways as it increases the mechanical impedance to root growth, which decreases root elongation rates. This limits root growth and exudation (Keller et al. 2019). Root derived carbon, however, contributes much more to soil carbon sequestration than carbon from above-ground plant biomass (Poeplau et al. 2021).

2.2 Total climate impact

The overall impact on total GHG balance due to reduced soil compaction has not been estimated yet. More detailed studies exist for controlled traffic systems. The adoption of seasonal controlled traffic farming system in organic arable vegetable farms in the Netherlands resulted in a 20 - 50% reduction in N_2O emissions. Controlled traffic resulted in either increased CH_4 uptake (by a factor 5 - 20) or decreased emission (by a factor 4) compared with the random traffic farming. (Vermeulen and Mosquera, 2009). These effects are due to more anaerobic zones due to soil compaction. Based on a review by Gaso et al. (2013), five years of controlled traffic farming has the potential to reduce N_2O emissions by 21 - 45% and methane emissions by 372 - 2100% in a wide range of soils compared to random traffic farming.

More efficient trafficking also results in fuel savings, and thus reduced CO_2 emissions from fuel (Tseganesh et al. 2022).

2.3 Limitations on the mitigation potential

Positive outcomes related to soil compaction are dependent on soil texture and also when combined with other management systems like reduced tillage (Soane et al. 1982). Moreover, the beneficial impact of the practice will not grow continuously but the practice needs to be continued indefinitely to maintain the positive results.

Reports on the actual effects on SOC sequestration rates are limited in currently available literature.

3 Adaptation and co-benefits

- **Soil structure:** Controlled traffic with farming practices e.g., permanent wheel track, can improve soil structure, fertilizer use efficiency and crop yields with crops like cereal, tubers and perennials e.g., apples. Non-trafficked rows commonly have better soil properties compared with trafficked rows (Soane et al. 1982; Antille et al. 2016). Water erosion, poor drainage and aeration problems associated machinery related (e.g., ploughing) soil compaction are reduced /avoided (Soane et al. 1982).

- **Soil biodiversity:** Since soil compaction has strong impact on soil physics and nutrient flows, it alters the size and composition of microbial communities in soils (Hartmann et al. 2012; Hartmann et al. 2014). Plant symbionts, like ectomycorrhizal fungi, and saprobic taxa, such as ascomycetes and actinomycetes, are among the most sensitive to harvesting disturbances. Given their significant ecological role in forest development, the fate of these taxa might be critical for sustainability of forest ecosystems (Hartmann et al. 2012). By reducing soil compaction, this benefits soil microbial diversity and symbiotic fungi in forest ecosystems (Hartmann et al. 2012). Research in compacted arable soils confirmed changes in archaeal, bacterial and fungal diversity with a tendency towards more anaerobic archaea and bacteria (Gattinger et al. 2002), but until now we are not aware of modern molecular analyses conducted in harmfully compacted arable and grassland soils as described for forest soils above.

- **Yields and profitability:** Avoiding soil compaction helps to maintain or even increase crop yields as has been shown by Keller et al. (2019). Across four countries in Europe including Germany, Chamen et al. (1992) recorded up to 21% yield increase for wheat and barley and up to 14% increase in sugar beets, onions, ryegrass and potatoes due to zero traffic farming compared to conventional systems. On arable land in the UK, yield benefit of 4.6% was reported for a reduced wheel passes of 30% (Godwin et al. 2019). Moreover, there is also an improvement in fertilizer use efficiency and energy savings in form of reduced diesel use (Antille et al, 2015), and in profit (Blanco-Canqui and Wortmann 2010).

- **Flooding:** Soil compaction has been estimated to be responsible for 3 - 10% (average 7%) of the increase in the depth of runoff, resulting in compaction-induced flooding damage costs for England and Wales of 193 M€ $year^{-1}$ (Graves et al. 2015).

4 Trade offs

- **Costs**: The costs of certain low-compaction measures such as controlled traffic farming is high and often not rewarding especially when considering immediate benefits. Thus, it is still most likely to be more profitable for farmers to use heavy machinery that results in soil compaction than to adopt preventive measures (Schjønning et al. 2013). Farmers will continuously need to balance different considerations such as profitability, capacity, efficiency, weather, labour and timing when planning their field traffic events (Schjønning et al. 2013).

- There is the problem of standardization of working widths of tractor implements of different manufacture and this inhibits the adoption of controlled traffic in commercial agriculture. Also, there may be the need to customize equipment to meet specific requirement of different farming systems (Antille et al. 2016), e.g. customised wheel spacing, which can be expensive and limited to use (Soane et al. 1982).

- Due to the large areas lost to wheelways, controlled traffic farming might not be economically viable in some cases (Chamen et al. 1992).

- As reduced or controlled field traffic might be accompanied by zero-tillage practice (Soane et al. 1982), this might favor pesticide run-off (Blanco-Canqui et al. 2020), thus increasing the need and use of pesticides.

- New tramlining or tracks may need to be created often as previous ones get destroyed especially if needed for use for the crops later. New tramlines are needed when switching from cereals to row crops such as potato or maize.

5 Implementation challenges

The knowledge and data on the extent and severity of soil compaction at society-relevant scales needs to be improved (Keller et al. 2019). This would increase the visibility of the problem and help to guide policy action towards areas most at risk. However, even in absence of this improved data basis, there is enough information to warrant systemic action on this problem.

Limited awareness and knowledge of the problems of soil compaction, in particular of subsoil compaction which is not easily noticed, costs of preventive measures, and outsourcing of field operations are all barriers to reducing risk of soil compaction (Thorsoe et al. 2019). Within the German context, the good agricultural practice standards in the current Soil Protection Law (BBodSchG Article 17) do not include practices that would address field traffic and soil compaction problems.

A significant hurdle in introducing low-compaction measures is also absence of any limitation for the maximum wheel load. While there is a limitation for public traffic roads, this is not the case for agricultural and forest soils (also not, for example, in the German Soil protection Regulation as the implementing act (Bundes-Bodenschutz- und Altlastenverordnung).

However, this limitation would need to be combined with other measures such as increasing awareness among farming community, introducing compulsory training and risk assessment under the conditionality requirements in the Common Agricultural Policy (in particular GAEC 6), funding R&D for technological innovations (Schjønning et al. 2019).

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