Catena 167 (2018) 353–362

Contents lists available at ScienceDirect

Catena

journal homepage: www.elsevier.com/locate/catena

Risk assessment of soil compaction in Europe – Rubber tracks or wheels on machinery

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ARTICLE INFO

Keywords:
Subsoil compaction
Rubber track
Risk assessment
Agricultural practice

ABSTRACT

Subsoil compaction is persistent and affects the wide diversity of ecological services provided by agricultural soils. Efficient risk assessment tools are required to identify sustainable agricultural practices. Vehicles should not transmit stresses that exceed soil strength. Wheel load is the primary source of high stress in the subsoil. However, very low contact stress without reduction of wheel load would also help reduce stress in the subsoil. The aims of our study were to: (i) test experimentally the use of tracks instead of tires as a technical solution to increase contact area and reduce the magnitude of contact stresses, (ii) compare effects of traffic on soil physical properties using tires or tracks, and (iii) evaluate a state-of-the-art method for risk assessment of soil compaction beneath tracks or tires at the European level. We measured contact stress below a fully-loaded sugar beet harvester equipped with either a large tire or with a rubber track in a realistic harvest situation. Seventeen stress transducers were installed across the driving direction at 0.1 m depth and covered with loose soil. Dry bulk density and air permeability were measured at 0.35 m depth after traffic. The contact area was larger and the maximum and vertical stress smaller beneath the rubber track than beneath the tire. Nevertheless, stress distribution beneath the rubber track was far from uniform, presenting high peak stresses beneath the wheels and rollers. Dry bulk density was similar after traffic for the two undercarriage systems, but air permeability was lower after traffic using the rubber track. Measured stress distributions beneath the tire and the track were used as input to calculate the soil profile vertical stress for comparison with soil strength at 0.35 m depth. Wheel load carrying capacity was calculated for European soils for assessment of subsoil compaction risk when using the tire, the rubber track, and the rubber track assuming an even stress distribution. As expected from the contact area and stress measurements, the rubber track could carry higher loads than the tire. However, the air permeability results are interpreted as soil distortion due to high shear forces under the rubber track. This calls for a further development of the risk assessment method.

1. Introduction

Agricultural soils provide a wide diversity of ecological services. Root growth, water movement, aeration, and heat transfer are directly influenced by the physical properties of soils. Therefore, food production, water storage, carbon sequestration, water quality and flood protection are all ecological services that depend on the structure of soils. One major threat to the quality of soil structure is compaction, especially in the soil layers beneath the usual primary tillage depth (i.e. the subsoil). Detrimental effects of subsoil compaction on soil ecological functions may persist for several decades (Schjønning et al., 2013).

Quantification of the acreage of agricultural soils likely to be compacted by field traffic requires measurements of soil physical properties, which is laborious, especially for the subsoil. Hence, only few inventories of the extent of soil compaction damage based on measured indicators exist. Schjønning et al. (2016a) calculated the Relative Normalized Density (RND) for European soils. In short, RND is an expression of the packing density relative to what is considered a natural state for a given soil. The exercise was based on the SPADE8 database, which includes estimates of soil texture and dry bulk density derived from expert judgments (Koue et al., 2008; Panagos et al., 2012). About one-quarter of European soils was found to have critically high densities in soil horizons covering the 0.25–0.70 m depth interval.

In the European Union (EU), society concerns prompted a comprehensive review of threats – including compaction – to the quality of agricultural soils. Following stakeholder consultation, a “Soil Thematic Strategy” was formulated as a follow-up to the review (van Camp et al.,

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https://doi.org/10.1016/j.catena.2018.05.015
Received 8 January 2018; Received in revised form 8 May 2018; Accepted 15 May 2018

Table 1
Topsoil (0.13–0.17 m) characteristics of the soil investigated: ρ_b, dry bulk density, θ, volumetric water content, k_a, air permeability, σ_{pc}, precompression stress, C, cohesion, φ, angle of internal friction.

Texture					ρ_b	θ		k_a[a]	σ_{pc}	C	φ
g 100 g^{-1}					g cm^{-3}	m^3 m^{-3}		µm^2	kPa	kPa	°
< 2 µm	2–20 µm	20–63 µm	63–2000 µm	Organic matter		Field	− 100 hPa				
8.0	13.5	12.2	63.4	2.9	1.32	0.246	0.253	35.6	43.3	8.3	33

[a] Geometric mean.

2004). A Soil Framework Directive (SFD) was proposed to oblige member countries to take actions to secure a sustained quality of the soil resources. However, the EU Commission withdrew the SFD proposal in 2014. At present (February 2018) it is unclear whether any initiatives to regulate field traffic in order to avoid compaction will be launched within the EU. Public endeavors to minimize soil compaction have been established at the local scale, for example in the Swiss canton of Bern and in some German federal states.

Mechanization in modern agriculture implies an increase in the mechanical stresses reaching subsoil layers (Vermeulen et al., 2013; Schjønning et al., 2015a). A range of studies clearly indicate that many agricultural field operations are very likely to induce compaction of the subsoil (e.g. Arvidsson et al., 2003; Duttmann et al., 2014; Gut et al., 2015). Irrespective of potential legislation targeting the compaction problem, it is therefore important to develop tools to identify the risk of soil compaction.

Jones et al. (2003) suggested a procedure to estimate the risk of soil compaction across soil types. This includes an initial estimate of the inherent susceptibility to compaction based on soil texture and soil density. Soils in their natural state display variation in bulk density (BD) related to their texture (Heinonen, 1960). A soil packing density (PD) may thus be normalized to the content of clay (Renger, 1970). Based on expert judgment, Jones et al. then suggested four classes of susceptibility for different combinations of soil textural classes and PD: low, moderate, high, and very high. This was to be followed by an assessment of climate on the actual vulnerability to compaction by calculating the potential soil moisture deficit (PSMD: evapotranspiration minus precipitation) during the growing season. However, van den Akker and Hoogland (2011) suggested that the expert model by Jones et al. (2003) was rather arbitrary with results that are not in agreement with reality. In any case, vulnerability estimated from PSMD will never be able to describe the specific vulnerability for a given traffic situation in winter or early spring. In addition, the approach suggested by Jones et al. (2003) does not consider the size and type of machinery used in field traffic.

Another approach in risk assessment for soil compaction involves a quantitative comparison of stresses transmitted to the soil profile with soil strength, which should not be exceeded by stresses (van den Akker and Hoogland, 2011). This includes modeling of stresses from machinery in combination with estimates of soil mechanical strength from pedotransfer functions (PTFs) using readily available soil properties. The stress distribution in a tire-soil contact area may be predicted from tire characteristics (Schjønning et al., 2015a). Transmission of stress from the soil surface to the subsoil can be reasonably estimated using the analytical solution obtained by Boussinesq (1885) for the problem of normal loading of the surface of a homogeneous, isotropic, elastic half-space by a concentrated normal force (Keller and Lamandé, 2010). Soil strength, in turn, may be estimated from only three soil parameters: clay content, dry bulk density, and matric potential (Schjønning and Lamandé, 2018).In contrast to the risk assessment procedure suggested by Jones et al. (2003), the mechanistic comparison of mechanical stresses with soil strength enables evaluation of the risk of soil compaction for specific machinery and soil conditions. The approach can be used for mapping purposes, as will be demonstrated in this study, as well as decision support systems (e.g. www.terranimo.dk).

Limiting the risk of subsoil compaction calls for the use of large tires. Schjønning et al. (2015b) estimated that sustainable traffic with a ~75 kN wheel load in moist soil conditions would require tires wider than 1.3 m (~2 m^2 contact area). However, there are limitations to the height and the width of agricultural vehicles driving on roads, which limits the size of tires. Using a rubber-tracked undercarriage instead of a wheeled undercarriage is a technical solution to increase the contact area without increasing vehicle width and height (Alakukku et al., 2003). However, the few studies available show an uneven distribution of stresses at the track/soil contact, characterized by high peak stresses below the track wheels and rollers (Blunden et al., 1994; Keller et al., 2002; Arvidsson et al., 2011).

The objectives of this study were: (i) to compare the stress distribution at the soil surface as well as the soil stress propagation beneath a large, low-inflation-pressure traction tire and a rubber track mounted on identical sugar beet harvesters; (ii) to evaluate the consequences of traffic with both vehicles on soil physical properties; and (iii) to evaluate the potential of using rubber tracks instead of tires to reduce the risk of subsoil compaction in Europe.

2. Materials and methods

2.1. Field test

The experiment took place in November 2013 at the Krenkerup Estate, which is located on the island of Lolland in Southwestern Denmark (54.773°N, 11.685°W). The soil was classified as a Eutric Cambisol (FAO, 1998). The soil texture class was a loamy sand in the topsoil (0–0.2 m depth; Table 1). Soil water potential was close to −100 hPa at the time of the experiment (Table 1). The test soil was ploughed annually to ~0.25 m. The field had been grown with small-grain cereals in the year of investigation (stubble not tilled after harvest two months prior to the tests).

2.2. Contact stress measurements

We measured the distribution of vertical stress at the interface between soil and wheel or track of a sugar beet harvester using the procedure described in Schjønning et al. (2008). Two identical single-axle harvesters were equipped with either a large traction tire (1050/50R32) with low inflation pressure (150 kPa) or a rubber track (0.92 m × 1.325 m; a front and a back wheel with two support rollers) (Fig. 1). The tire and the rubber track did not pass in the same track as the tractor towing the harvester, therefore characteristics and consequences of solely the tire or the rubber track could be tested here (Fig. 1). Note that both wheels of the rubber track were lowered to increase the contact area. The tanks of both harvesters were filled with beets to yield a load of approx. 10.5 Mg on the tire or rubber track at a weighbridge. During the tests with the rubber track, the experimental conditions required a slight twist of the harvester relative to the tractor. This resulted in a higher load being put on the rubber track. Based on the readings of the stress transducers, the real load under the track was approx. 12 Mg. The track unit by itself weighs approx. 1 Mg more than the rim-mounted tire. Thus, the tests are close to a comparison of a rubber track and a tire with identical loads of beets in the tank.