This PhD investigated processes of soil compaction, with a particular focus on tyre-soil interactions as affected by tyre evolution, traction and repeated wheeling. Stresses induced by wheels onto and/or into soil were measured in vertical and horizontal (in the driving) direction in field compaction experiments. The soil response to the experimental traffic was quantified by measurements of penetration resistance and/or soil structural properties. The studies revealed that the risk of soil deformation by compaction was reduced for machinery equipped with tyres with a large tyre-soil contact area and low tyre inflation pressure, for machinery with limited traction and by limiting the number of repeated wheeling. These research findings are of strong importance for the development and application of intelligent mitigation measures to reduce the risk of soil compaction.
Revealing key processes of soil structure deformation after traffic

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PhD Dissertation
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Preface

The present dissertation entitled “Revealing key processes of soil structure deformation after traffic” is submitted in partial fulfilment of the requirements for the Doctor of Philosophy (PhD) degree at the Graduate School of Technical Sciences, Aarhus University, Denmark. The reported research is a compilation of three studies performed at the Department of Agroecology, Aarhus University, Denmark, in cooperation with businesses and scientists in Denmark and abroad over the course of three years (from February 2018 – February 2021).

The dissertation is based on four research papers submitted to peer-reviewed journals and on data from a third experiment. The dissertation includes an introduction of the rationale behind the research, followed by material and methods providing a description of the experimental sites and set-ups as well as on the measurements and analyses of soil stress and soil response. Next, major findings are presented and discussed. The main conclusions and perspectives for future studies are presented, and the supporting papers are added as appendices. Parts of the dissertation are adapted from the progress report for the qualifying exam submitted to the Graduate School, then called the Graduate School of Science and Technology, in 2019.

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I want to conclude by expressing my gratitude to my family for their unlimited support of my choices, for their visits and for them always trying to understand. Same goes for Joris, who would cheer me up, would come around to field and lab, who built my PhD-recharge station, gave me cause to take my mind of the PhD and made my home in Denmark.

Lorraine ten Damme

April 2021
Summary (English)

One of the main threats to the quality of agricultural soil in Europe and elsewhere is soil compaction, mainly due to excessively heavy traffic driving in non-optimal conditions. Over the past decades, machinery has become increasingly heavy and more powerful, thereby increasing stresses exerted on soil. When the strength is exceeded, the soil structure changes and the ability of a soil to deliver its functions (e.g. provide food, habitat, flood regulation and nutrient recycling) can be seriously hampered. Critical aspects of soil compaction are its persistence, especially in the subsoil, as well as the perpetual risk of compaction. Reducing this risk is therefore essential. The effect of a passing wheel on soil strength and structure is, however, complex and not all machinery-soil interactions are understood yet.

This dissertation aims to summarise the setup and results of three field compaction studies that were designed to fulfil the following objective: To deepen our understanding of key processes of soil structure deformation after traffic, with a particular focus on tyre-soil interactions as affected by tyre evolution, traction and repeated wheeling. The effect of different tractor tyre designs was tested, as was the performance of a novel trailer designed to reduce the risk of soil compaction during heavy traffic, and the effect of traction for a given wheel load and inflation pressure. Measurements included drawbar pull, stresses in the contact area, soil stress in an undisturbed soil profile, and soil structural properties and penetration resistance.

The choice of tyres plays an important role in mitigating the risk of soil compaction (experiment Ladoux). Measured mean normal stress and calculated vertical stress under the centreline of tractor tyres of a newer design were significantly reduced compared with the tyres of an older design, even in the subsoil (at 0.6 m), when tested at similar static wheel loads (4.3 Mg rear wheel) and using the manufacturer-recommended inflation pressures (240–60 kPa). The differences were explained by the increase in the tyre-soil contact area for the newer tyres, the associated lower tyre inflation pressure and the resulting improved distribution of vertical contact stresses. The differences between tyres of similar dimensions but different constructions disappeared if the tyres were inflated to the same pressure. The benefit of the newer designs to the distribution of vertical contact stresses is quickly lost if the tyre is overinflated, hence regulating tyre inflation pressure is essential. Further contributions of tyre evolution to the reduction of soil stress may be limited, as tyres need to be of large dimensions to prevent unsustainable field traffic.

Different levels of traction (expressed as drawbar pull) on a tractor with a similar static wheel load (3.6 Mg rear wheel) and tyre inflation pressure (80 kPa) revealed that traction affects more aspects of tyre-soil interaction than the magnitude of horizontal stresses (experiment Foulumgaard A and Foulumgaard B). Substantially different tyre-soil interactions were
observed for towed and driven tyres, i.e., without and with traction. Traction affects the loading time and magnitude of vertical and horizontal stresses in the contact area. For higher levels of traction, the maximum vertical stress was significantly lower due to a larger contact area (with corners becoming squarer rather than circular) and a better distribution of the vertical stresses therein. In the upper subsoil, no effect of traction on soil stress was measured, but soil stress increased with wheel load for passive trailer tyres. These results revealed a relation between horizontal and vertical soil stress that may reflect a soil’s ability to transmit stresses, similar to the concentration factor introduced by Fröhlich. A significant effect of traction on soil structural properties was quantified in Foulumgaard A (6.5 and 9.1 kN drawbar pull), but no effect was found in Foulumgaard B (towed and 41.6 kN drawbar pull). A modelling exercise to predict horizontal stress in the soil profile was performed.

Three repeated wheeling of a passive trailer tyre (5.5 Mg, 140 kPa) did not alter tyre-soil contact characteristics (Foulumgaard A), nor were the soil stress measurements significantly affected by the repeated measurements (Ladoux and Foulumgaard A). The soil structural response to the increasing number of passive wheel passes (1–3 and 6) was, however, gradual (Foulumgaard A). No significant soil response was measured during the first three passes, but the soil was seriously densified after six passes, although not to the extent that functional pore space had diminished.

In conclusion, the risk of compaction is reduced for machinery equipped with tyres with a large contact area and low tyre inflation pressure, with limited traction and limited number of repeated wheeling.
Sammendrag (Danish Summary)

Pakningsskader påvirker en række nøglefunktioner i landbrugsjord (f.eks. afdræning, udbytte og drivhusgasudledning) som følge af hæmmet rodudvikling og reduceret transport af vand og luft igennem jorden. Det mest kritiske aspekt er, at strukturen er svær at genoprette, når pakningsskaden er sket. Det gælder især i underjorden under normal jordbearbejdningsdybde (> ca. 0,25 m dybde). Derfor er det meget vigtigt at mindske risikoen for jordpakning forårsaget af kørsel med tunge maskiner. Det kan gøres ved at køre, når jorden har en god bæreevne (dvs. ikke for våd) og/eller ved at begrænse belastningen på jorden. I løbet af de sidste årtier er maskinerne blevet tungere og stærkere, hvilket har øget belastningen. Dette er en vigtig årsag til øgede pakningsproblemer over tid. For at mindske risikoen for jordpakning er en detaljeret forståelse af nøgleprocesser i forhold til jordpakning nødvendig, som omfatter komplekse vekselvirkninger mellem hjul og jord. Ikke alle aspekter og deres sammenhænge er kendt endnu.

Formålet med dette PhD-projekt var at øge forståelsen af nøgleprocesser af jordpakning som følge af kørsel i marken med landbrugsmaskiner. Specifikt blev der fokuseret på effekten af gamle og nye dæk, trækraft og gentagne overkørsler på stressfordeling og jordens respons i form af fysiske egenskaber. Tre markforsøg blev udført, hvor trædefladeareal og fordelingen af trykket under hjulene blev målt og supplered med målinger af trykfordeling i underjorden. Desuden blev responsen i jorden målt, i form af penetreringsmodstand i marken og egenskaber, såsom massefyldte og luftpermeabilitet, på jordprøver i laboratoriet.

Valg af dæk har stor betydning for risikoen for pakningsskader, fordi det påvirker både trædefladeareal og trykfordelningen i trædefladen (Ladoux forsøget). Både den målte gennemsnitlige normale trykfordelning og den beregnede lodrette trykfordeling var lavere for nye dæktyper end for ældre typer. Det gjaldt selv i 0,6 m dybde for samme hjullast (4,3 Mg) og ved brug af det anbefalede dæktryk til 10 km h⁻¹ (240–60 kPa) for alle dækkene. Forskellene skyldtes et større trædefladeareal og lavere dæktryk for de nyere dæktyper, som resulterede i en bedre fordeling af det lodrette tryk på overfladen. Der var ingen forskel mellem dæk af samme dimensioner (20.8 (R)38 og 710/70 R42) ved kørsel med samme dæktryk (240 og 80 kPa). Den mindske risiko for pakningsskader for nyere sammenlignet med ældre dæktyper forsvinder, hvis dæktrykket er sat for højt. Det betyder, at regulering af dæktryk er vigtigt for at kunne opnå fuld fordel af at anvende nyere fleksible lavtryksdæk. Mulighederne for at udvikle en endnu bedre dæk med hensyn til minimering af risikoen for jordpakning vurderes at være begrænsede. Det vil kræve udvikling af dæk med meget store dimensioner, som kan være et problem ved kørsel på vej.

Trækraft var forventet primært at påvirke de vandrette kræfter i jorden. Det viste sig dog at en ændring af trækraft, for samme hjullast (3,6 Mg) og dæktryk (80 kPa), ændrede flere
aspekter end vekselvirkningen mellem hjul og jord (forsøgene Foulumgaard A og Foulumgaard B). Der blev observeret væsentligt forskellige interaktioner mellem hjul og jord for trækkende og kørende dæk, dvs. med og uden trækraft. Trækraft påvirker belastningstiden og størrelsen af de lodrette og vandrette kræfter i trædefladearealet. Det maksimale lodrette tryk var signifikant lavere for højere trækraft. Det skyldtes et større trædefladeareal (uden signifikant forskel på længden og bredden men med en mere kvadratisk end cirkulær fordeling) og en bedre fordeling af de lodrette tryk indenfor trædefladearealet. Dybere i jorden (0,3–0,4 m) var der ingen sikker effekt af trækraft på hverken den vandrette eller lodrette trykfordeling. Dog blev der målt en stigning i disse med hjullasten for passive kørende vognhjul. Disse resultater viste en sammenhæng mellem vandrette og lodrette tryk påvirkninger i jorden, der afspejler jordens evne til at forplante tryk. En signifikant effekt af trækraft på jordens strukturelle egenskaber blev kvantificeret i Foulumgaard A i 0,15 m dybde (6,5 og 9,1 kN trækraft), men det blev ikke målt i Foulumgaard B i 0,10 m dybde (trukket og 41,6 kN trækraft).

Trædefladeareal og fordeling af tryk inden for arealet ændrede sig ikke signifikant for 1–3 gentagne overkørsler af et passivt kørende vognhjul (6,6 Mg hjullast, 140 kPa dæktryk, Foulumgaard A). Der blev heller ikke målt en effekt af gentagne overkørsler med trækkende traktorhjul på trykfordelingen (Ladoux og Foulumgaard A). Jordens strukturelle egenskaber i 0,15 m dybde reagerede gradvist på de stigende antal passive hjul (1–3 eller 6, Foulumgaard B). Der blev dog ikke målt en signifikant forskel i løbet af de første tre overkørsler, men betydelige pakningsskader blev kvantificeret efter den sjette, dog ikke i en sådan grad at det funktionelle porevolumen blev påvirket.

Sammenfattende viste projektet, at man minimerer risikoen for pakningsskader bedst ved at bruge dæk med stort trædefladeareal og lavt dæktryk, begrænset trækraft og ved at have ingen eller kun få gentagne overkørsler.
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The supporting papers will be referred to by their Arabic numbers in this dissertation.
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**Nomenclature**

- $a$: Half-length of the contact area, m
- $A$: Contact area, m$^2$
- $A_t$: Contact area in front of the axle
- $A_2$: Contact area behind the axle
- $A_{ellip}$: Estimated contact area, m$^2$
- $A_{num}$: Measured contact area, m$^2$
- $b$: Half-width of the contact area, m
- $DC$: Degree of compactness, %
- $DP$: Drawbar pull, kN
- $E$: Young’s modulus, kPa
- $F_{app}$: Apparent wheel load, Mg
- $F_{dynamic}$: Dynamic wheel load, Mg
- $F_{static}$: Static wheel load, Mg
- $k_a$: Air permeability, $\mu$m$^2$
- $k_{a,App}$: Apparent air permeability, $\mu$m$^2$
- $k_{a,Darcy}$: Darcian air permeability, $\mu$m$^2$
- $K_r$: Variable for the ratio of tyre inflation pressure
- $l_1$: Length of contact area in front of the axle
- $l_2$: Length of contact area behind the axle
- $L$: Tyre deflection, %
- $n$: Parameter describing the squareness of the contact area
- $p_i$: (Bolling probe) inclusion pressure, bar
- $p_{i,\text{max}}$: Maximum (Bolling probe) inclusion pressure, bar
- $p_{\text{max}}$: Model-fitted maximum vertical contact stress, kPa
- $p_{\text{mean}}$: Mean ground pressure, kPa
- $PO$: Pore organisation, specific air permeability, $\mu$m$^2$
- $p_{\text{peak}}$: Measured maximum vertical contact stress, kPa
- $PR$: Penetration resistance, kPa
- $p_{\text{tyre}}$: Tyre inflation pressure, kPa
- $S$: Slip, %
- $sc$: Soil core sampling
- $SLR$: Static loaded radius, m
- $Sq$: Soil structural quality
- $UCCT$: Uniaxial confined compression test
- $UUCT$: Uniaxial unconfined compression test
- $v$: Poisson’s ratio
$V$  Fröhlich’s concentration factor

$V_{\text{act}}$  Actual forward speed, ms$^{-1}$

$V_{\text{th}}$  Theoretical forward speed, ms$^{-1}$

$W$  Tyre width, m

$a$  Parameter describing the distribution of vertical stress in the contact area in the driving direction

$\beta$  Parameter describing the distribution of vertical stress in the contact area across the driving direction

$\varepsilon$  Fraction of total porosity, cm$^3$ cm$^{-3}$

$\varepsilon_a$  Fraction of air-filled porosity, cm$^3$ cm$^{-3}$

$\varepsilon_{\text{a-blocked}}$  Fraction of blocked air-filled porosity, cm$^3$ cm$^{-3}$

$\varepsilon_{\text{eff}}$  Fraction of effective air-filled porosity, cm$^3$ cm$^{-3}$

$\theta$  Volumetric soil water content, m$^3$ m$^{-3}$

$\rho_b$  Bulk density, Mg m$^{-3}$

$\rho_{\text{b-ref}}$  Reference bulk density, Mg m$^{-3}$

$\sigma$  Stress, kPa

$\sigma_m$  Mean normal stress, kPa

$\sigma_{\text{pc}}$  Confined precompression stress, kPa

$\sigma_x, \sigma_{x-\text{in}}, \sigma_{x-\text{out}}$  Horizontal stress (in the driving direction), kPa

$\sigma_z$  Vertical stress, kPa

$\sigma_{z-0.5}$  Vertical stress at 0.5 m depth, kPa

$\tau$  Shear stress, kPa
1 Introduction

1.1 Background

The use of excessively heavy machinery in agriculture in non-optimal, often waterlogged, soil conditions triggers one of the main threats to soil quality in Europe (Brus and van den Akker, 2018; Schjønning et al., 2016b) and brings a considerable risk to the quality of agricultural soils around the world (Ishaq et al., 2001; Oldeman et al., 1991). When a soil’s internal strength is exceeded by an applied stress, the soil deforms, creating a soil state that is referred to as compacted soil. Compaction reduces the number of structural pores and increases the inter-aggregate bonds (Guérif, 1990; Obour et al., 2017), which increases soil strength (especially after drying) and restricts root growth and transport of water and air. Soil compaction effects have been measured to depths of one meter (Alakukku, 1999).

Consequences (Fig. 1) range from increased leaching of nutrients and pollutants, loss of soil biodiversity, risks of erosion, flooding and greenhouse gas emissions, to higher energy inputs required during cultivation, a reduction in the number of days when soil is trafficable and workable, and impaired crop development and yield loss (Alblas et al., 1994; Arvidsson and Håkansson, 2014; Edwards et al., 2016; Horn and Peth, 2011; Shafiq et al., 1994; Soane and van Ouwerkerk, 1995). The economic costs of compaction (including yield and fertiliser loss, extra fuel, and environmental costs in terms of flooding, loss of nitrogen and phosphorus to freshwater, and greenhouse gas emissions) has been estimated at € 140 ha⁻¹ yr⁻¹ (Graves et al., 2015; Keller et al., 2019).

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Figure 1: A conceptual diagram showing the major consequences of soil compaction (Horn and Peth, 2011).
Back in 1991, more than 68 million ha were estimated to be compacted globally – an area larger than France – of which ~33 million ha were within Europe (Oldeman et al., 1991). Since 1991, the risk of compaction has only increased with the further intensification of agriculture. Farms have been expanding to increase productivity and efficiency (Keller et al., 2019; Kutzbach, 2000; Schjønning et al., 2015a), but with expansion it has become more difficult to delay field operations if soil conditions are not optimal. Especially on larger farms, the planning of field operations involves a number of trade-offs, such as field size and distance between farm and field, capacity, efficiency, economy and timing (Thorsøe et al., 2019). At the same time, machinery has become increasingly heavy and more powerful in order to be more cost-efficient (Keller et al., 2019; Kutzbach, 2000; Schjønning et al., 2015a). The weight of fully loaded self-propelled harvesters, for example, increased by a factor of six between 1958 and 2009. Typical wheel loads are now 15 Mg for loaded self-propelled harvesters, and up to 6 Mg for tractors (Schjønning et al., 2015a; Verein Deutscher Ingenieure, 2014).

The magnitude of soil stress decreases with increasing depth, but this happens less rapidly the greater the wheel load. The increase in wheel loads thus risks soil compaction deeper into the soil profile, since stresses then distribute to a greater depth (Söhne, 1958). Schjønning et al. (2012) suggested that the depth at which vertical stress equals 50 kPa increases by 0.08 m for each additional tonne increase in wheel load. Keller et al. (2012) found compaction of the subsoil for vertical stresses exceeding 40 kPa, regardless of soil type but at soil water contents close to field capacity (~100 hPa matric potential).

Assessments of the actual extent of subsoil compaction are rare as quantification is laborious, but a few studies have indicated the substantial scale of the problem. Schjønning et al. (2016b) reported critically high densities in soil horizons at 0.25–0.70 m depth for nearly a quarter of the European soils. Graves et al. (2015) estimated that in England and Wales combined, about 40% of the agricultural area was negatively affected by compaction. Brus and Van den Akker (2018) found, based on probability sampling and measurements of bulk density and porosity, that about 43% of subsoils in the Netherlands were over-compacted. Schneider and Don (2019) estimated that 51% of all cropland in Germany was compacted to the extent that it limits vertical root elongation, of which 27% was caused by agricultural management.

Lamandé et al. (2018) made an assessment of the wheel load carrying capacity of soils in Europe if permanent soil deformation at 0.35 m were to be prevented. The authors concluded that only 1.3% of the soils in Europe could carry a wheel load above 8 Mg on a large traction tyre on a wet soil (a matric potential of -50 hPa). This indicates that many European soils are prone to persistent subsoil compaction. Schjønning et al. (2012) suggested a rule of thumb for sustainable traffic at soil water contents slightly drier, namely around field capacity. This rule of thumb states that vertical stress below 0.5 m depth should preferably not exceed 50 kPa to
minimise the risk of subsoil compaction. Schjønning et al. (2015a) estimated that a tyre with a wheel load of 5.6 Mg then needs to be of extraordinary dimensions: 1.14 m width, 1.4 m² in contact area and 2.4 m³ tyre volume.

Besides the perpetual risk of compaction, its persistence is problematic. Alleviation of compaction remains a slow process (Alakukku, 1996; Håkansson and Reeder, 1994; Wahlström et al., 2021) despite the biotic and abiotic processes of soil structural regeneration that take place such as root growth and bioturbation (Besson et al., 2013; Pulido-Moncada et al., 2020), macro- and mesofauna (Brussaard et al., 2007), and wet-dry (Dexter, 1991; Dexter et al., 1988) and freeze-thaw cycles (Sivarajan et al., 2018; Six et al., 2004; Voorhees, 1983) that break up compacted soil and form and stabilise aggregates (Dexter, 1991). Tillage can effectively loosen compaction in the topsoil, yet often has a limited lasting effect in the subsoil (Schneider et al., 2017). A loosened soil often becomes compacted again and the subsoil structure may then be even less favourable than before (Håkansson, 2005; Olesen and Munkholm, 2007). Considering that subsoil compaction persists for decades (Berisso et al., 2012; Håkansson and Reeder, 1994; Schjønning et al., 2013), the reduction of the risk of soil compaction is extremely important. Yet, soil deformation below a wheel is complex and not all machinery-soil interactions are understood.

1.2 Stress-strain theory

Whether or not soil deforms depends on the stress applied to a soil, the distribution of stress through the soil and the stress-strain behaviour of the soil (Keller and Lamandé, 2010). The magnitude of the applied stress is in itself relatively unimportant: depending on the soils strength, its reaction to stress (strain) results in either elastic (reversible) or plastic (irreversible) deformation. Soil’s strength is related to various soil characteristics, but especially the soil water content at the time of stress exposure is critical; in most situations, the strength decreases with increasing soil water content (Saffih-Hdadi et al., 2009; Utomo and Dexter, 1981).

The stress propagation in the soil beneath a wheel is dependent on soil strength. Generally, the load is more concentrated beneath the wheel and the stress propagates deeper into the soil profile when the soil is weak (either because the soil is wet or has a low density) compared to strong (either because the soil is dry or has a high density) (Dexter, 1988; Lamandé and Schjønning, 2011a). Stress decreases more rapidly with depth in stronger than in weaker soils. However, even with traffic on dry soils, stresses can be transferred to deep soil layers (Arvidsson, 2001; Lamandé and Schjønning, 2011a). Moreover, the different soil layers in agricultural soils will often be of different strengths, for example due to natural layerings or due to tillage. Most characteristic is the difference between the plough layer in conventional systems, or the layer of cultivation in reduced-tillage systems and the plough pan below
Soil compaction refers to different soil deformation processes, of which compression and distortion are the most generally observed (van den Akker, 2008). The resistance of soil to compression is generally defined by the uniaxial precompression stress, which is conceptually the maximum vertical stress a soil has been exposed to in the past (Casagrande, 1936). When exceeding the soil’s resistance to compression, axial strain results in a decrease of soil volume and size of soil pores, in particular those of arterial macropores and branching marginal pores (Schjønning et al., 2013). Distortion occurs when the resistance of a soil to shearing is exceeded. During distortion, shear strain can cause disconnection of soil pores. With pure distortion, the soil volume does not change, but during field traffic compression and distortion occur generally simultaneously and are driven by the magnitude and direction of different stresses that act on the soil.

The stress state of a point in the soil can be divided into nine components fitted to a chosen coordinate system (Fig. 2 A–D). Three components can be drawn perpendicular to the point loaded, these are the normal stresses $\sigma_{zz}$, $\sigma_{xx}$ and $\sigma_{yy}$ (Fig. 2 C). The average of the three normal stresses yields the mean normal stress, $\sigma_m$. The remaining six (tangential) components are shear stresses, $\tau$ (Fig. 2 D). It is always possible to choose a coordinate system (Fig. 2 A) in which all six $\tau$ are zero. In this case, the normal stresses are called principal stresses. When the principal stresses are of unequal magnitude, the stresses are called the major (or first) principal stress, $\sigma_1$, the intermediate (or second) principal stress, $\sigma_2$, and the minor (or third) principal stress $\sigma_3$, in decreasing order of magnitude.

\[ \begin{align*}
A & \quad \sigma_{zz} \\
B & \quad \sigma_{xx} \\
C & \quad \sigma_{yy} \\
D & \quad \tau_{xx} = \tau_{yy} = \tau_{yx} = \tau_{zx} = \tau_{zy} = 0
\end{align*} \]

**Figure 2:** Stress components that act on a point in the soil (here represented by planes of an infinitely small cube) in an xyz-coordinate system. Adapted from Koolen and Kuipers (1983).

### 1.3 State of the art and research gaps

#### 1.3.1 Complexity of the stress state during wheeling

The soil stress state beneath a wheel on an agricultural field is complex, both in the driving direction and across the tyre. The soil surface is generally uneven and tyres have treads to develop pull and prevent clogging, among other things. The tread and tyre-soil friction induce shear stresses at the soil surface, in addition to the vertical load (Koolen and Kuipers, 1983).
Moreover, as different tyres are designed for different purposes, the tyre-soil interaction may also differ between tyres. For example, traction tyres for driven wheels are designed with focus on tractive potential and working speed, whereas trailer tyres for towed wheels are designed with focus on, for example, load bearing capacity and stability (Diserens, 2009). Differences in tyre-soil interaction between the two types of tyres were observed by Schjønning et al., (2015b), who showed that the tyre-soil contact length relative to the tyre circumference is larger for implement than for traction tyres.

Berisso et al. (2013) found different soil compaction effects across the wheel track of a passive tyre. The authors showed that this could be attributed to differences in the stress state across the wheel rut. A consistently lower air-filled porosity was found below the centreline of the tyre compared to the lateral edge of the tyre, whereas the opposite was observed for air permeability, i.e., lower air permeability at the lateral edge compared to the centreline. The trends in air-filled porosity were determined by mean normal stress [that led to compression], while the trends in air permeability were determined by both mean normal and shear stress [that led to distortion]. The assumption of a homogeneous wheeling effect on soil pore system across a tyre is then too simple.

That the stress state beneath a tyre is complex also in the driving direction has been shown in studies that used six-faced stress sensors, sensors that measure stress in six directions, buried in soil (e.g. Bailey et al., 1996; Pytka, 2009, 2005; Pytka et al., 2006; Pytka and Konstankiewicz, 2002; Way et al., 1996). Way et al. (1996) showed that the orientation of the major principal stress changed during wheeling. With the use of soil strain transducers, Way et al. (2005) captured a soil compression in the vertical direction, an elongation across the tyre, and compression followed by elongation and again compression in the driving direction. At some distance behind the wheel, where the compressive stress is low, shear deformation takes place (Peth et al., 2006).

1.3.2 Key drivers of soil stress

Numerous studies have focussed on compaction from traffic and identified some key drivers of soil stress, hence drivers of compaction. Understanding the processes triggered by the drivers means mitigation measures may be established. Studies found that the magnitude of stress, thus the risk of soil deformation, generally increases with increasing load, increasing tyre inflation pressure, and smaller soil contact area (e.g. Keller and Arvidsson, 2004).

Tyre inflation pressure is a known driver of stress in the upper part of the soil profile. The inflation pressure influences the tyre-soil contact area and the load distribution therein. At high inflation pressures, the contact area is relatively small and the load is more concentrated near the lateral centre of the tyres, and therefore so is the contact stress (Raper et al., 1995a; Schjønning et al., 2008). The contact area becomes larger at lower inflation pressures, which
allows for a lower mean ground pressure and a more even distribution of the vertical stresses in the contact area, which consequently reduces peak stresses in the soil (Bailey et al., 1996; Lamandé and Schjønning, 2011; Schjønning et al., 2008; Van den Akker et al., 1994). Too low inflation pressures, however, can cause undesired peak stresses near the edge of a tyre (Raper et al., 1995b; Schjønning et al., 2008).

For pneumatic tyres, the tyre-soil contact area increases for tyres with larger dimensions. The increase in tyre dimensions then also had a mitigating effect on soil stress caused by the increasing wheel load, yet the increases in wheel loads have outrun the ability of tyres to offset the risk of compaction (Schjønning et al., 2015a). However, tyre technologies and tyre designs may also influence the stress distribution in the tyre-soil contact area, and thereby the stress in the soil. For example, Plackett (1984) showed that the load distribution in the tyre-soil contact area was better for a radial than diagonal tyre of similar dimensions. Advanced flexion technologies have been introduced over the last decades, which allow tyres to carry high loads at rather low inflation pressures (Schjønning et al., 2012).

The contact area is generally larger for rubber tracks. This reduces the mean ground pressure and vertical soil stress compared to tyres (Arvidsson et al., 2011; Keller et al., 2002; Lamandé et al., 2018). However, the stress distribution beneath a rubber track is not uniform; vertical stress concentrates beneath the supporting rollers and wheels (Arvidsson et al., 2011; Keller et al., 2002; Lamandé et al., 2018) and the stress distribution is heavily affected by the distribution of the load over the tractor’s axles (Keller et al., 2002). Although tracks may be beneficial for reducing the risk of compression, the risk of distortion may increase due to high shear forces beneath tracks (Lamandé et al., 2018).

The benefit of reducing inflation pressure falls the deeper into the soil profile the stress propagates. Stress in the subsoil is more closely related to wheel load (Arvidsson and Keller, 2007; Lamandé et al., 2007; Lamandé and Schjønning, 2011b). Vertical stress in the subsoil is generally well explained by the Söhne (1953) summation procedure, which is a pseudo-analytical continuum concept based on the Boussinesq (1885) solution for stress propagation in an isotropic half space medium. Reducing wheel loads has therefore long been the key advice to limit the risk of subsoil compaction.

Wheel loads also reduce when the total load is distributed over a larger number of wheels, either next to each other (dual wheels) or behind each other (tandem wheels), but the benefits regarding soil stress are flawed. Dual wheels act as separate wheels with respect to soil stress (Keller and Arvidsson, 2004), and whilst the recommended tyre inflation pressure will be lower from single wheels due to the reduced wheel load, the potential area of compaction becomes larger because of the larger contact area. Tandem wheels can also reduce soil stress due to the lower wheel load and tyre inflation pressure, yet the number of wheel passes in the
same track increases. At the first wheel pass soil generally increases the soil strength, which means that repeated wheeling takes place on a more rigid soil surface than the first wheeling. The tyre-soil contact area may then be smaller for the successive (e.g. tandem) wheels (Way et al., 1995), which may lead to high soil stress, especially at shallow depths (Wiermann et al., 1999). Multiple wheel passes on a single wheel track have been shown to increase soil deformation, especially in the topsoil (Naderi-Boldaji et al., 2018; Pulido-Moncada et al., 2019), yet many studies on the effect of repeated wheeling are performed with a tractor, i.e., with two wheels passing in a single event.

1.3.3 Risk calculations
Multiple models exist that calculate the risk of soil compaction based on the Söhne (1953) summation procedure, by comparing soil strength and applied stress. Examples are SOCOMO (van den Akker, 2004), SoilFlex (Keller et al., 2007), and Terranimo (Stettler et al., 2014). De Pue et al. (2020) showed that, when including effects of traction, the Söhne model could not account for the traction effects on horizontal stress the way discrete element models can. This may partly be explained by the lack of understanding of the effect of traction on the stress distribution beneath tyres, which means it is not yet well incorporated in Söhne-based models. Only a few studies focussed on the effects of traction on soil stress and soil structure, and generally no decisive conclusions can be drawn on cause-effects. Diserens and Alaoui (2011) note that the tyre-soil contact area is related to, among others, traction forces, but it is unclear how traction alone changes the contact area [when wheel load and inflation pressure are kept equal]. Pytka et al. (2006) measured an increase in stress (measured in six directions) in a disturbed upper subsoil under driven tyres with increasing traction, but the higher traction was achieved by reducing tyre inflation pressure. Kirby (1989) concluded, by model evaluation, that shear stress from traction may be found at depths 1.5–2 times the width of a tyre in a profile of uniform strength. The effect of traction vanishes rapidly with depth according to Koolen et al. (1992). As traction induces additional shear stresses in the soil beneath a driven wheel, the ratio of horizontal to vertical soil stress should then be influenced by the wheel load as well as by the traction forces that act on the soil (Koolen and Kuipers, 1983).

The lack of this understanding means that predictions of the risk of compaction can be oversimplified. This was the case in Danish compaction trials (Schjønning et al., 2016a), where a larger deformation in the subsoil was predicted for a 12 Mg wheel load (self-propelled with three wheels and without repeated wheeling) than for 8 and 6 Mg wheel loads (tractor-slurry spreader with wheels passing in the same track), also when the 8 and 6 Mg wheel loads passed several times, i.e., several axles. Nevertheless, penetration resistance was found to be highest for the 6 Mg wheel load in the upper subsoil (25–40 cm depth), while the 12 Mg wheel load did not show a yield loss. Pulido-Moncada et al. (2019) compared the structure of the subsoil (here
...two years after these trials were finished: the treatment with 8 Mg wheel load had significantly reduced the structural quality, while the 12 Mg wheel load showed no distinct signs of significant subsoil compaction. These experiments did not allow decisive cause-effect conclusions. The authors suggested their observations may be explained by the repeated wheeling from a single pass in the tractor-trailer combination, or the traction needed to pull the machinery across the field. These results call for better understanding of some specific aspects of machinery-soil interaction.

1.4 Objective and hypothesis

The overall objective of this dissertation is to deepen our understanding of key processes of soil structure deformation. Particularly, the focus is on tyre-soil interactions and soil response as affected by tyre evolution, traction and repeated wheeling. The effect of different tractor tyre designs was tested, as well as the performance of a novel trailer designed to reduce the risk of soil compaction during heavy traffic, and the effect of traction for a given wheel load and inflation pressure.

The following hypotheses are tested in this dissertation:

1. Newer tyres with a more advanced flexion technology that allows lower inflation pressures at similar loads have improved tyre-soil contact area characteristics and thereby reduce soil stress in the upper part of the soil; consequently, they have less negative impacts on soil structure (Papers 1 and 2);

2. With the level of traction on driven tyres, the tyre-soil contact area increases, the distribution of vertical and horizontal stresses in the contact area changes, and the level of horizontal soil stress is higher for a given vertical load and increases with traction for a given vertical load (Paper 3, unpublished data);

3. Repeated wheeling of towed tyres decreases the tyre-soil contact area and changes the distribution of vertical stress therein, and repeated wheeling increases soil stress (Papers 1 and 3);

4. Soil structural deformation increases with traction as the magnitudes of the three principal normal stresses become larger, and with an increased number of wheel passes due to higher stress in the soil profile (Paper 4, unpublished data).

1.5 Dissertation outline

Chapter 1 provides the motivation for this dissertation, the concepts of the stress-strain relationship and the state of the art highlighting research gaps, which in turn lead to the general objective and specific hypotheses presented in this dissertation. Chapter 2 provides a description of the experimental sites, test configurations and of the methodology used to assess the risk of soil compaction as well as the soil response. A synthesis of the outputs from the various studies conducted in this PhD study is provided in Chapters 3–5. Chapter 3
focusses on the effects of tyre evolution; Chapter 4 on the effects of traction; Chapter 5 on the effects of repeated wheeling. Chapter 6 provides a general discussion of the methodology and interpretation of the results of the studies presented in Chapters 3–5. Lastly, Chapter 7 covers the conclusion of the studies and hypotheses presented, and Chapter 8 presents the perspectives for future studies.
2 Methods and methodology

This dissertation contains three compaction studies that each has been performed on a different experimental site: Ladoux, Foulumgaard A and Foulumgaard B. All three studies focused on both the risk of compaction and on the soil response. The particular measurements overlapped but also differed between studies. Table 1 provides the overview of the measurements for each study. In the Sections following in this chapter, the experimental set-up for each experiment is described (Section 2.1) as well as the measurements (Section 2.2) that relate to the results and discussion (Chapters 3–6).

Table 1: Overview of in this dissertation presented measurements for each experiment

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Ladoux</th>
<th>Foulumgaard</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>RISK ASSESSMENT</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Traction</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Drawbar-pull</td>
<td>DP</td>
<td>x</td>
</tr>
<tr>
<td><strong>Stress measurements</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Contact stress</td>
<td>$\sigma_{z}$</td>
<td>x</td>
</tr>
<tr>
<td>$\sigma_{x}$</td>
<td></td>
<td>x</td>
</tr>
<tr>
<td>Soil stress</td>
<td>$\sigma_{z}$</td>
<td>x</td>
</tr>
<tr>
<td>$\sigma_{x}$</td>
<td></td>
<td>x</td>
</tr>
<tr>
<td>$\sigma_{m}$</td>
<td></td>
<td>x</td>
</tr>
<tr>
<td><strong>Stress calculations</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Contact stress</td>
<td>$\sigma_{z}$</td>
<td>x</td>
</tr>
<tr>
<td>$\sigma_{x}$</td>
<td></td>
<td>x</td>
</tr>
<tr>
<td>Soil stress</td>
<td>$\sigma_{z}$</td>
<td>x</td>
</tr>
<tr>
<td>$\sigma_{x}$</td>
<td></td>
<td>x</td>
</tr>
<tr>
<td><strong>SOIL CHARACTERISTICS AND RESPONSE</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Soil mechanical characteristics</td>
<td>$\sigma_{pc}$</td>
<td>x</td>
</tr>
<tr>
<td>$E$</td>
<td></td>
<td>x</td>
</tr>
<tr>
<td>$v$</td>
<td></td>
<td>x</td>
</tr>
<tr>
<td>PR</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Soil structural characteristics</td>
<td>$\rho_{b}$</td>
<td>x</td>
</tr>
<tr>
<td>$\varepsilon$</td>
<td></td>
<td>x</td>
</tr>
<tr>
<td>$k_{a}$</td>
<td></td>
<td>x</td>
</tr>
</tbody>
</table>

For all three studies the experimental layout (plots within blocks) was greatly influenced by spatial constraints. On the one hand, the layout attempted to limit the size of the experimental field because of potential spatial variability of soil texture and structure; even on rather short distances (decimetres), soil characteristics, hence properties, can vary (Koszinski et al., 1995; Usowicz and Lipiec, 2017). Differences in soil characteristics would add an extra variable to
the study and not allow replicate blocks, which are, together with the number of repetitions, important for analysis and conclusions. Because of the potential spatial variability of soil characteristics, randomisation of plots and identification of soil characteristics of soil without experimental traffic, are vital. On the other hand, sufficient distance between measurements is needed for them not to influence each other (e.g. if plots are too narrow, the soil in a plot may be exposed to the stress field of a vehicle passing in the neighbouring plot). Likewise, the area around plots and between blocks has to allow vehicles to get around and line up to pass the different plots without risking crossing areas where measurements still have to be made.

2.1 Experimental sites and test configurations

2.1.1 Ladoux

The Ladoux Michelin Technology Centre, France (45°51′28.3″N 3°07′24.4″E), was the base of the field experiment focussing on the effect of tyre evolution on the reduction of the risk of soil compaction (Papers 1 and 2). The soil there has developed on calcareous Oligocene fluviolacustrine sediments and classifies as a Chernozem according to the WRB (FAO, 1998) system. The experimental site was part of an agricultural field that had not been ploughed for five years, but tilled with a small tractor to 0.10–0.15 m depth. Wheat had been cultivated for five years and stubble covered the soil surface (Fig. 3). The spade method of visual evaluation of the soil structure based on Guimarães et al. (2011) was performed (Fig. 3) to quickly evaluate the soil structural quality. The overall soil structural quality (Sq) was good (Sq1–2); the block on the spade was easy to break up, larger pieces easily fragmented into pieces < 6 mm, and roots were found throughout the extracted soil. The soil profile was, to the eye, homogeneous, even to a depth of 0.6 m. Textural, chemical and mechanical characteristics are provided in Table 2.

Figure 3: Example of the soil spade test at the experimental site at the Ladoux Michelin Technology Centre, France (overall score Sq 1–2).
Table 2: Textural, chemical and mechanical characteristics of the soil of the experimental site in Ladoux, France.

<table>
<thead>
<tr>
<th>Depth (m)</th>
<th>Particle density (g cm⁻³)</th>
<th>Clay (g 100g⁻¹)</th>
<th>Silt (g 100g⁻¹)</th>
<th>Fine sand (g 100g⁻¹)</th>
<th>Coarse sand (g 100g⁻¹)</th>
<th>SOM (g cm⁻³)</th>
<th>CaCO₃ (g cm⁻³)</th>
<th>ρb (g cm⁻³)</th>
<th>θ (°)</th>
<th>σpc (kPa)</th>
<th>E (kPa)</th>
<th>ν</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.10</td>
<td>2.67 ± 0.0</td>
<td>25.3 ± 1.4</td>
<td>49.5 ± 2.0</td>
<td>4.2 ± 0.7</td>
<td>7.3 ± 0.5</td>
<td>4.8 ± 0.4</td>
<td>11.2 ± 2.8</td>
<td>1.13 ± 0.0</td>
<td>0.41 ± 0.0</td>
<td>36</td>
<td>1316 ± 234</td>
<td>0.48 ± 0.006</td>
</tr>
<tr>
<td>0.30</td>
<td>2.68 ± 0.0</td>
<td>27.3 ± 2.4</td>
<td>47.3 ± 3.8</td>
<td>4.2 ± 0.9</td>
<td>7.1 ± 0.7</td>
<td>4.6 ± 0.4</td>
<td>12.1 ± 3.6</td>
<td>1.14 ± 0.0</td>
<td>0.40 ± 0.0</td>
<td>29</td>
<td>1376 ± 241</td>
<td>0.48 ± 0.005</td>
</tr>
<tr>
<td>0.60</td>
<td>2.71 ± 0.0</td>
<td>32.0 ± 6.3</td>
<td>45.6 ± 3.2</td>
<td>7.1 ± 2.6</td>
<td>7.2 ± 1.6</td>
<td>3.1 ± 0.5</td>
<td>6.3 ± 3.6</td>
<td>1.12 ± 0.0</td>
<td>0.41 ± 0.0</td>
<td>34</td>
<td>1527 ± 373</td>
<td>0.48 ± 0.010</td>
</tr>
</tbody>
</table>

Clay < 2 µm; silt 2–50 µm; fine sand 50–200 µm; coarse sand 200–2000 µm; CaCO₃, calcium carbonate; ρb, dry bulk density; θ, volumetric soil water content; σpc, (confined) precompression stress; E, Young’s modulus; ν, Poisson’s ratio. * median. ± Standard deviation. Table 2 is adapted from Paper 1.

Table 3: The specifications of the rear tyres used in the experiment to study the effect of tyre evolution in Ladoux. (Papers 1 and 2)

<table>
<thead>
<tr>
<th>Configuration</th>
<th>Tyre</th>
<th>Launched Date</th>
<th>Type</th>
<th>Flexion</th>
<th>Tyre specification</th>
<th>Fstatic (Mg)</th>
<th>ptyre (kPa)</th>
<th>ID</th>
<th>Data</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>Bias</td>
<td>&lt; 1970</td>
<td>D</td>
<td>-</td>
<td>20.8-38</td>
<td>4.3</td>
<td>240</td>
<td></td>
<td>x</td>
</tr>
<tr>
<td>B</td>
<td>AgriBib</td>
<td>1990’s</td>
<td>R</td>
<td>-</td>
<td>20.8 R38</td>
<td>4.3</td>
<td>240</td>
<td></td>
<td>x</td>
</tr>
<tr>
<td>C</td>
<td>AxioBib</td>
<td>2004</td>
<td>R</td>
<td>IF</td>
<td>710/70 R42</td>
<td>4.3</td>
<td>80</td>
<td>Axio</td>
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<td>F</td>
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<td>D</td>
<td>CerexBib</td>
<td>2010</td>
<td>R</td>
<td>IF, CFO</td>
<td>710/70 R42</td>
<td>4.3</td>
<td>140</td>
<td></td>
<td>x</td>
</tr>
<tr>
<td>G</td>
<td>CerexBib</td>
<td>2010</td>
<td>R</td>
<td>IF, CFO</td>
<td>710/70 R42</td>
<td>4.3</td>
<td>80</td>
<td></td>
<td>x</td>
</tr>
<tr>
<td>E</td>
<td>EvoBib</td>
<td>2018</td>
<td>R</td>
<td>VF</td>
<td>710/70 R42</td>
<td>4.3</td>
<td>60</td>
<td>Evo</td>
<td>x</td>
</tr>
<tr>
<td>J</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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<td>H</td>
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<td>I</td>
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</tbody>
</table>

D = diagonal tyre; R = radial tyre; IF = increased flexion; CFO = Cyclical Field Operation; VF = Very High Flexion; Fstatic = static wheel load; ptyre = tyre inflation pressure; σm = mean normal stress; σz = vertical stress; sc = soil core sampling.
Bulk soil and 100-cm³ soil cores sampled from untrafficked soil (the Reference plots) were used for characterisation of soil textural, structural and mechanical properties (Table 2). A detailed account of the methods of textural determination is provided in Paper 1 and those of structural and mechanical properties are also described in Section 2.2. The soil water content at the time of the field experiment was around field capacity (-100 hPa matric potential).

The test configurations were based on five sets (front and rear) generations of tyres (Table 3) introduced from before the 1970s and until 2018. The two ‘oldest’ tyres (in design, not in use), Bias and AgriBib, are by the European Tires and Rim Technical Organisation (ETRTO) classified as standard small tyres (rear dimensions in the experiment 20.8/38). The difference between the two is the technology of how the layers of ply overlap. Bias is of the diagonal type, in which all plies cross at angles, creating a criss-cross pattern (Fig. 4 A) and a uniform tyre-structure with a rigid tyre sidewall. AgriBib is of the radial type (indicated by the R in the tyre specification, e.g. Table 3). For radial tyres, the ply on the tyre body radiates out from the centre of the tyre whereas the ply on the tyre crown fits like a belt over the tyre body (Fig. 4 B). The tyre sidewall and crown of radial tyres have different mechanical properties, which creates a more flexible tyre compared to diagonal-tyres.

The three other tyres included in this experiment are products of flexion technologies that allow tyres to carry similar loads at lower tyre inflation pressures (p_{tyre}) than the small tyres. These low-inflation pressure tyres are wider than the small tyres (Fig. 4 A–C) (rear dimensions in the experiment 710/70, Table 3). AxioBib was the first tractor tyre with increased flexion. CerexBib is a copy of AxioBib but meant for rather heavy loads for usage on, e.g., harvesters and is therefore reinforced with steel belts. EvoBib has a 2-in-1 technology that allows the shoulders of the tyre to sink/lift around 120 kPa (below and above, respectively, Fig. 4 D). This changes the size of the contact area (both in length and in width, Vervaet, personal communication, 2018).

Figure 4: A-B, Differences in diagonal (A) and radial (B) tyre technology. C-D, Difference in size of standard small (C) and low-inflation pressure (D) tyres. E, EvoBib changes of shape (lift/sink of the tyre’s shoulders, the lightest patches) with change of tyre inflation pressure. Sources: A-B, www.nokiantyres.com; C-D, agricultural.michelin.co.uk; E, TractorLab.
The capital letters for the configurations A-J (Table 3) are used to describe the experimental set-up, whereas in the results the tyres are referred to by their ID. For the configurations A-H, the ID is built-up by an abbreviation of the tyre (name) and the $p_{tyre}$, *Evo+* (configurations I) indicates an optimisation of *Evo60* and the *RL* in *EvoRL* stands for reduced load.

The experiment in Ladoux was replicated in four blocks (~ 38 x 12 m). In each block, 100-cm³ soil cores were sampled for measurements of soil structural properties (at 0.3 m depth) and soil mechanical properties (at 0.1, 0.3 and 0.6 m depth) for the Reference (without experimental traffic) and below the centreline of the wheel track after a single pass of the configurations A-E in Table 3. Moreover, measurements of mean normal soil stress ($\sigma_m$) were made beneath the centre of the tyres for the configurations A-I in Table 3 at 0.2, 0.4 and 0.6 m depth with Bolling probes (Section 2.2.2). More information on soil sampling and the stress measurements are provided in Papers 1 and 2. The aimed (theoretical) forward speed ($V_{th}$) on the experimental plots was 0.83 ms⁻¹.

In each block, the first $\sigma_m$ measurements were first made for the configurations A-E (Table 3) to test the effect of tyre evolution. The static wheel load ($F_{static}$) was similar for the configurations (2.9 Mg front, 4.3 Mg rear) and $p_{tyre}$ was set to the manufacturer’s load-recommended pressure (240–60 kPa, Table 3). These five configurations each passed the Bolling probes three times; the order of the 15 passes was randomised. Next, three $\sigma_m$ measurements were made for each of the configurations F-I. The $p_{tyre}$ and $F_{static}$ were adjusted to test the effect of tyre construction (configurations A-C, G-I), the effect of $p_{tyre}$ for low-inflation pressure tyres (configurations E and H) and the effect of different weight-pull ratio (tractive potential, configurations F and I). The three passes for each of these configurations were completely randomised in the first block, but the strategy needed to be changed since changing $p_{tyre}$ took too much time. Randomisation was essential for the first five configurations because it reduced the risk of one configuration systematically influencing the measurements of another. Yet, taking into consideration that the soil was already quite heavily trafficked, loaded 30 times (front and rear wheel of configurations A-E passing), it was assumed that the impact of the order of these additional passes on the stress readings would be minimal (confirmed by analysis of the effect of repeated wheeling on the Bolling probe inclusion pressure, Chapter 5). In the other three blocks, the configurations were then randomised, but the three passes of the same configuration were completed without another configuration passing the probes in between.

Calculation of vertical soil stress (Section 2.2.5) were made for the all configurations mentioned in Table 3.
2.1.2 Foulumgaard A and B

Two wheeling experiments were performed at Research Centre Foulum, Denmark (56°29"N, 9°34"E), hereafter referred to as Foulumgaard A and Foulumgaard B (Fig. 5). The distance between the centres of the field was about 470 m. Foulumgaard A was performed to study vertical contact- and vertical and horizontal subsoil stresses (Paper 3), as well as the soil response to traction and repeated wheeling with a passive wheel (Paper 4). Foulumgaard B was performed to study the effect of traction on the magnitude and distribution of vertical and horizontal contact stresses and soil response (Chapter 4). The soil around Foulumgaard is a typical sandy loam, developed on Weichselian glacial till (Krogh and Greve, 1999) and classifies as a Luvic Umbrisol according to the WRB system (Food and Agriculture Organization of the United Nations, 2015). Soil textural analysis (Table 4) was performed by Abdollahi et al. (2014) and by Hansen et al. (2010) on the experimental sites’ neighbouring fields.

Foulumgaard A, performed in (a dry) June, 2018, was irrigated in the week prior to the experiment to reach soil water conditions around field capacity during the experiment. With the soil being dry, it would be too strong for the stresses induced to result in compaction. Neither should a soil be too wet because this leads to plastic behaviour of the soil. In both cases, the soil water content obstructs gaining a better understanding of the processes causing soil compaction. Foulumgaard A is generally ploughed to ~0.22 m depth. Over the preceding four years, the crop rotation was grass-clover, grass-clover, spring barley, and oats.

Foulumgaard B was performed in (another dry) June, 2020, but with precipitation in the week prior to the experiment. This led to a difference in weight (caused by changing water content) between the soil samples at field conditions and when equilibrated to -100 hPa matric potential (Section 2.3) of 2.2 ± 0.6 g (at the time of writing the soil cores have not been through all analyses and not yet dried). The experimental site is generally used as a testing area to adjust machinery before field operations on other experimental sites take place. Foulumgaard B was performed on rye-stubble, which was preceded by spring barley.

Figure 5: The locations of the two wheeling experiments (Foulumgaard A and B) performed at Research Centre Foulum, Denmark, with the blocks within the experimental areas highlighted.
Table 4: Soil textural, structural and mechanical characteristics of the two experimental sites at Foulumgaard, Denmark.

<table>
<thead>
<tr>
<th>Experimental site</th>
<th>Source, if not field experiment</th>
<th>Depth</th>
<th>Particle density</th>
<th>Clay</th>
<th>Silt</th>
<th>Fine sand</th>
<th>Coarse sand</th>
<th>OC</th>
<th>$\rho_b$ *</th>
<th>$\theta$ *</th>
<th>$\sigma_{pc}$ * *</th>
<th>$\sigma$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Foulumgaard A</td>
<td>Abdollahi et al., 2014</td>
<td>0.15–0.19</td>
<td>1.4 ± 0.13</td>
<td>0.30 ± 0.02</td>
<td>1.5 ± 0.07</td>
<td>0.29 ± 0.02</td>
<td>123</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.40–0.44</td>
<td>2.61</td>
<td>9.0</td>
<td>23.5</td>
<td>27.9</td>
<td>36.9</td>
<td>1.6</td>
<td>1.4</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Foulumgaard B**</td>
<td>Hansen et al., 2010</td>
<td>0.10–0.14</td>
<td>1.4 ± 0.08</td>
<td>0.27 ± 0.02</td>
<td>1.4</td>
<td></td>
<td></td>
<td></td>
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<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.0–0.25</td>
<td>9.2</td>
<td>12.6</td>
<td>44.4</td>
<td>30.7</td>
<td>1.8</td>
<td></td>
<td></td>
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<td></td>
</tr>
</tbody>
</table>

Clay < 2 µm; silt (2–63 µm for Foulumgaard A, 2–20 µm for Foulumgaard B); fine sand (63–200 µm for Foulumgaard A, 20–200 µm for Foulumgaard B); coarse sand 200–2000 µm; OC, organic carbon; $\rho_b$, dry bulk density; $\theta$, volumetric soil water content; $\sigma_{pc}$, (confined) precompression stress; $E$, Young’s modulus. * At field conditions for Foulumgaard A and B. *median. ** Based on part of the Reference soil samples, those that were already oven-dried at time of writing. ± Standard deviation.

Table 5: The configurations in experiment focussing on the effect of traction and repeated wheeling on stress and soil response in Foulumgaard A.

<table>
<thead>
<tr>
<th>ID</th>
<th>Load</th>
<th>Steering mode*</th>
<th>Number of machinery- passes</th>
<th>Tyres passing N</th>
<th>$F_{dynamic}$ [Mg]</th>
<th>Measurements of</th>
<th>DP</th>
<th>PR</th>
<th>$\sigma_{contact}$</th>
<th>$\sigma_{soil}$</th>
<th>sc</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reference</td>
<td>NA</td>
<td>NA</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
</tr>
<tr>
<td>2+2 L</td>
<td>Low</td>
<td>Standard</td>
<td>3**</td>
<td>2</td>
<td>2</td>
<td>1.4+3.5</td>
<td>4.2+3.8</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
</tr>
<tr>
<td>2+2 H</td>
<td>High</td>
<td>Standard</td>
<td>3**</td>
<td>2</td>
<td>2</td>
<td>1.2+4.1</td>
<td>5.2+5.5</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
</tr>
<tr>
<td>2+0 L1</td>
<td>Low</td>
<td>Offset</td>
<td>1</td>
<td>2</td>
<td>0</td>
<td>1.4+3.5</td>
<td>0</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
</tr>
<tr>
<td>2+0 H1</td>
<td>High</td>
<td>Offset</td>
<td>1</td>
<td>2</td>
<td>0</td>
<td>1.2+4.1</td>
<td>0</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
</tr>
<tr>
<td>o+1 H1</td>
<td>High</td>
<td>Offset</td>
<td>1</td>
<td>2</td>
<td>0</td>
<td>1+5.5</td>
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<td>x</td>
<td>x</td>
<td>x</td>
</tr>
<tr>
<td>o+1 H2</td>
<td></td>
<td></td>
<td></td>
<td>2</td>
<td>2</td>
<td>2+5.5</td>
<td>x</td>
<td>x</td>
<td>x</td>
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<tr>
<td>0+1 H3</td>
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<td>3+5.5</td>
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<tr>
<td>o+1 H6</td>
<td></td>
<td></td>
<td></td>
<td>6</td>
<td>6</td>
<td>6+5.5</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
</tr>
</tbody>
</table>

$F_{dynamic}$ = dynamic wheel load for the wheels after which measurements were collected (indicated by the red dots in Fig. 6 A); $DP$ = drawbar pull; $PR$ = penetration resistance; $\sigma_{contact}$ = contact area and vertical contact stress distribution; $\sigma_{soil}$ = vertical and horizontal soil stress; sc = soil core sampling; * = see Fig. 6 B; ** up to three passes on the same plot.
**Foulumgaard A**

The test configurations in Foulumgaard A were based on a tractor-trailer combination with two different loads (low, \(2+2 L = 17 \text{ Mg}\), and high, \(2+2 H = 24 \text{ Mg}\), Table 5) and two different steering modes, standard and offset (Fig. 6 A), to yield different levels of traction (6.5 and 9.1 kN drawbar pull (DP) for low and high load, respectively, when corrected for the slope of the field, Paper 3) and the option to carry out (repeated) single wheeling. Both the tractor and the trailer were equipped with low-inflation pressure tyres inflated to the \(p_{\text{tyre}}\) recommended by the tyre manufacturer for the respective static wheel loads and for speeds of up to 10 km h\(^{-1}\) (Table 5). The activated standard 4WD with locked differential ensured traction on all tractor wheels. The speed was GNSS-controlled (Global Navigation Satellite System) and set to 0.83 ms\(^{-1}\) \((V_{th})\). The actual speed \((V_{\text{act}})\) was derived from a laser sensor (Sections 2.2.3 and 2.2.4). The slip percentage \((S)\) was estimated according to Eq. 1 based on Koolen and Kuipers (1983) and was \(2.4 \pm 1.9 \%\) and \(4.1 \pm 0.5 \%\) for \(2+2 L\) and \(2+2 H\), respectively.

\[
S = \left( 1 - \frac{V_{\text{act}}}{V_{th}} \right) \times 100
\]

**Eq. 1**

\(S\) = number of configurations; see Table 5 for explanation of the treatments’ IDs.

Foulumgaard A was replicated in three blocks (Fig. 6 B, ~60 x 13.5 m). In each block, measurements of the tyre-soil contact area and the distribution of vertical stress therein (Section 2.2.3, Paper 3) were made for five configurations (Table 5, Fig. 6 B). These configurations were randomised over the plots in the first block, but not between blocks, because of resources required to change \(p_{\text{tyre}}\) and \(F_{\text{static}}\). The contact area measurements were used for calculations of horizontal soil stress (Section 2.2.5) for the tractor tyres in the configurations \(2+2 L\) and \(2+2 H\). Measurements of vertical stress \((\sigma_z)\) and horizontal stress in the driving direction \((\sigma_x)\) in the upper subsoil were made (Section 2.2.4) for all tyres in the configurations \(2+2 L\) and \(2+2 H\) (Paper 3). The sensors were inserted into the soil wall at...
0.40 m depth, but the actual depth of the sensors varied with mean depths of 0.39 and 0.33 m for \( \sigma_z \) and \( \sigma_x \), respectively. The measurements (three per configuration per block) were made for \( 2+2 L \) before \( 2+2 H \), i.e., with low traction before high traction. Ideally, the configurations would have passed their own set of sensors, but the experimental area was limited and the installation of the stress sensors too time consuming (it took two full days to install the sensors in the three blocks). In the remaining plots (Fig. 6 B), penetration resistance (\( PR \), Section 2.3.1) was measured to 0.71 m depth and 100-cm\(^3\) soil cores were sampled for measurements of soil structural properties (at 0.16 m depth) for eight configurations (Table 5, Paper 4). Additionally, 100 cm\(^3\)-soil cores were sampled from the Reference for measurements of soil mechanical properties around 0.42 m depth.

The driving direction was with the slight slope of the experimental site. The three blocks were positioned on the least-sloping part of the site, because of possible interference of the slope on \( DP \) and soil stress. The elevation derived from the digital elevation model DK-DEM/Terrain (© The Danish Agency for Data Supply and Efficiency) with a 0.4 m raster in ArcGIS 10.4.1 revealed a maximum elevation of 0.3 m within a plot (over a length of 13.5 m). The highest point was in the middle block (55.0 m) and the southern-most block was generally lowest (54.3 m). The DEM was also used to calculate the slope of the field (%) in between the trailer’s axles, which was used to study the effect of the slope of the field on the \( DP \) for the different configurations. The \( DP \) increased by 0.57 kN for each %-unit increase in slope (Paper 3).

**Foulumgaard B**

The effects of traction on the distribution of vertical and horizontal stresses in the contact area and on soil properties were compared for a towed and driven tractor. A Claas Arion 640 was used in both situations. A rotavator was attached to the rear, yielding a total static weight of 8.7 Mg, with 6.7 Mg static weight on the rear axle. The tractor was equipped with low-inflation pressure tyres (520/60 R28 front, 650/60 R38 rear) inflated to 80 kPa.

Another tractor of ~10 Mg static load was used to tow the [towed] tractor and to be towed by the driven tractor (the latter is the set-up in Fig. 7). The two tractors were connected with a chain that was long enough to have the tractor for which data was collected pass the stress sensors (Section 2.2.3, yellow in Fig. 7) and the area for soil sampling (Section 2.3.2, blue in Fig. 7), but not the facilitating tractor. The driving direction in the plots was opposite for the towed and driven configurations due to the limited size of the experimental site and the immediate surroundings (trees on the west and experimental sites on the east Fig. 7). We had to ensure, for example, that the facilitating tractor would not change from travelling on grass-covered soil to travelling on stubble; this would change the grip, slip and \( DP \). Likewise, we had to make sure that the facilitating tractor could drive far enough forward to ensure measurements in a straight line over the plots.
The forward speed in the experimental area was GNNS-assisted. The actual speed was derived from measurements of a laser sensor installed at the surface to keep track of the position of the passing tractor relative to the load cells (Section 2.2.3, Fig. 10 E). For the measurements of the towed configuration (i.e., without traction), the speed was controlled for the facilitating [pulling] tractor at $V_{th} 0.83$ ms$^{-1}$. The towed tractor (for measurements) was set in neutral with the handbrake slightly on, just enough to reduce rocking when pulled into motion. The rocking would have resulted in variable forward speed and changing stress fields, but both these factors needed to be as stable as possible during motion. The towed tractor (for measurements) started to the west of the plots, with all wheels on the grass. There was nevertheless one jerk when pulled into motion, but still at a distance from the area for stress measurements (yellow area in Fig. 7), after which the movement was smooth. The facilitating [pulling] tractor started east of the area used for sampling (blue area in Fig. 7). According to the laser sensor, $V_{act}$ (Eq. 1) for the towed configuration was $0.86 \pm 0.01$ ms$^{-1}$, which equals an $S$ of $-3.1 \pm 0.8$ % (Eq. 1).

A high $DP$ (42.8 kN, measurements described in Section 2.2.1) for the measurements of the driven configuration (i.e., with traction) was achieved by the difference in the set speed between the two tractors, as well as by the facilitating tractor having activated its 4WD. The pulling tractor was set to $V_{th} 0.83$ ms$^{-1}$ whereas the facilitating tractor was set to 0.56 ms$^{-1}$. This increased $DP$ (Section 2.2.1) and slowed the pulling tractor; based on measurements from the laser sensor, $V_{act}$ was $0.62 \pm 0.0$ ms$^{-1}$, which equals an estimated $S$ of $25.1 \pm 0.7$ %.
The experiment was repeated in four blocks (~ 12 x 18 m, Fig. 7). In each block, three configurations were randomized over three plots: the towed and driven tractor and a Reference without experimental traffic. The plots were 5 m wide for the configurations with the tractor but only 2 m wide for the Reference. The Reference plots were smaller to limit how far north we would operate – the setup of the configurations (with regard to forward speed and the distance between the tractors) was tested on the northern side prior to the experiment.

Vertical and horizontal contact stresses were measured (Section 2.2.3) in the plots with experimental traffic. The towed configuration passed the plots twice for stress measurements (N = 8). The driven configuration passed the first two plots twice, but when digging up the stress sensors in the second plot, a substantial displacement of one installation stress sensors (for rearward horizontal measurements, the last to pass) was found (Fig. 30). In the last two plots, measurements were therefore made for a single pass of the pulling tractor. Due to some mistakes in the set-up of the tractors for the driven configuration (Section 2.2.2), a total of four measurements with high DP were completed. In all plots (towed, driven, and the Reference), nine 100-cm³ soil cores were sampled (for the configurations with traffic after the first pass) at 0.10 m depth to measure soil structural properties in the lab. Additionally, ten 100-cm³ soil cores were sampled at 0.10 m depth from the Reference only to measure soil mechanical properties (Table 4).

2.2 Risk assessment – measurements and calculations

2.2.1 Drawbar pull

Measurements of drawbar pull (DP, kN) yielded a measure of traction in both Foulumgaard A and Foulumgaard B. The measuring method differed between the experiments, but in both cases, DP was measured when driving in the experimental plots.

Foulumgaard A

Three load cells on three joints (lift arms and top linkage) built on a frame and mounted between the tractor and trailer (Fig. 8 A) recorded DP. Total DP was calculated as the sum of these three load cells for each pass. Measurements were recorded with a frequency of 0.2 kHz.

Foulumgaard B

Instead of a three-point hitch, a strain-gauge transducer with four individual strain-gauges measured DP in Foulumgaard B (Fig. 8 B, for the driven configuration). The strain-gauge transducer was attached to the front of the facilitating (towed) tractor. Measurements were recorded with a frequency of 0.2 kHz for about 6 m travelling distance from the far side of the sampling area until behind the stress sensors. The rolling means were calculated over each subset of 50 ms. The dataset was then limited to each 25th ms and a Kruskal-Wallis test was performed to test for differences in the rolling means. With no differences (p-value > 0.05), the mean of the rolling means was taken as DP for each pass. In one of the plots for the driven
configuration, the facilitating tractor had not activated its 4WD which resulted in only half the DP (21.4 kN), and in another plot, this tractor was not set in gear and the DP therefore relatively low (6.1 kN).

Figure 8: Traction was measured by drawbar pull with A, load cells attached to three joints (Foulumgaard A), and B, a strain-gauge transducer (Foulumgaard B).

2.2.2 Mean normal stress

Mean normal soil stress ($\sigma_m$, kPa) was derived from measurements with Bolling probes (Berli et al., 2006; Bolling, 1987) in Ladoux. These probes consist of a rubber membrane head with an inner diameter of 10 mm and a length of 150 mm (Fig. 9 A). Each probe is connected to a syringe and a pressure transducer through a PVC pipe with the same diameter as the rubber membrane head. The pressure transducer is in turn connected to a data-logger. The Bolling probes are deformable and are cylindrical fluid inclusion sensors that allow the probes inclusion pressure ($p_i$, bar) to be converted to $\sigma_m$ during traffic. Bolling probes thus yield a direct measure of $\sigma_m$, where $\sigma_m$ needs to be calculated for measurements that make use of stress-state transducers with load cells facing in different directions (as the mean of the major, intermediate, and minor principal stress. Bolling probes, in contrast, yield no knowledge of the direction or magnitude for each of the three principal stresses separately, which may be different for different configurations.

Figure 9: A, Bolling probes (top), the transducer boxes (left), and supporting materials. B, holes drilled at predefined angles allow measurements at the desired depths. C, Bolling probes installed and the syringes and transducers attached. (Ladoux)
The Bolling probes allow installation with minimal soil disturbance. The probes are installed in a drilled hole, which is drilled at a predefined angle to reach the desired depth of measurements (Fig. 9 B). Bending of the probes may be a problem, which can largely be prevented by inserting them through a (hollow) metal or PVC pipe. When installed, the probes are filled with an incompressible fluid (like water), and then connected to the syringe and pressure transducer (Fig. 9 C). A pressure of circa 100 kPa assures good soil contact.

From the measurements, the maximum inclusion pressure \( p_{i-max} \) was converted to \( \sigma_m \) according to Eq. 2, a method adapted from Berli et al. (2006) and Naderi-Boldaji et al. (2018). The coefficient \( k_s \) is an empirical factor introduced by Bolling (1987) and a function of Poisson’s ratio \( \nu \), Section 2.3.3), as long as the probe is far less compressible than the surrounding soil (Keller et al., 2016):

\[
\sigma_m = p_{i-max} k_s = p_{i-max} \frac{1 + \nu}{3(1-\nu)} \quad \text{Eq. 2}
\]

2.2.3 Tyre-soil contact area and contact stress

Measurements of the tyre-soil contact area and the distribution of vertical and horizontal stresses therein were made in Foulumgaard A and Foulumgaard B with stress-state transducers – in this case with load cells embedded in cylindrical steel transducer housings. Each housing contained a piston (ø 20 mm) that transmitted the force applied to it to the load cell (DS Europe and X-SENSORS, Series BC-302). Each load cell was connected to the data-logger and measurements were made at 1 kHz. Calibration of the load cells prior to the field experiments allowed conversion of the measured voltage to load. The specific sensors used, as well as their installation differed between Foulumgaard A (vertical contact stress) and Foulumgaard B (vertical and horizontal contact stress). In both cases, a laser sensor (Fig. 10 E) allowed for identification of the positioning of the passing vehicle relative to the load cells and yielded \( V_{act} \).

Foulumgaard A

A 1.0 x 0.15 m rubber blanket with 17 similar cylindrical steel transducer housings (ø 50 mm, 32 mm high, spaced 10 mm apart, i.e., with 60 mm between the centres of two load cells) glued to it was used for measurements of the tyre-soil contact area and distribution of vertical stress therein. The blanket was placed in a fitted trench with the top of transducer housings at 0.10 m; the trench was dug with a constructed Dutch hoe in undisturbed soil layers after the upper 0.10 m soil was rotovated (Fig. 10 A–C). The cables of the load cells ran through a PVC tube. Each piston was then pushed with the back of a long stick to test the connection. Next, the soil around the transducer housings was repacked by hand to approximately similar densities as the non-tilled soil in which the trench was dug (Fig. 10 D). Finally, 0.1 m of rotovated soil was loosely restored on top to cover the sensors, aiming for similar soil conditions on top of the sensors as the rotovated soil that was not put aside for the installation
of the blanket (Fig. 10 E). This measuring method was introduced by Schjønning et al. (2008), where further details can be found. The tyres first passed the transducer housings and then the tube in order not to risk disturbance of the measurements.

Figure 10: A-E, Installation of the rubber blanket with seventeen load cell transducers for measurements of the tyre-soil contact area and the vertical stress distribution in the contact area. (Foulumgaard A)

Foulumgaard B
A battery of twelve cylindrical steel transducer housings (ø 52 mm, length 80 mm, with 83 mm between the centres of two load cells) were laid down one-by-one in trenches. Each trench was dug with a special constructed Dutch hoe with a semicircle (ø 50 mm). The trench was thus slightly narrower than the transducer housings. This improved the stability of the housing in the soil and the contact between the soil and load cells. The two transducer housings on both far sides of the battery were dummies, i.e., without load cell, to reduce the risk of elongation of the battery of housings with load cells and thereby aiming to fix their lateral position. The cables of the 10 load cells (in the transducer housings) ran through the battery of transducer housings (Fig. 11 A).

This was the measuring method was used for both vertical and horizontal (in the driving direction) contact stresses, measured horizontally both forwards and rearwards in the driving direction (\(\sigma_{x-in}\) and \(\sigma_{x-inr}\), respectively, Fig. 11 A). The three trenches were spaced \(~0.7\) m apart, close enough for the wires to reach the data-logger (Fig. 11 B), but far enough from each other to reduce the chance of the housings influencing the measurements in another trench due to differences in stiffness between housing and soil. The trenches for measurements of vertical and horizontal stress were of different depths (0.025 m deeper for vertical stresses, i.e., half the transducer housing ø), to ensure that all stresses were measured at 0.10 m depth.

The trenches were dug in undisturbed soil (Fig. 11 A). This assured the best possible contact between the soil and pistons in the transducer housings for the measurements of horizontal stress. However, due to the cylindrical form of the transducer housing, only the lower half of the piston was in contact with the undisturbed soil – the upper half was exposed to free air. To limit differences in soil stiffness in front of the pistons, we tightly pressed some of the removed soil onto the upper half of the piston to mimic the density on the lower half. After a trench was
filled with transducer housings and the position of a middle piston marked, the excavated soil was restored on top of the housings. For the battery installed for measurements of vertical stress, a V-shape cut by a spade from the soil surface (from 0.2 m on each side, Fig. 11 C) to the transducer housings disturbed the soil strength. This reduced the risk of the load of the passing vehicle being carried by the walls of the trench rather than transmitted to the piston.

Aiming at a uniform restoration of the excavated soil between the sensors and between plots, a hollow concrete roller (1.2 Mg \( F_{\text{static}} \), Fig. 11 D–E) attached to the rear of a small tractor rolled over the area with the sensors twice (to and fro). The concrete roller was wide enough for the metal bands on its sides to pass outside of the installed battery of transducers housings. The concrete roller could reach the far installation of horizontal stress without the tractor reaching the nearest. After each pass, the width of the wheel track was measured. After the last pass, the soil above the transducer housings was removed and measurements were taken to identify the position of the load cells in the wheel track, i.e., under the passing wheel.

![Figure 11: A-E, Installation of the stress transducer for measurements of the tyre-soil contact area, and of horizontal (\( \sigma_{x-\text{in}} \) and \( \sigma_{x-\text{out}} \)) and vertical stress (\( \sigma_z \)) distribution in the contact area. In A, two transducer housings with the pistons marked white indicate the direction the load cell was facing. (Foulumgaard B)](image)

**Data processing and calculations**

The data from Foulumgaard B was processed prior to the calculations of the tyre-soil contact area described further below. The lateral position of the load cells in the wheel track was used to correct the data of some load cells; despite precautions of assuring good contact, the measurements of some of the load cells were missing or too inaccurate. For measurements of vertical contact stress, the data was then replaced by the data from the load cell on the equidistance of the tyre’s centre across the driving direction (i.e., mirrored, Fig. 12). In one case, however, it meant that further calculations could not be performed well (the super-ellipse...
could not be fitted), hence this measurement was not mirrored prior to those calculations. In this case, for the driven configuration where \(DP\) was \(-21\) kN (instead of \(-41\)), the wheel track was nearly 7 cm wider (14 cm in total) than the width that the load cells with measurements covered. This led to a relative low contact area, and is further discussed in Section 4.2.1.

![Image](image_url)

**Figure 12:** Example of data processing in which the load-cell measurements were related to the position of the load cells under the passing tyre \(\sigma_z\) is corrected.

The tyre-soil contact characteristics derived from the vertical contact stresses are as follows: The contact area was numerically calculated \((A_{num}, \text{m}^2)\) based on the measurements \(> 10\) kPa, assuming 10 kPa as the expression of tyre-soil contact. Taking the integral of the measured stresses in \(A_{num}\) yielded the apparent wheel load \((F_{app}, \text{Mg})\). The load factor is calculated as \(F_{static}/F_{app}\), and has been used to correct the measured stresses for potentially inaccurate measurements due to differences in stiffness between the transducer housings and the surrounding soil (e.g. Lamandé et al., 2015; Schjønning and Lamandé, 2010). However, for the measurements in Foulumgaard A and Foulumgaard B the dynamic wheel load \((F_{dynamic})\) was calculated instead, based on Lamandé et al. (2015) who studied the differences between actual and measured vertical stress for different stress transducers. The authors reported an 18 % overestimation for the transducers used in Foulumgaard A \((F_{dynamic} = 0.82 \times F_{app})\) and a 7 % underestimation for the transducers used in Foulumgaard B \((F_{dynamic} = 1.07 \times F_{app})\). The corrected maximum vertical stress in the contact area is denoted \(p_{peak}\) (kPa). The mean ground pressure \((p_{mean}, \text{kPa})\) was calculated as \(F_{dynamic}/A_{num}\).

Next, the limits of the measured contact area \((\sigma_z > 10\) kPa\) were centred in and across the driving direction (i.e., in the longitudinal and lateral direction) and used to fit a super-ellipse \((\text{Fig. 13})\) to describe the shape of the contact area (Hallonborg, 1996). Three points were added at both lateral edges at \(-0.1, 0.0\) and \(0.1\) m from the axle to help the fit. In Foulumgaard A, the lateral edges were defined as the outer-most load cells with measurements. In Foulumgaard B, the lateral edges defined as the outer-most load cells \(+/- 0.0415\) m to improve the fit by taking into account that the tyre-soil contact to the outer side of the last load cell with measurements was \(0.083\) m on average. The periphery of the ellipse yields another estimate of the tyre-soil...
The contact area \( (A_{\text{clip}}, \text{m}^2) \). The ellipse itself is described by three parameters: \( a, b \) and \( n \), where \( a \) and \( b \) describe the half-length and half-width, respectively, and \( n \) describes the squareness of the ellipse. For \( n = 2 \), the contact area is circular if \( a \) and \( b \) are equal, and elliptical if \( a \) and \( b \) are not equal. For higher \( n \) values, the shape of the contact area becomes squarer or more rectangular, i.e., the corners are less rounded (Schjonning et al., 2015b, 2006).

![Diagram of fitting the super-ellipse to the contact area.](image)

**Figure 13:** Fitting the super-ellipse to the contact area. A, Foulumgaard A. B, Foulumgaard B. The light points are the contact area limits \( (\sigma_z > 10 \text{ kPa}) \), the dark points are the points added, the line is the fitted ellipse.

The magnitude of the stresses was compared between the three installations \( (\sigma_{x\text{-in}}, \sigma_z \) and \( \sigma_{x\text{-out}}) \) and the two configurations, but only for the first passes \( (N = 4 \text{ and } 2 \) for the towed and driven tractor). The magnitudes were compared by the average maximum stresses calculated for each pass and installation based on the maximum \( \sigma \) for each load cell of the installation with \( \sigma > 10 \text{ kPa} \) (used as expression of tyre-sensor contact). The contact stresses were also plotted for visual evaluation.

### 2.2.4 Vertical and horizontal soil stress

Measurements of vertical and horizontal stress \( (\sigma_z \) and \( \sigma_x \), respectively) in the upper subsoil were made in Foulumgaard A with stress-state transducers; in this case, using load cells embedded in cylindrical steel transducer housings like the ones used for measurements of contact stress in Foulumgaard B \( (\phi 52 \text{ mm, length } 80 \text{ mm}) \). The \( \sigma_x \) was measured in the driving direction, the pistons facing forward. Each calibrated load cell was connected to a data-logger and measurements were made at 1 kHz. The laser sensor kept track of the position of the axles relative to the load cells installed. For both the measurements of \( \sigma_x \) and \( \sigma_z \), two transducers housings were installed, one on either side of the aimed tyre centre.

The transducer housings were installed in the upper subsoil by a method that caused only minimal soil disturbance. The installation followed a similar procedure to that used in Lamandé et al. (2007) and Lamandé and Schjønning (2011c) and is described in more detail in **Paper 3**. The measurements of \( \sigma_z \) for two of the sensors (in the same block) were excluded,
as well as the measurements of $\sigma_x$ for one sensor. The data for $\sigma_x$ was smoothed with the smooth.spline function from the R (R Core Team, 2017) package Stats, version 3.4.3, in which the smoothing parameter ‘spar’ was set to 0.4 to reduce the noise (Fig. 14). In line with the measurements of vertical contact stress, was $\sigma_z$ corrected with 1.07 (Lamandé et al., 2015) for potential inaccuracies between actual and measured stress. For $\sigma_z$, the same deviation was assumed, hence the measurements were corrected for a 7 % underestimation. The maximum $\sigma_z$ and $\sigma_x$ were derived for each axle and each pass, and the average maximum stress was calculated for each axle and configuration within each block.

![Figure 14: Example of the smoothing applied to the measurements of horizontal soil stress ($\sigma_x$) (Foulumgaard A) with the dashed bar the smoothed curve that was used for further calculations of $\sigma_x$. The four (double)peaks are the four axles passing (from left to right: tractor front to trailer rear).](image)

### 2.2.5 Calculated vertical contact stress

The FRIDA model (Schjønning et al., 2008) was used to fit the distribution of vertical stress in the tyre-soil contact area for the tyres in Ladoux, Foulumgaard A and Foulumgaard B. The FRIDA model estimates two shape parameters, $\alpha$ and $\beta$, that describe the ability of the tyre to distribute vertical stress in the contact area in and across the driving direction, respectively, by combining a power law and decay function. The distribution in the driving direction is better for higher values of $\alpha$, meaning that the distribution is more even in the length of the tyre-soil contact area (Schjønning et al., 2008). The distribution across the tyre is optimal for $1.79 < \beta < 2.08$; $\beta < 1$ reflects a stress distribution with a single-peak, while $\beta > 1$ reflects a dual-peak distribution (Schjønning et al., 2008). The model-fitted maximum vertical stress in the contact area is denoted $p_{max}$ (kPa).

The model-input data was different for Ladoux than for Foulumgaard A and Foulumgaard B. For the Ladoux-configurations, the tyre loading characteristics (traction tyres, tyre volume, tyre width, a ratio between recommended and actual $p_{tyre}$ ($K_r$, $F_{static}$, tyre deflection ($L$), and a correction of contact area due to tillage and estimate of soil strength) were used. In both Foulumgaard experiments, $F_{static}$ was combined with the results of the contact area
measurements and calculations: \( a \), \( b \), and \( n \). Two additional modelling exercises were performed for the Ladoux tyres. First, the distribution of vertical contact stress was calculated for \( \text{Evo}_60 \) with an optimised \( \beta \) \((\beta = 2, \ \text{Evo}^+\)\). Then, tyre and contact area dimensions were calculated for a tyre named \( \text{Opti} \), which had the diameter and actual and recommended inflation pressures as \( \text{Evo}_60 \), but for which the maximum \( \sigma_z \) at 0.5 m depth \((\sigma_{z-0.5})\) equalled 50 kPa. To achieve this, \( \alpha \) was adjusted in adjusted to the chosen \( \beta \) of 2 \((\text{for} \ \text{Evo}^+)\). The dimensions were then derived from Eq. 3–6, where Eq. 3 yielded \( b \), Eq. 4 yielded \( a \), Eq. 5 yielded \( W \) and Eq. 6 yielded \( A_{\text{elli}} \) for \( k = 0.895 \) \((\text{for} \ n \approx 3.2 \ \text{(data not shown)}, \ \text{Hallonborg}, 1996)\).

\[
\beta = \exp(-1.787 + 2.443b - 0.4647K_r + 4.72L) \quad \text{Eq. 3}
\]

\[
\alpha = \exp(0.376 + 4.301a^2 - 0.00631F_{\text{static}}) \quad \text{Eq. 4}
\]

\[
b = 0.0296 + 0.484W - 0.0164K_r \quad \text{Eq. 5}
\]

\[
A_{\text{elli}} = 4kab \quad \text{Eq. 6}
\]

2.2.6 Calculated vertical and horizontal soil stress
Vertical and horizontal soil stresses \((\text{i.e.}, \sigma_z \text{ and } \sigma_x \text{ at depth})\) were calculated using the analytical Söhne (1953) model, where the vertical contact stress characteristics \((F_{\text{static}}, \alpha, \beta, a, b, n)\) were used as the main input. The Söhne model is a summation procedure based on the Boussinesq (1885) solution for the problem of the load transfer from a concentrated normal force \((\text{on the soil surface})\) to an elastic, isotropic half-half space \((\text{soil})\). In this model, the contact area is divided into \( N \) small elements, for each point which stress is calculated.

Vertical and horizontal soil stresses are calculated for each \( i \) element with Eq. 7 and Eq. 8, respectively, from the vertical point load \((P_i)\), shear point load \((H_i)\) and the polar coordinates \( r_i \) \((\text{the distance from} \ P \text{ to the point of interest})\), \( \theta_i \) \((\text{the angle between the normal load vector and the position vector from the point load to the desired point})\) and the angle between the \( x \)-axis and the vertical plane that contains the position vector to the desired point \((\delta_i)\), and a concentration factor \((V)\). This factor was introduced by Fröhlich (1934) to account for the elastoplastic behaviour of the experimental soil conditions. The concentration factor increases as soils become softer \((\text{Koolen and Kuipers, 1983})\). For the calculations of vertical soil stress for the configurations in Ladoux, \( V = 5 \). Both vertical and horizontal soil stress were calculated for the driven tractor tyres in Foulumgaard A with a concentration factor of \( V = 4 \).

\[
\sum_{i=0}^{N} (\sigma_z) = \sum_{i=0}^{N} \frac{VP_i}{2\pi r_i^2} \cos^v \theta_i \quad \text{Eq. 7}
\]

\[
\sum_{i=0}^{N} (\sigma_x) = \sum_{i=0}^{N} \frac{VP_i}{2\pi r_i^2} \cos^{v-2} \theta_i + \frac{VH_i}{2\pi r_i^2} \sin^{v-2} \theta_i \cos \delta_i \quad \text{Eq. 8}
\]
The horizontal soil stress was estimated from the vertical contact stress distribution, whereby the same ratio of $\sigma_x$ to $\sigma_z$ was assumed in the soil profile as near the soil surface, i.e. a similar propagation. The ratio $\sigma_x$ to $\sigma_z$ was derived for the tractor tyres of the two configurations in Foulumgaard A ($2+2 \, L$ and $2+2 \, H$), i.e., for the two levels of $DP$, based on the relationship between $DP$ and the ratio of maximum $\sigma_x$ to maximum $\sigma_z$ for the different levels of $DP$ in Foulumgaard B (Fig. 15). The ratios were 0.283 and 0.338 for $2+2 \, L$ and $2+2 \, H$, respectively, for configurations mean $DP$s of $5.7 \pm 0.9$ and $6.9 \pm 1.2 \, kN$, respectively. These levels of $DP$ differ from the $DP$ mentioned in the Sections 2.1.2, 4.1 and 4.2.1. In those sections, the $DP$ is based on the first passes in all plots and corrected for the slope of the field. The 5.7 and 6.9 kN $DP$, on the other hand, is the mean $DP$ near the stress sensors, particularly.

![Graph](image)

**Figure 15:** The relation between drawbar pull ($DP$) and the ratio of measured maximum horizontal to maximum vertical stress ($\sigma_x$ to $\sigma_z$) in the contact area for the individual passes with $DP$ (Foulumgaard B). The white point ($DP = 0$, ratio = 0.13) was added to prevent the intercept from being $\leq$ zero.

### 2.3 Soil characteristics and response – Analytical methods and calculations

#### 2.3.1 Soil penetration resistance

Soil penetration resistance ($PR$, MPa) was measured to 0.71 m depth for Foulumgaard A, for the plots with experimental traffic in the centre of the wheel track immediately after traffic (Paper 4). The number of replicate recordings (measurements per plot) varied from 9–12, because sometimes it was doubtful whether a recording went well or was disturbed by the cone hitting a stone. Prior to calculations and analysis, the data was then also corrected for outliers (often caused by stones).

#### 2.3.2 Soil sampling and processing

In all three experiments, 100-cm$^3$ cylinder soil cores (34.82 mm high, 60.05 mm inner ø) were sampled from the Reference plots (i.e., without traffic, randomly, but in a small area) and from below the centreline of tyres. For the configurations with traffic, sampling was not done at
random because the effect of wheeling is not homogeneous across the tyre (Berisso et al., 2013). The samples were stored at 2°C until used for lab measurements.

The samples used for measurements of soil mechanical properties (Section 2.3.3, confined precompression stress ($\sigma_{pc}, \text{kPa}$), Young’s modulus ($E, \text{kPa}$) and Poisson’s ratio ($\nu$)) were tested at field conditions, i.e., without equilibration of the soil water content. The samples used for measurements of soil structural properties (bulk density ($\rho_b, \text{Mg} \text{m}^{-3}$), porosity ($\varepsilon, \text{m}^3 \text{m}^{-3}$) and air permeability ($k_a, \text{µm}^2$), Section 2.3.4) were equilibrated to a matric potential of -100 hPa, also pF2, using sand tables. The soil cores were first slowly wetted to saturation to remove entrapped air and then drained to -100 hPa, the selected matric potential.

All soil cores were finally placed in an oven (at 105°C for 48 h) to remove all water. At the time of writing, the soil cores from Foulumgaard B taken for measurements of soil structural properties have not all been oven-dried.

### 2.3.3 Soil mechanical characteristics

#### Confined precompression stress

The confined precompression stress ($\sigma_{pc}$) was derived from the stress-strain relationship of the uniaxial confined compression tests (UCCT), performed in principle as described by Koolen (1974). The soil cores were loaded with 2945 Nm$^{-2}$ using a 5969 Dual Column Tabletop Testing System (INSTRON®; Norwood, MA, USA) with a strain-controlled piston ($\phi$ 59 mm) at a velocity of 1 mm min$^{-1}$. The $\sigma_{pc}$ was then determined following a method developed by Lamandé et al. (2017). The load (N) and displacement (mm) were converted to stress ($\sigma, \text{kPa}$) and strain ($d\varepsilon, \text{mm}$). The $\sigma$ was log-transformed. A polynomial (Eq. 9) was fitted to each subset of 23 pairs of stress-strain values to derive the maximum increase in strain (the maximum positive B-coefficient) and the $\sigma_{pc}$ (corresponding stress-level to the maximum positive B-coefficient):

$$d\varepsilon = A \log \sigma + B(\log \sigma)^2$$  \hspace{1cm}  \text{Eq. 9}

#### Poisson’s ratio

Poisson’s ratio ($\nu$, Eq. 10) was determined following a method described by Eggers et al. (2006), based on the stress-strain relationship of the reloading curve of the UCCT in combination with Young’s modulus (Section Young’s Modulus). The samples were, after being loaded with 2945 Nm$^{-2}$ for estimation of $\sigma_{pc}$ and left unloaded for 15 minutes, reloaded with 3534 Nm$^{-2}$ with the same strain-controlled velocity of 1 mm min$^{-1}$ as the first loading. The load and displacement were converted to stress (and log-transformed) and strain. The part of the stress-strain relationship used to determine $\nu$ was limited to 40–1000 kPa. The lower limit was set to exclude possible internal friction and the upper limit was set to have the reloading curve represent the unloading of the first loading:

$$\nu = \frac{-1}{4} \left[ \frac{dE}{d\sigma} + \left( \left( 1 - \frac{d\varepsilon}{d\sigma} E \right) \left( 9 - \frac{d\varepsilon}{d\sigma} E \right) \right)^{0.5} \right]$$  \hspace{1cm}  \text{Eq. 10}
Young’s modulus
Young’s modulus, \(E\), kPa was derived from the stress-strain relationship (Eq. 11) of the reloading curve of the uniaxial unconfined compression tests (UUCT) using a 5969 Dual Column Tabletop Testing System. The soil samples were removed from their cylinder cores and loaded with a strain-controlled piston (ø 59 mm) at a velocity of 1 mm min\(^{-1}\) with 50 Nm\(^2\), unloaded for three minutes and reloaded with 74 Nm\(^2\). These rather low loads ensured that the elastic limits of the soil samples was not exceeded.

\[ E = \frac{d\sigma}{d\varepsilon} \quad \text{Eq. 11} \]

2.3.4 Soil structural characteristics

Bulk density
Bulk density \((\rho_b, \text{Mg m}^{-3})\) was calculated from the oven-dried soil cores. For Foulumgaard A, the reference bulk density \((\rho_{b-ref}, \text{Mg m}^{-3})\) in compacted state was calculated from Eq. 12 in Keller and Håkansson (2010) and yielded 1.67 Mg m\(^3\). The degree of compaction \((DC, \%)\) was then given as (Eq. 12):

\[ DC = 100 \frac{\rho_b}{\rho_{b-ref}} \quad \text{Eq. 12} \]

Porosity
For Ladoux, total porosity \((\varepsilon, \text{cm}^3 \text{ cm}^{-3})\) and air-filled porosity \((\varepsilon_a, \text{cm}^3 \text{ cm}^{-3})\) were calculated based on their balance-weights and the measured particle density (Table 1).

For Foulumgaard A, \(\varepsilon\) and \(\varepsilon_a\) were calculated based on their balance-weights. Additionally, the fraction of effective air-filled porosity \((\varepsilon_{eff}, \text{cm}^3 \text{ cm}^{-3})\), i.e., the air-filled pores connected to a surface of the soil sample, was estimated using the air pycnometer. The difference yields an estimate of the fraction of remote (blocked) air-filled pores \((\varepsilon_{a-blocked}, \text{cm}^3 \text{ cm}^{-3})\) (Eq. 13):

\[ \varepsilon_{a-blocked} = \varepsilon_a - \varepsilon_{eff} \quad \text{Eq. 13} \]

Air permeability
The measurements of air permeability \((k_a, \mu\text{m}^2)\) yielded both apparent air permeability \((k_{a-App})\) and Darcian air permeability \((k_{a-Darcy})\). \(k_{a-App}\) accounts for laminar flow conditions and equals the volumetric air flow at a 5-hPa pressure head. \(k_{a-Darcy}\) was measured by the Forchheimer approach (1901) as introduced and described by Schjønning and Koppelgaard (2017) and accounts for the nonlinear relation between flow and an infinitesimal pressure gradient (5, 2, 1 and 0.5 hPa). The ratio \(k_{a-App}/k_{a-Darcy}\) yields an estimate of the tortuosity of the pores connected to the sample surfaces.
**Specific air permeability**

Specific air permeability, a measure of pore geometry, was calculated for Foulumgaard A and Foulumgaard B based on Eq. 14 as suggested by Groenevelt et al. (1984) and labelled pore organisation \((PO, \mu\text{m}^2)\).

\[
PO = \frac{k_{\text{Darcy}}}{\varepsilon_{\text{eff}}}
\]  
**Eq. 14**

### 2.4 Statistical analyses

All statistical analysis were performed in R (R Core team, 2017).

An ANCOVA analysis was performed to test for differences in \(DP\) between the four types of configurations for Foulumgaard A: standard and offset steering mode, low and high trailer load (Paper 3). Only the first passes on each plot were part of the analysis. The `emmeans_test` function of the `emmeans R package` (version 1.4.3.01) was used as a post-hoc pairwise comparison, with a Bonferroni adjustment.

The non-parametric Kruskal-Wallis test of the `stats R package` (version 3.6.0) was used to test for differences in \(\sigma_m\) between the configurations (different tyres) that were part of the Ladoux experiment (Paper 1 and paper 2). In case of significant difference (p-value < 0.025), the Conover-Iman test of the `conover.test R package` (version 1.1.5) was used as the post-hoc analysis, with the Holm-Sidak adjustment method.

The non-parametric Kruskal-Wallis test was also used to test for differences in the tyre-soil contact characteristics (contact area and contact stress) in Ladoux (Paper 1), in Foulumgaard A (Paper 3) and in Foulumgaard B (different \(DP\) for the tractor tyre). In case of significant difference (p-value < 0.05), the Conover-Iman test was used as the post-hoc analysis with the Bonferroni adjustment method. Moreover, the Kruskal-Wallis test was used to test for differences in the average maximum stress vertical and horizontal stresses in the contact area for Foulumgaard B. In case of significant difference (p-value < 0.05), the Conover-Iman test was used as the post-hoc analysis.

For the Ladoux experiment, differences in the ratio \(\sigma_z/(\sigma_m \times 3)\) between the standard small and the low-inflation pressure tyres at a given depth were tested for with the non-parametric Kruskal-Wallis test. The same test was performed for to test for differences in the ratio \(\sigma_z/(\sigma_m \times 3)\) between depths for both groups of tyres. In case of significant difference (p-value < 0.05), the Conover-Iman test with the Holm-Sidak adjustment method was used as the post-hoc analysis.

For Foulumgaard A, differences in maximum \(\sigma_z\) and \(\sigma_x\) in the upper subsoil were tested for the axles between the configurations 2+2 L and 2+2 H (Paper 3). A linear model using the `gls function of the nlme package` (version 3.1–142) was used, with the configuration (axle\textsuperscript{load}),
repeated measurements (1–3) and their interaction as main effects, and a correlation between the number of wheeling (1–12) in each block to account for the potential effect of repeated wheeling. Differences in the ratio of \( \sigma_x \) to \( \sigma_z \) (Foulumgaard A) were tested with the same model, but only for the (four) tractor tyres. The test was followed by a multiple comparison (Tukey’s test) in case of significant differences (p-value < 0.05).

A linear mixed-effect model was built with the lme function of the nlme R package (version 3.1–142) to test for differences in the geometric mean \( PR \) between configurations for the Foulumgaard A soil (Paper 4). The geometric mean was calculated for each depth over the replicate recordings within each plot. The test was followed by a multiple comparison (Tukey’s test) in case of significant differences (p-value < 0.05).

The datasets with soil structural properties of the Ladoux soil and Foulumgaard A soil were corrected for outliers (Paper 1 and Paper 3, respectively). For the Foulumgaard B soil (Chapter 4), the soil samples where the driven tractor (by mistake) did not pass with high \( DP \) in the first pass were excluded. The analyses included then 36 samples for both the Reference and the towed tractor and 18 for the driven tractor. Properties were transformed if the model-residuals did otherwise not follow a normal distribution. For the Ladoux soil, both \( k_a \)-darcy and \( k_a \)-App and followed a gamma-distribution (Paper 1). For the Foulumgaard A soil, \( \varepsilon_a \)-blocked, \( k_a \)-Darcy and \( PO \) were log-transformed, and for the Foulumgaard B soil, \( \varepsilon_a \)-eff, \( k_a \)-Darcy and \( PO \) were log-transformed in the analyses.

Differences in soil structural properties of the Ladoux soil (Paper 1) were tested with a mixed model, the GroupClusterEffects function of the pairwiseComparisons R package (version 0.1.3), with the configuration as main effect and the interaction between configuration and block as random effects. For the Foulumgaard A (Paper 4) and Foulumgaard B soil, another linear mixed model was used to test for differences in soil structural properties: the lme function of the nlme-package (version 3.1–142). The configurations were used as main effects and the blocks as random effects. A pairwise comparison was completed in case of significant differences (p-value < 0.05) with the lsmean-function of the lsmeans package (version 2.30–0).
3 Effects of tyre evolution

3.1 Tyre-soil contact area characteristics and soil stress
The increase in wheel loads in the previous decades has been substantial (Keller et al., 2019) and the increase in tyre size has not been able to offset the impact on soil stress (Schjønning et al., 2015a). Tyre design might, however, still be able to reduce the risk of soil compaction [at a given wheel load]. Tyre development from 1970–2018 has namely brought about a reduction in soil stress (Paper 1); specifically, soil stress related primarily to the width and length of the contact area ($2a$ and $2b$, respectively) and to the tyre inflation pressure ($p_{tyre}$) of the tyre at a given static wheel load ($F_{static}$), regardless of the specific tyre construction (Papers 1 and 2).

3.1.1 Improvements over five generations
The results of the five generations of tractor tyre testing, at $F_{static}$ 4.3 Mg and load-recommended $p_{tyre}$ (Table 3, configurations A–E), showed that a considerable reduction in mean normal stress ($\sigma_m$) can be achieved with the use of tyres of newer designs (Paper 1). The biggest reduction in $\sigma_m$ beneath the centreline of the wheel tracks was observed with the introduction of the low-inflation pressure tyres (rear dimensions 710/70 R 42) to replace the standard small tyres (rear dimensions 20.8 (R)38). This was true for both the front and rear tyres, but the reduction in $\sigma_m$ was largest for the rear tyres. Because the rear axle generally is the heavier axle, it is here the risk of subsoil compaction can be reduced. Noteworthy is the significant reduction in $\sigma_m$ from the first radial tyre, Agri240, to the most recently introduced radial tyre, Evo60, even at 0.6 m depth (28 %, from 29 to 20 kPa, for the rear tyres) (Paper 1). At 0.2 m depth, the reduction in $\sigma_m$ was 50 % (from 145 to 73 kPa) and at 0.4 m depth 39 % (from 79 to 48 kPa).

Within the two sets of tyres, grouped by dimensions, $\sigma_m$ did not differ significantly for the tyres inflated to the same $p_{tyre}$ (240 kPa for the standard small tyres and 80 kPa for the low-inflation pressure tyres, Table 3) (Papers 1 and 2). These results indicate that the differences in $\sigma_m$ for the five sets of tyres tested at load-recommended $p_{tyre}$ did not result from differences in the tyre constructions per se. Rather, the differences in $\sigma_m$ were well explained by the tyre-soil contact area characteristics (Paper 1); Fig. 16 A–C show an increasing calculated contact area ($A_{clip}$) from Agri240 to Axio80 to Evo60, which results from differences in tyre dimension and $p_{tyre}$, respectively. The parameters describing the stress distribution in the contact area in and along the driving direction ($\alpha$ and $\beta$, respectively) indicated an improved distribution in both directions in the order Agri240, Axio80, Evo60. This then reduced the calculated maximum vertical stress in the contact area ($p_{max}$) in the same order.
Figure 16: Vertical stress distribution in the contact area in response to tyre evolution (Agri240, Axio80, Evo60) at 4.3 Mg and load-recommended inflation pressure (A-C) and the effect of over-inflated low-inflation pressure tyres (B, D).  

\[ A_{\text{dip}} = \text{calculated contact area; } \alpha, \beta = \text{parameters describing the distribution of vertical stress in the contact area in and across the driving direction, respectively; } p_{\text{max}} = \text{maximum calculated vertical stress.} \]

The reduction in \( \sigma_m \) for the low-inflation pressure tyres compared to the standard small tyres even at depths of 0.6 m is noteworthy. Stress in the subsoil is closely related to wheel load (Arvidsson and Keller, 2007; Lamandé and Schjønning, 2011b; Smith and Dickson, 1990), yet the experiment was based on tyres with similar, moderate \( F_{\text{static}} \) values for the different tyres and, hence, significant differences in the level of stress at 0.6 m depth were quite unexpected. The reduction in \( \sigma_m \) at depth was explained by the improved distribution of vertical stress (\( \sigma_z \)) in the contact area (Paper 1); this can help reduce soil stress in the upper soil, which in turn influences the stress level deeper in the soil (Schjønning et al., 2008). The results are also in line with the results of Schjønning et al. (2015a), who reported an estimated reduction of vertical stress at 1 m depth by 32 % due to a reduced mean ground pressure (for track compared to tyre).
### 3.1.2 The theoretical stress-state for different tyres

Calculated $\sigma_z$ was systematically higher than $\sigma_m$, as expected. Moreover, $\sigma_m$ was well-explained by $\sigma_z$ at each of the three depths (Fig. 17, $R^2 = 0.87–0.92$). This allows to study the relation between the two stresses inversed; Because $\sigma_m = (\sigma_1 + \sigma_2 + \sigma_3)/3$, then $\sigma_z/(\sigma_m*3)$ provides an indication of the ratio of $\sigma_z$ to $\sigma_m$, though under the assumption that $\sigma_z$ is a (major) principal stress. The remaining (i.e., $\sigma_m*3 - \sigma_z$) is then an indication of the intermediate and minor principal stresses, which are, for a driven though not pulling tyre, horizontal in the direction of travel and horizontal perpendicular to the direction of travel (Koolen and Kuipers, 1983). In relation to this experiment, a couple of assumptions need emphasising: it is assumed that the maximum $\sigma_m$ was measured under the centre of the tyres, and that $\sigma_m$ was measured precisely at 0.2, 0.4 and 0.6 m depth.

Analysis of the ratio $\sigma_z/(\sigma_m*3)$ (data not shown) revealed a significantly higher ratio for the standard small than for the low-inflation pressure tyres at 0.2 m depth (p-value 0.004). The difference faded with depth (p-values 0.114 and 0.396 at 0.4 and 0.6 m depth, respectively). A higher ratio indicates a relatively high contribution of $\sigma_z$ to $\sigma_m$ compared to the intermediate and minor principal stresses, and a low ratio a relatively low contribution of $\sigma_z$ to $\sigma_m$. In others words, the results indicated that the intermediate and minor stresses contributed more to $\sigma_m$ at 0.2 m depth for the low-inflation pressure tyres than for the standard small tyres. This might indicate a better tractive performance of the low-inflation pressure tyres than for the standard small tyres (Gee-Clough, 1980).

Differences in the ratio $\sigma_z/(\sigma_m*3)$ between depths are more tricky to discuss. Lamandé and Schjønning (2011b) showed that the Söhne model underestimates $\sigma_z$ in the upper part of the soil profile while it overestimates $\sigma_z$ deeper in the soil profile. This means that the actual ratio $\sigma_z/(\sigma_m*3)$ would differ from the calculated ratio, being actually higher at the shallower depths and lower deeper in the subsoil.

![Figure 17](image.png)

**Figure 17:** The relation between calculated vertical and measured mean normal stress ($\sigma_z$ and $\sigma_m$) for the front and rear tyres of the configurations A-E and G-I in Table 1 at the three depths of $\sigma_m$ measurements. $\sigma_m$ is presented as the mean with standard deviation. (Ladoux)
3.1.3 Tyre inflation pressure is crucial

The benefit that low-inflation pressure tyres have over standard small tyres in terms of lower soil stress at a given wheel load is essentially lost if \( p_{tyre} \) is not adjusted appropriately. Adjusting \( p_{tyre} \) is highly recommended between driving on public paved roads (where high \( p_{tyre} \) is required to improve drivability and reduce tyre wear) and fields. Also, \( p_{tyre} \) should ideally be adjusted with changing wheel loads, for example during manure spreading (which requires a decrease of \( p_{tyre} \)) and harvesting (which requires an increase of \( p_{tyre} \)). Adjusting \( p_{tyre} \) can be bothersome and time-consuming, yet is crucial if the soil structure is to be protected, even for low-inflation pressure tyres. Tyres with a high \( p_{tyre} \) carry a higher risk of soil compaction due to the poorer distribution of vertical stress at the contact area, and the associated higher maximum stress (Keller and Arvidsson, 2004; Raper et al., 1995a; Schjœnning et al., 2008). This means that it is critically important to develop and promote Central Tyre Inflation Systems (CTIS) to further reduce the risk of soil compaction and protect the soil structure.

An example of the effect of higher than recommended \( p_{tyre} \) for a low-inflation pressure tyre on the contact area characteristics is shown for Axio in Fig. 16, B and D: at the load-recommended \( p_{tyre} \) (80 kPa), \( p_{max} \) is 148 kPa, which increases by 34 % to 198 kPa for \( p_{tyre} \) 120 kPa. This is due to a smaller estimated contact area (\( A_{ellip} \)) and a poorer distribution of vertical stresses in the contact area for the higher \( p_{tyre} \). The difference is expected to be even larger for Evo, which changes shape at \( p_{tyre} \) around 120 kPa, which means that from around 120 kPa and up, Evo will have a contact area very similar to Axio. Measurements of \( \sigma_m \) also resulted in significantly higher \( \sigma_m \) at 0.2 m depth and a strong tendency for a higher \( \sigma_m \) at 0.4 m depth (p-value 0.069) for Evo at 80 kPa than for Evo at 60 kPa (Paper 2). The effect of \( p_{tyre} \) decreases with soil depth (e.g. Arvidsson & Keller, 2007; Schjœnning et al., 2012), but the depth at which its influence fades can vary with soil conditions (Dexter, 1988; Lamandé and Schjœnning, 2011a).

Although a lower \( p_{tyre} \) thus served to reduce soil stress here, it is not always beneficial to reduce \( p_{tyre} \). Underinflated tyres can result in peak stresses near the edge of the tyre (Raper et al., 1995b; Schjœnning et al., 2008), whereas the recommended \( p_{tyre} \) seems to produce the optimal contact stress distribution (Schjœnning et al., 2008).

Considering the results discussed above, it is fair to suggest that the statement that ‘no tyres can be selected to minimise subsoil compaction’ (Botta et al., 2002) can be nuanced. Namely [for a given \( F_{static} \)], the choice of tyre and \( p_{tyre} \) can reduce the risk of soil compaction, also deeper in the soil profile, as the choice of tyre and \( p_{tyre} \) influences the tyre-soil interaction and, hence, the distribution of stress in the contact area (Fig. 16, Paper 1). The more even the distribution of \( \sigma_z \), the lower the \( \sigma_z \) in the upper part of the soil. Although the effect of a better contact stress distribution on soil stress does decrease with increasing depth, it can reduce the level of \( \sigma_z \) also deeper in the soil profile (Paper 1).
3.1.4 Further improvements to the contact area characteristics

While the tyre evolution assessed in the previous sections showed that stress in the top- and upper subsoil are reduced for tyres with a larger contact area \( A \) in combination with a lower \( p_{\text{tyre}} \), there are limits to how much tyre evolution can further reduce the risk of soil compaction. Calculations with \( \text{Evo} (F_{\text{static}} \, 4.3 \, \text{Mg} \, \text{and} \, p_{\text{tyre}} \, 60 \, \text{kPa}) \), for example, showed that the effect of further optimisation of tyre-soil contact stress distribution, without changing tyre dimensions, on the reduction of \( \sigma_z \) is marginal (\( \text{Evo}+, \text{Paper 1} \)). In these calculations \( \beta \) was increased to 2, which reflects an optimisation of the distribution of \( \sigma_z \) across the tyre (Schjønning et al., 2008).

This can be achieved without changing dimensions of the tyre and contact area by reducing the static loaded radius \( (\text{SLR}) \) from 0.91 to 0.88 m and increasing tyre deflection \( (L) \) from 24 to 31 % (Schjønning et al., 2015b). Without the change in \( A \), the \( p_{\text{mean}} \) remains 66 kPa. The \( p_{\text{max}} \) decreased from 108 only to 107 kPa, and \( \sigma_z \) at 0.5 m depth \( (\sigma_{z-0.5}) \) decreased from 64 to 62 kPa (\( \text{Paper 1, Fig. 16 C} \) and \( \text{Fig. 18 A} \)). Considering a practical rule of thumb, the “50-50 guideline for sustainable traffic”, field traffic should not result in \( \sigma_{z-0.5} > 50 \, \text{kPa} \) [at water contents around field capacity, -100 hPa matric potential] in order to minimise subsoil compaction (Schjønning et al., 2012), hence the results discussed here indicate that further development of tyre design and technology is necessary to reduce the risk of soil compaction.

It is also possible to optimise the distribution of \( \sigma_z \) stress in the driving direction, i.e., optimise \( \alpha \). This requires a change of the tyre dimensions, because \( \alpha \) relates to the length of the contact area, which in turn is related with the width of the contact area (Schjønning et al., 2015b, Section 2.2.5). Tyre dimensions and the contact area were calculated for \( \text{Opti} \), the theoretical tyre based on \( \text{Evo}_{60} \) with an optimised \( \alpha \) as well as \( \beta \), so that the tyre complies with the 50-50 guideline (Schjønning et al., 2012). It should be noted that complying with this guideline does not ensure that subsoil compaction is prevented. In this exercise, the rim and tyre diameter were kept similar to the tyre \( \text{EvoBib} \), to allow this calculations to yield a tyre that could, theoretically, be mounted on existing tractors. Moreover, it was assumed that \( \text{Opti} \) had similar recommended and actual \( p_{\text{tyre}} \) and a similar \( L \) (Section 2.2.5). This exercise may, however, have resulted in a pneumatic tyre that cannot be constructed – it is merely meant as an illustration of opportunities of further tyre development that may further reduce soil stress.

These calculations yielded a tyre (\( \text{Fig. 18 B} \)), with a contact area width \( (2^b) \) of 1.05 m and an \( A_{\text{clip}} \) of 0.86 m², i.e., 33 % and 34 % larger for \( \text{Opti} \) than for \( \text{Evo}+ \), respectively. The length of the contact area \( (2^a) \) remained nearly the same \( (0.90 \, \text{and} \, 0.92 \, \text{m} \) for \( \text{Evo}+ \) and \( \text{Opti} \), respectively) because \( \beta \) was already optimised \( (=2) \) for \( \text{Evo}+ \). The \( \alpha \) increased from 2.68 to 2.77, \( p_{\text{max}} \) reduced from 107 to 79 kPa and \( \sigma_{z-0.5} \) reduced from 62 to 50 kPa. The width of the tyre itself \( (W) \) increased from 0.75 to 1.03 m. If, however, \( L \) could increase, then the length of the contact area will increase and \( \sigma_{z-0.5} \) will be 50 kPa for a tyre smaller than \( \text{Opti} \).
Schjønning et al. (2015a) calculated the tyre-soil contact area and width for a tyre with various wheel loads at which $\sigma_{z-0.5}$ would not exceed 50 kPa. For a wheel load of 7.5 Mg, the authors found that $A$ should be 2 m² and $W$ 1.36 m. This means that the width of a tractor by tyre size only is 2.72 m. Not only would this wide contact area be troubling for traffic in certain crop and growth stages, it may be impossible to design a tractor fit for those tyres and still comply with law and regulations during traffic on public roads. In Denmark, a width of 3.00 m is allowed for tractor-trailers if the width beyond 2.55 m is related to wheels and wheel guards only (Trafik- og Byggestyrelsen, 2016).

Changing the contact area may also effect the tractive potential of a tyre, i.e., it may allow a tyre to pull higher loads at lower $p_{\text{tyre}}$ and with lower $F_{\text{wheel}}$. This potentially reduces stresses both in the top-and subsoil. The tyres $\text{Axio}80$ and $\text{EvoRL}$ (-20 % $F_{\text{wheel}}$ and -25 % $p_{\text{tyre}}$ for the latter, Table 3) allowed for a quick comparison (Paper 2), but $\sigma_m$ did not differ significantly at any of the three depths measured. There must thus be other aspects of tyre-soil interaction contributing to the measured mean normal soil stresses. A similar tractive potential was assumed for the test of these two tyres but tractive forces were not quantified. Traction may thus be a factor that led the results to differ from expectations. Moreover, there might have been an effect of a longer contact area for $\text{EvoRL}$ that cancelled out lower stress at depth, where stress is related with $F_{\text{wheel}}$. According to Söhnes (Söhne, 1953) summation procedure is a given point in the soil loaded by more point loads if the contact is longer for a given width.

![Figure 18](image-url)

**Figure 18**: Vertical stress distribution in the contact area for two theoretical tyres, at $F_{\text{static}} = 4.3$ Mg and $p_{\text{tyre}} = 60$ kPa. A, Optimisation of $\text{Evo60}$ (Fig. 16 C) with $\beta = 2$. B, Further optimisation of the tyre-soil contact characteristics that is needed for $\text{Evo60}$ to comply with the “50-50 rule of thumb” (see text Section 3.1.3 for clarification). $A_{\text{ellip}}$ = calculated contact area; $\alpha$, $\beta$ = parameters describing the distribution of vertical stress in the contact area in and across the driving direction, respectively; $p_{\text{max}}$ = maximum calculated vertical stress in the contact area; $\sigma_{z-0.5}$ = calculated vertical stress at 0.5 m depth.
3.2 Soil response to tyre evolution

The risk of soil compaction is trivial if the soil is strong enough to withstand the magnitude of stresses induced. Soil mechanical properties are thus of critical importance, and might be able to explain unexpected results. This was observed in this experiment focusing on the effect of tyre evolution. Against expectations, there were very little indications of soil structural deformation (dry bulk density ($\rho_b$), porosity ($\epsilon$) and air permeability ($k_a$)) at 0.30 m depth under the centreline of the tyres after a single pass of the five generations of tyres (Paper 1); the precompression stress ($\sigma_{pc}$) at 0.3 m depth (33 ± 9 kPa for the Reference soil) was exceeded by $\sigma_z$ at 0.3 m depth (calculated, 79–175 kPa, data not shown). At 0.5 m depth, calculated $\sigma_z$ exceeded 50 kPa for all front and rear tyres. Such levels roughly indicate a risk of soil deformation even in the subsoil (Keller et al., 2012; Schjønning et al., 2012). The soil of this study was, however, characterised by a relatively high Poisson’s ratio ($v$, 0.48, Table 2, Paper 1). This indicates a high elasticity of the soil, which could be translated into a relatively resilient soil that might have recover from the stresses induced.

Surprisingly, Evo60, the tyre with the largest $A$ and lowest $p_{tyre}$ for which soil structure response was measured, could somehow significantly increase Darcian air permeability ($k_{a-Darcy}$) and the ratio of $k_a$ ($k_{a-App}/k_{a-Darcy}$) at 0.3 m depth (Paper 1). These results indicate that more continuous, air-filled macropores were present after a single pass of Evo60 compared to no traffic, or to a single pass of the other tyres. This might be related to the tractive performance of the tyre, and a theory could be that the tractive forces caused some cracking of the soil.
4 Effects of traction

The forces applied to soil by driven and towed tyres differ; the biggest difference being the additional shear forces exerted on soil by driven tyres due to the torque acting around the axis, i.e., traction (Soane et al., 1981). The experiments on Foulumgaard A and Foulumgaard B soils indicated that the effects of traction influence more aspects of tyre-soil interaction than the magnitude of horizontal stresses ($\sigma_x$). Traction, in these studies expressed as levels of drawbar pull ($DP$), changed tyre-soil interaction for tyres with equal static wheel loads ($F_{\text{static}}$) and tyre inflation pressures ($p_{\text{tyre}}$) in that the tyre-soil contact area increased, the distribution of vertical stress ($\sigma_z$) in the contact area improved and the loading time of $\sigma_z$ and $\sigma_x$ in the contact area increased (Paper 3, Section 4.2.2). In the upper subsoil, no direct effect of traction on $\sigma_z$ or $\sigma_x$ was measured, but a relation between the propagation of the two stresses into the soil profile could be drawn (Paper 3). A substantial effect of increased traction on soil structural properties at 0.15 m depth was quantified in Foulumgaard A (Paper 4), but no effect was found at 0.10 m depth in Foulumgaard B.

4.1 Traction puts the tyre to work

Visualisation of the measured vertical stress in the contact area for the tractor rear tyres from Foulumgaard A illustrate the way the driven tyres are put to work for different levels of $DP$. In Fig. 19 A-B (and Paper 3), differences in the distribution of $\sigma_z$ in the contact area are clear: the replicates with the low $DP$ (configuration 2+2 L) are characterised by a double-peaked stress distribution with the peaks situated at approximately similar distance from the centreline of the tyre. These peaks result from tyre deflection; a moderate double-peak stress distribution has been shown to minimise vertical stress in the soil profile (Schjønning et al., 2012, 2008). The replicates with the high $DP$ (configuration 2+2 H), on the other hand, show a much more variable distribution of vertical stress across the contact area. The measured vertical contact stress distribution differed also between the configurations of Foulumgaard B, being more jagged for the driven than for the towed tyres (Fig. 19 C-F). The differences across the tyre were, however, not as clear as they were for the measurements for Foulumgaard A, even though they might have been expected to be even clearer given that the difference in $DP$ was larger in Foulumgaard B than in Foulumgaard A (41.6 and 9.1 kN, respectively).

The differences between the experiments may be partly explained by the different stress sensors used and differences in the installation of these sensors (Section 2.2.3). In Foulumgaard A, the resolution across the tyre was higher than in Foulumgaard B, with two load cells spaced 60 and 83 mm apart, respectively. The sensors in Foulumgaard A were installed at the bottom of rotovated soil, and loose rotovated soil was restored on top, whereas in Foulumgaard B the sensors were installed in a fitted trench in firm soil, with the removed soil restored on top and pressed by a concrete roller. Yet if this had influenced the load transfer
Figure 19: Measured vertical stress distribution in the contact area for individual tests for the rear tyres in Foulumgaard A (A-B, means, means of 6.5 kN and 9.1 kN DP, respectively) and Foulumgaard B (C, E, towed tyres and D, F, driven tyres at 41.6 kN DP). The Figures A-B are included in Paper 3.
to the load cells, we might have observed a similar (jagged) picture for the towed tyres. It has to be noted that the data of some load cells were replaced by the data of other load cells in the data processing prior to analysis (Section 2.2.3), but this was not done for the plots in Fig. 19. The jagged results may therefore also be caused by the level of traction.

In addition to the distribution of $\sigma_z$ across the contact area, the difference in the driving direction is noteworthy as well, especially for the measurements in Foulumgaard B. In this experiment, the distribution was more variable in the driving direction for the driven than for the towed tyre, which may reflect the way the tyre is put to work also over the length of the contact area at high $DP$s. Individual plots of the raw (non-mirrored) measurements of $\sigma_z$ in the contact area for a towed and a driven tyre are shown in Fig. 20 as examples. For the towed tyre (Fig. 20 A), the peaks of $\sigma_z$ are observed near the wheel’s axle, which is generally observed in the contact area (Keller, 2005; Keller et al., 2016; Lamandé and Schjønning, 2011b; Schjønning et al., 2008) and in the upper subsoil (Ding et al., under review, Paper 3). For the driven tyre, however, the peaks of $\sigma_z$ occur more random in the contact area (Fig. 20 B). A reason why this was not observed for Foulumgaard A might be the difference in the level of $DP$.

![Figure 20: Soil contact stress measurements of two individual tests in Foulumgaard B. Load cell zero is nearest to the tyre centre. These two plots show data that have not been mirrored nor corrected for potentially inaccurate measurements due to differences in stiffness between the transducer housings and the surrounding soil.](image)

**4.2 Tyre-soil interface characteristics for towed and driven tyres and for different levels of traction**

Measurements of the vertical contact stress in Foulumgaard A revealed fundamentally different tyre behaviours for tyres with different traction but equal $F_{static}$ and $p_{tyre}$ values (Paper 3). These observations were largely confirmed by the measurements in Foulumgaard B. Traction affected the wheel load distribution over the tractor’s front and rear axles, the size and shape of the tyre-soil contact area, the distribution of $\sigma_z$ in the contact area and the total loading time as well as the loading time in front of and behind the axle for $\sigma_z$ and $\sigma_x$. 

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4.2.1 Tyre-soil contact area and vertical contact stress distribution

The vertical contact stress measurements revealed a strong effect of traction on the contact area characteristics and the distribution of $\sigma_z$ therein. The results described in this section are specified for Foulumgaard B and only where explicitly mentioned do the results differ from the findings in Foulumgaard A (Paper 3).

Although $F_{\text{static}}$ was similar for the tractor in both configurations, the rear tyre’s $F_{\text{dynamic}}$ was significantly higher for the pulling tractor than for the towed. At the same time, the contact area was significantly larger for the driven than the towed tyre, both for the measured ($A_{\text{num}}$) and FRIDA-estimated ($A_{\text{ellip}}$) values. This indicates a redistribution of the tractor’s load from the front to the rear axle when pulling, which has also been reported by Osetinsky and Shmulevich (2004). Due to tyre deflection, the tyre-soil contact area then increased. Figure 21 displays the positive relationship of $DP$ with $F_{\text{dynamic}}$ and $A_{\text{num}}$ for the tractor rear tyre for Foulumgaard B. The $F_{\text{dynamic}}$ for the measurement with ~21 kN $DP$ is rather low and impairs the regression. No errors were found in the measurements, however, the load cells with measurements were found to not represent the full width of the tyre (Section 2.2.3). Without this measurement, the $F_{\text{dynamic}}$ of the rear tyre increased ~0.14 Mg ($R^2 = 0.47$) for every increase in kN $DP$. The $A_{\text{num}}$ increased ~0.0014 m$^2$ for each additional kN $DP$ both with and without the ~21 kN $DP$ measurement.

The significantly larger $A_{\text{num}}$ (+16 %) cancelled out a substantial effect of a significantly higher $F_{\text{dynamic}}$ (+23 %) for the pulling than for the towed tyre on $p_{\text{mean}}$, which increased by 6 % (from 54 to 57 kPa). The effect of $DP$ on the size of the contact area was explained by its shape ($n$), which differed significantly between the configurations (Table 6, p-value 0.001). The contact area was squarer (for higher values of $n$, Schjønning et al., 2008) for the pulling than for the towed tractor. The effect of $n$ is illustrated in Fig. 22 for two individual tests of Foulumgaard A (Paper 3), where the effect of $n$ was more pronounced. The half-length and half-width ($a$ and $b$) did not differ significantly between the configurations (Table 6).
Table 6: Characteristics of the contact area and the vertical stress distribution at the tyre-soil interface for the towed and driven (41.6 ± 1.2 kN drawbar pull) rear tyre (Foulumgaard B). Different letters indicate a significant difference between the two configurations (p-value < 0.05).

<table>
<thead>
<tr>
<th></th>
<th>(F_{\text{dynamic}}) [Mg]</th>
<th>(A_{\text{num}}) [m²]</th>
<th>(A_{\text{ellipse}}) [m²]</th>
<th>(p_{\text{mean}}) [kPa]</th>
<th>(p_{\text{peak}}) kPa</th>
<th>(a) [m]</th>
<th>(b) [m]</th>
<th>(n)</th>
<th>(\alpha)</th>
<th>(\beta)</th>
<th>(p_{\text{max}}) [kPa]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Towed (N=8)</td>
<td>2.1 ± 0.3 b</td>
<td>0.37 ± 0.02 b</td>
<td>0.37 ± 0.02 b</td>
<td>54 ± 8</td>
<td>211 ± 37 a</td>
<td>0.35 ± 0.02</td>
<td>0.33 ± 0.02</td>
<td>2.00 ± 0 b</td>
<td>3.18 ± 0.59 b</td>
<td>1.96 ± 0.57 b</td>
<td>146 ± 6 a</td>
</tr>
<tr>
<td>Driven (N=4)</td>
<td>2.5 ± 0.4 a</td>
<td>0.43 ± 0.03 a</td>
<td>0.43 ± 0.03 a</td>
<td>57 ± 7</td>
<td>152 ± 29 b</td>
<td>0.36 ± 0.02</td>
<td>0.35 ± 0.02</td>
<td>2.66 ± 0.41 a</td>
<td>10.01 ± 5.7 a</td>
<td>2.29 ± 0.37 a</td>
<td>107 ± 19 b</td>
</tr>
</tbody>
</table>

\(F_{\text{dynamic}}\) = dynamic wheel load; \(A_{\text{num}}, A_{\text{ellipse}}\) = measured and calculated contact area, respectively; \(p_{\text{mean}}\) = mean ground pressure; \(p_{\text{peak}}\) = corrected measured maximum vertical stress in the contact area; \(a, b\) = half-length and half-width of the contact area, respectively; \(n\) = squareness of the contact area; \(\alpha, \beta\) = shape parameter describing the distribution of vertical stress in the tyre-soil contact area along the centreline of the tyre in and across the driving direction, respectively; \(p_{\text{max}}\) = model-fitted maximum vertical stress in the contact area; ± Standard deviation. Significance: ns = p-value > 0.05, * = p-value <0.05, ** = p-value <0.01 and *** = p-value <0.001.
The individual vertical contact stress measurements of Foulumgaard B, however, revealed a longer contact length for the driven than the towed tractor (Fig. 20). The loading time in Foulumgaard B was then, due to the combination of the contact length (l) and the difference in forward speed (\( V_{act} \)), 0.814 ± 0.038 s for the towed and 1.218 ± 0.039 s for the driven tractor rear tyre (p-value 0.008, data not shown). Horn et al. (1990) and Çarman (1994) studied the effect of loading time in-situ on soil stress and soil response, respectively, by driving a tractor at different forward speed. Horn et al. (1990) observed that stress propagated wide into the soil at slow wheeling (0.8 ms\(^{-1}\)), i.e., for a longer loading time, whereas it acted as a rigid body with relatively low lateral propagation of stress to fast wheeling (2.2 ms\(^{-1}\)), i.e., for a shorter loading time. Çarman (1994) found significantly lower tyre sinkage at 0.78 ms\(^{-1}\) compared to 1.67 ms\(^{-1}\) (at 1–4 % slip) and reported significantly lower penetration resistance, bulk density and shear strength in the upper 0.1 m for at the higher speed, i.e., for the shorter loading time.

\[ a = 0.53, \ b = 0.30, \ n = 2.00 \]
\[ A_{num} = 0.54 \text{ m}^2, \ A_{ellip} = 0.50 \text{ m}^2 \]

\[ a = 0.52, \ b = 0.32, \ n = 3.00 \]
\[ A_{num} = 0.67 \text{ m}^2, \ A_{ellip} = 0.59 \text{ m}^2 \]

**Figure 22:** The contact area for the tractor rear tyres with two levels of drawbar pull of Foulumgaard A (left, \( 2+2 \ L \) and right, \( 2+2 \ H \), respectively). The plots show two individual tests. The open circles represent the contour of the measured data and the solid line is the model-fitted contour. \( a, b \) = half-length and half-width of the contact area, respectively; \( n \) = squareness of the modelled-contact area; \( A_{num}, A_{ellip} \) = measured and calculated contact area, respectively.

The overall distribution of \( \sigma_z \) in the contact area was better for the pulling than for the towed tractor. The parameters describing the distribution of \( \sigma_z \) in the contact area (\( \alpha \) and \( \beta \), in and across the driving direction, respectively) did not differ significantly between the configurations, but \( \alpha \) tended to be higher, hence better (Schjønning et al., 2008), for the driven tyre (p-value 0.07, Table 6). Both the measured and model-fitted maximum \( \sigma_z \) in the contact area (\( p_{peak} \) and \( p_{max} \)) were significantly lower for the driven tyre. Here the results differ from those obtained in Foulumgaard A where \( \alpha \) significantly improved and \( \beta \) differed significantly (decreased from 2.81 to 1.31 (Paper 3), when \( \beta \) is optimal for 1.79 < \( \beta \) > 2.08, Schjønning et al., 2008) for the high compared to the low DP, but where no significant differences were observed for \( p_{peak} \) or \( p_{max} \) (although \( p_{peak} \) reduced from 213 to 172 kPa, Paper 3).
It has been suggested to use $p_{\text{tyre}} + 50$ kPa as an estimate of the mean ground pressure ($p_{\text{mean}}$) (van den Akker, 1992) or of the expected maximum vertical stress ($p_{\text{max}}$) (Lamandé and Schjønning, 2008), based on tests with tyres without tractive forces. The measurements from Foulumgaard A and B taken together (driven and towed tyres, N = 47) support the latter ($p_{\text{max}} = 47.2 + 1.07 \times p_{\text{tyre}}, R^2 = 0.78$, $p_{\text{mean}} = 15.0 + 0.60 \times p_{\text{tyre}}, R^2 = 0.75$, data not shown). The results thus indicate that $p_{\text{max}}$ was about 45 kPa higher than $p_{\text{tyre}}$ for both driven and towed tyres. Both relationships were, however, slightly better for Foulumgaard A alone ($p_{\text{max}} = 45.9 + 1.08 \times p_{\text{tyre}}, R^2 = 0.82$; $p_{\text{mean}} = 25.7 + 0.53 \times p_{\text{tyre}}, R^2 = 0.84$). Further analysis of the data from Foulumgaard B showed a gradual effect of $DP$ on $p_{\text{peak}}$ and $p_{\text{max}}$, with a lower maximum $\sigma_z$ for a higher $DP$ (Fig. 23). This indicates that although $p_{\text{tyre}}$ is to be the main driver of vertical contact stresses, regardless of wheel load or tyre type (Lamandé and Schjønning, 2008; Schjønning and Lamandé, 2010), the level of traction on a driven tyre may have a definite effect on $\sigma_z$.

![Graph](image.png)

**Figure 23**: A, corrected measured maximum vertical stress in the contact area ($p_{\text{peak}}$) and B, model-fitted maximum vertical stress in the contact area ($p_{\text{max}}$) as a function of drawbar pull ($DP$) (Foulumgaard B). The regressions include all individual points for the towed tyre (eight for which $DP = zero$, presented as mean and standard deviation).

In addition to differences in the tyre-soil contact area characteristics, it was found that the distribution of $F_{\text{dynamic}}$ and of the measured length of the contact area ($l$) over the contact area in front of and behind the wheels’ axle ($A_1$ and $A_2$) differed between towed and driven tyres. In Foulumgaard A, $F_{\text{dynamic}}$ was quite evenly distributed between $A_1$ and $A_2$ for the towed (trailer) tyres, and the length of the contact area was also similar on both sides of the axle (Paper 3, Fig. 24 A). For the driven (tractor) tyres, on the other hand, the majority of $F_{\text{dynamic}}$ was transferred in $A_2$. Due to tyre deflection, the measured length of the contact area was then significantly longer to the rear ($l_2$) of the driven tyre’s axle than to the front ($l_1$). In effect, $p_{\text{mean}}$ did not differ significantly between $A_1$ and $A_2$ for the driven tyres (Paper 3). No significant differences in $p_{\text{peak}}$ was measured for $A_1$ and $A_2$ for the driven tyres either (data not shown). This was the case for the tractor’s rear tyres in both configurations, i.e., with the low as well as the high level of $DP$ (6.5 and 9.1 kN, respectively, Fig. 24 B-C) (Paper 3) and may therefore be the result of even a little traction.
Figure 24: Corrected measured vertical contact stress distribution for three individual tests (Foulumgaard A); A, trailer rear tyre; B, tractor rear tyre; and C, tractor rear tyre (configurations 0+1, 2+2 L and 2+2 H in Paper 3, respectively, with static wheel loads of 5.3, 3.5, and 3.9 Mg, respectively). $DP =$ drawbar pull; $A_2$ and $A_1 =$ contact area behind and in front of the wheels’ axle, respectively. In each sub-figure, the vertical and horizontal lines indicate the tyre’s centres, with the line in the driving direction having the same length in front of and behind the axle.
The differences in the contact area to the front and to the rear of the tyres axles between towed and driven tyres were, however, not observed in Foulumgaard B. In Foulumgaard B, the $l_z$ was larger than $l_x$ for both configurations: 56 % and 55 % for the towed and driven rear tyres, respectively (data not shown). For the driven tyre this trend was similar to Foulumgaard A. A comparison of $F_{\text{dynamic}}$ carried by $A_x$ and $A_z$ was not performed because of the need to mirror some of the load cells to get a full contact area, yet symmetry of the distribution across the contact area cannot be assumed (Fig. 19 and Fig. 20). The deviating results for the towed (tractor) tyres may result from the slightly pulled handbrake (Section 2.1.2, Foulumgaard B); braking might also influence the contact area (Diserens et al., 2011).

These results highlight a fundamental difference in tyre-soil interaction between driven and towed tyres, namely that the contact area may not be symmetrical in the driving direction (longitudinal) for driven (and possibly for braking) tyres. This symmetry is, however, an implicit assumption for models being based on a super-ellipse (Hallonborg, 1996), like the FRIDA model (Schjønning et al., 2008). The super-ellipse has been accurate to describe the contact area of a range of tyres at different wheel loads and inflation pressures, however, no driven tyres have been included in measurements before. So far, measurements of vertical contact stress and fitting the FRIDA model have been done for trailer tyres (Lamandé and Schjønning, 2008; Schjønning et al., 2008; Schjønning and Lamandé, 2010), traction tyres being towed across (Schjønning et al., 2015b, 2012), or traction tyres driven but without pulling (Keller, 2005). Still, differences in the tyre-soil interaction for different tyre types have previously been noted: Schjønning et al. (2015b) found that less of the tyre periphery is in contact with the soil for traction tyres (~14 %) than for implement tyres (~18 %). Calculations for Foulumgaard A and Foulumgaard B yielded similar fractions of the tyre periphery in contact with the soil (traction tyres $0.14 \pm 0.02$ and trailer tyres $0.18 \pm 0.02$). Moreover, the data from Foulumgaard B showed that traction did not affect the fraction; the ratio was $0.13 \pm 0.01$ for 16 measurements: eight passes towed, four passes at $41.6 \pm 1.2$ kN $DP$, one pass at 21.4 kN $DP$ and one pass at 6.1 kN $DP$.

More measurements with traction tyres at different levels of traction are, however, needed to verify the results of the studies discussed here. They may further improve our understanding of the tyre-soil interactions for driven tyres, and may provide more accurate modelling. It has to be noted here that in both experiments the model-fitted maximum vertical contact stress ($p_{\text{max}}$) did follow the same tendencies as the measured maximum vertical contact stress ($p_{\text{peak}}$). However, no significant differences were found between configurations in Foulumgaard A (Paper 3), while both $p_{\text{max}}$ and $p_{\text{peak}}$ were significantly lower for the driven than towed tractor rear tyre in Foulumgaard B (Table 6).
All in all, these results indicate that traction, both its presence and the level, affects the contact area and the distribution of $\sigma_z$ therein. In fact, the distribution of $\sigma_z$ improved for the higher $DP$ in both experiments, reducing the risk of compaction from $\sigma_z$. This does, however, not take into account any effects traction may have on the magnitude and distribution of horizontal stresses ($\sigma_z$) in the contact area. In fact, where the compressive stress is low, risks of shear deformation are higher (Peth et al., 2006).

### 4.2.2 Horizontal stress in the contact area

In Foulumgaard B, $\sigma_x$ in the driving direction was measured for the towed and driven tractor tyres, concurrently with the vertical contact stresses discussed in Section 4.2.1. The measurements of $\sigma_x$ were made both two directions (with load cells facing the incoming tyres (horizontal in, $\sigma_x$-in) and 180° rotated, i.e., facing the leaving tyres (horizontal out, $\sigma_x$-out), Fig. 11. The measurements showed that the level of $\sigma_x$ is affected by the driving direction; for both the towed and the driven tyre, the maximum stresses in the first pass were generally higher for $\sigma_x$-out then for $\sigma_x$-in (Fig. 25, p-values < 0.01). Between the towed and the driven tractor, the average maximum $\sigma_x$-in and $\sigma_z$ did not differ significantly (p-values 0.181 and 0.159, respectively), but a significant higher $\sigma_x$-out was measured for the driven tractor (184 kPa compared to 97 kPa, p-value 0.011). The additional $\sigma_x$, the difference in $\sigma_x$-out between the two configurations, may be considered the additional forces due to traction. The $\sigma_x$-out for the driven tractor tyre was significantly higher than $\sigma_x$ for the same configuration (Fig. 25, p-value 0.027) and only not significantly different from $\sigma_z$ for the towed tractor (p-value 0.091).

**Figure 25:** Average maximum stresses ($\sigma$) in the contact area for the towed and driven tractor rear tyres (Foulumgaard B). The average is taken over the maximum stresses of the load cells ($\sigma > 10$ kPa) installed in the same installation; $\sigma_x$-in and $\sigma_x$-out = horizontal in (first to pass) and horizontal out (second to pass), respectively; $\sigma_z$ = vertical (Fig. 11). Different letters indicate a significant different magnitude stress ($\sigma$) (p-value < 0.05).
The measurements also showed a longer loading time for \( \sigma_x \) than for \( \sigma_z \) (Fig. 26 Fig. 27 and Fig. 28). For the towed tyre (Fig. 27), the loading time in \( A_1 \) (in front of the wheel’s axle) was relatively long compared to the loading time in \( A_2 \) (behind the axle), which may be translated as an effect of rolling resistance. For the driven tyre (Fig. 28), on the other hand, the loading time was generally more pronounced in \( A_2 \) than in \( A_1 \) which may be translated as an effect of traction. These tendencies were observed for both installations of sensors for \( \sigma_x \), i.e., for both \( \sigma_{x\text{-in}} \) and \( \sigma_{x\text{-out}} \).

\[\text{Figure 26: Individual measurements of contact stresses (horizontally with the load cell facing in both driving directions and vertically) near the (lateral) centre of the passing tyre for the towed tyre A-C and the driven tyre D-F (Foulumgaard B). The dotted vertical line indicates the (approximate) position of the axle.}\]
Figure 27: Contact stress measurements for four individual passes of the towed tractor’s rear tyre (Foulumgaard B). The data has been centred in and across the driving direction according to notes taken, the level of stress corrected (* 1.07), but the data is not mirrored nor corrected for errors or outliers. The dotted vertical line indicates the axle. Please note that the x-axis is longer for the horizontal stress measurements in the right-hand column.
Figure 28: Contact stress measurements for four individual passes of the driven tractor’s rear tyre (Foulumgaard B). The data has been centred in and across the driving direction according to notes taken, the level of stress corrected (* 1.07), but the data is not mirrored nor corrected for errors or outliers. The dotted vertical line indicates the axle. Please note that some x-axes differ for the horizontal stresses from the axes in Fig. 27.
4.2.3 Vertical and horizontal soil stress for driven and towed tyres

According to the Boussinesq (1885) solution for stress propagation, both $\sigma_z$ and $\sigma_x$, at depth increase proportionally to the wheel load (e.g. Davis and Selvadurai, 1996; Söhne, 1958, 1953). For $\sigma_z$, the relation with wheel load is supported in several studies (e.g. Lamandé et al., 2007). The relation was also confirmed by measurements of $\sigma_z$ in the upper subsoil (~0.39 m depth) for the tractor-trailer combination of Foulumgaard A ($R^2 = 0.84$ for $F_{dynamic}$, Fig. 29 A, Paper 3). Although the $\sigma_x$ component is not studied to the same extent, it is expected that $\sigma_x$ increases with traction (which is confirmed in Fig. 27 and Fig. 28) and that the effect of traction on $\sigma_x$ diffuses rapidly with depth. In Foulumgaard A, no different magnitudes of $\sigma_x$ were found in the upper subsoil (~0.33 m depth) under the driven tyres (Paper 3). This could indicate that the differences in $\sigma_x$ that might have been present due to $DP$ did not reach this depth.

Regarding the Boussinesq (1885) solution for stress propagation, the $\sigma_x$ measured under the towed (trailer) tyres – a proportional increase of $\sigma_x$ with $F_{dynamic}$ ($R^2 = 0.83$, data not shown) – supported his theory. For the trailer tyres, $\sigma_x$ in the upper subsoil was also well explained by $\sigma_z$ in the upper subsoil ($R^2 = 0.79$, Fig. 29 B), which is practical since $\sigma_z$ can be modelled well by, e.g., the FRIDA model. It was not possible to test the relation between $\sigma_z$ and $\sigma_x$ for the driven tyres, since $\sigma_z$ is then not only influenced by the wheel load but, to a certain depth, also by shear forces due to traction (Koolen and Kuipers, 1983; Soane et al., 1981a).

The slope of the regression between $\sigma_z$ and $\sigma_x$ for the towed tyres might, however, be considered as a soil’s ability to transmit stresses, comparable to the concentration factor introduced by Fröhlich (1934). In this case, the effect of wheeling on soil mechanical properties and pore water can be disregarded, which may or may not affect the transmission of $\sigma_z$ in the upper subsoil. An assumption that the slope reflects the soil’s ability to transmit stresses implies that the slope of the relation between $\sigma_z$ and $\sigma_x$ could be similar for towed and driven tyres. In other words, the increase of $\sigma_x$ with $\sigma_z$ is then expected to be the same for driven and towed tyres in similar soil conditions. Tractive forces applied to the surface will increase the ratio of $\sigma_x$ to $\sigma_z$. This would come to expression as a higher intercept when linear regressions are drawn for the relation between $\sigma_x$ and $\sigma_z$ for driven tyres (Fig. 29 B), which was clear for the tractor front tyres in Foulumgaard A, but not observed for the tractor’s rear tyres. This difference might be related to the difference in the speed of revolution between the smaller front and the larger rear tyres on the tractor. The higher speed of revolution for the front tyres may cause higher shear stresses in the contact area and, if slip is the same for the front and rear tyres, the horizontal stresses in the soil might then as well have been higher for the front than the rear tyres.
Figure 29: A, Vertical stress ($\sigma_z$) at ~0.39 m depth as a function of the dynamic wheel load ($F_{\text{dynamic}}$), presented as their means and standard deviations (Foulumgaard A). Different letters indicate a significant different $\sigma_z$ between the tyres (p-value < 0.05). B, horizontal stress ($\sigma_x$) at ~0.33 m depth (Foulumgaard A) as a function of $\sigma_z$ in Fig. 29 A, presented as their means and standard deviations. Figure 29 is adapted from Paper 3.

4.2.4 Perspectives of modelling of horizontal soil stresses

Modelling of $\sigma_x$ is complicated by traction and by the limited measurements that have been collected. De Pue et al. (2020) showed that discrete element models revealed effects of traction on $\sigma_x$ that their Söhne simulations could not. The results from Foulumgaard A and B combined allowed for an alternative approach based on the Söhne model (Section 2.2.5).

Figure 30 shows that the prediction of $\sigma_x$ in the soil profile matched well the measured $\sigma_x$ for the tractor in Foulumgaard A. No model prediction of $\sigma_x$ was made for the passive trailer tyres, as the ratio maximum $\sigma_x$ to maximum $\sigma_z$ at the surface for passive tyres could not be deducted from Foulumgaard B. For the towed tractor in Foulumgaard B, this ratio was $0.9 \pm 0.3$ (data not shown) and although not much of the ratio of the two stress components is known, it comes unexpected to have a higher ratio of $\sigma_x$ to $\sigma_z$ for towed than driven tyres, especially considering that the ratio increased with increasing level of $DP$ (Fig. 15, 0.283 and 0.338 for 2+2 L and 2+2 H, respectively). The distribution of stresses for the towed tractor might, however, have been affected by the handbrake that was slightly on (Sections 2.1.2 and 4.2.1).

Further experimental research is then also needed to provide additional insights and test the approach chosen. In the modelling exercise presented, no consideration was given to where under the tyre the maximum stresses occurred. Moreover, the regression of the ratio of maximum $\sigma_x$ to maximum $\sigma_z$ at the surface and the $DP$ from Foulumgaard B is based on a limited number of data points and further experimental research is needed to test this...
relationship. Although the lower DP were unintended, they might have revealed important findings worth further investigations, at relationships with DP could allow for a relative easy approach to model \( \sigma_x \) in the soil profile.

![Figure 30](image_url)

**Figure 30:** Measured and predicted horizontal soil stress (\( \sigma_x \)) for driven tyres (Foulumgaard A), presented as the mean and standard deviation for each axle and configuration.

### 4.3 Soil response to different levels of traction

The effect of traction on soil structural properties at \( \sim 0.16 \) m depth was clear in Foulumgaard A (**Table 7, Paper 4**). No significant effect was observed between the Reference and the tractor with the low DP (configuration 2+0 L), but several measured properties were significantly different from the Reference for the tractor with the high DP (configuration 2+0 H). Even though Darcian air permeability (\( k_{a-Darcy} \)) for the Reference would be classified as very slow according to Fish and Koppi (1994) with a geometric mean of 12.9 \( \mu \)m\(^2\), it was reduced to 1.4 \( \mu \)m\(^2\) (geometric mean) after a single pass from the tractor with high traction. This is rather close to the limit of 1 \( \mu \)m\(^2\) suggested by Ball et al. (1988); below this limit soils may be considered impermeable for transport of water and air. Moreover, blocked air-filled pore space increased significantly (\( \varepsilon_{a-blocked} \), 231 \%) from the Reference, while the reductions in effective air-filled pore space (\( \varepsilon_{a-eff} \)) and pore organisation (PO, calculated as specific air permeability) were vast (33 \%, 89 \% and 83 \%, respectively, **Table 7, Paper 4**). These differences indicate a densification and homogenisation of the soil (Schjønning and Thomsen, 2013). Two structural properties did not differ significantly from the Reference for 2+0 H: dry bulk density (\( \rho_b \)) and the volume of small pores (\( \varepsilon_{<30\mu m} \)) (**Table 7, Paper 4**).
With no substantial change of the wheel load and no change in $p_{tyre}$ between the two configurations with traffic, these effects can be ascribed to traction with the additional $DP$ for $2+0 \ H$ leading to the increased soil deformation. In fact, an additional analysis with $DP$ included as a continuous variable (in addition to the configuration) revealed that traction explained all the differences in the soil structural properties between the $Reference$ and $2+0 \ H$ (p-value $<$ 0.05, data not shown). The $k_{a-Darcy}$ was thus also rather well explained by the measured level of $DP$ per plot (Fig. 31).

**Table 7:** Soil structural response after a single tractor pass for two levels of drawbar pull ($DP$) (Foulumgaard A, Paper 4).

<table>
<thead>
<tr>
<th>$DP$ [kN]</th>
<th>$\rho_b$ [Mg m$^{-3}$]</th>
<th>$\varepsilon_{&lt;30\mu m}$ [m$^3$ m$^{-3}$]</th>
<th>$\varepsilon_{a-eff}$ [m$^3$ m$^{-3}$]</th>
<th>$\varepsilon_{a-blocked}$ [m$^3$ m$^{-3}$]</th>
<th>$k_{a-Darcy}$ [$\mu$m$^2$]</th>
<th>$PO$ [$\mu$m$^2$]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reference</td>
<td>0</td>
<td>1.47 ± 0.07 a</td>
<td>0.28 ± 0.01 ab</td>
<td>0.16 ± 0.04 b</td>
<td>0.002 a</td>
<td>12.9 b</td>
</tr>
<tr>
<td>$2+0 \ L_1$</td>
<td>6.5</td>
<td>1.51 ± 0.05 a</td>
<td>0.27 ± 0.02 a</td>
<td>0.14 ± 0.03 ab</td>
<td>0.002 a</td>
<td>8.2 b</td>
</tr>
<tr>
<td>$2+0 \ H_1$</td>
<td>9.1</td>
<td>1.55 ± 0.03 a</td>
<td>0.30 ± 0.02 b</td>
<td>0.10 ± 0.03 a</td>
<td>0.008 b</td>
<td>1.4 a</td>
</tr>
</tbody>
</table>

$DP$ = drawbar pull; $\rho_b$ = dry bulk density; $\varepsilon_{<30\mu m}$ = volume of small pores, $< 30 \mu m$; $\varepsilon_{a-eff}$ = effective air-filled pore space; $k_{a-Darcy}$ = Darcian air permeability; $PO$ = pore organisation, calculated as specific air permeability; $◊$ = presented as geometric mean; ± = standard deviation.

It is unclear to which depths effects of traction may have been found. Measurements of penetration resistance ($PR$) showed significantly higher $PR$ levels for $2+0 \ H$ than for the $Reference$ at 0.22–0.25 m depth (Paper 4), with $PR$ even exceeding 2 MPa. Such a high $PR$ indicates that root growth can be seriously slowed down, by as much as half of its unhampered rate (Bengough et al., 2011; Dexter, 1987). Yet, at 0.31 m depth, no differences of horizontal stress were measured for the tractor’s axles (Paper 3). This indicates that the horizontal stresses, which were of significant importance at 0.16 m depth, had faded at 0.31 m depth.
Surprisingly, no significant difference from the Reference was found for soil structural properties for the configuration with the trailer in the standard steering configuration, 2+2 H, even though this configuration was a combination of two driven tyres with high DP (9.1 kN) followed by two passive trailer wheels ($F_{\text{dynamic}}$ 5.2 and 5.5 Mg) for which both $\sigma_z$ and $\sigma_x$ in the upper subsoil were the highest of the four wheels passing (Paper 3). PR was significantly higher (> 2 MPa) for 2+2 H than for the Reference in the soil layer just below the sampling layer (0.19–0.25 m depth, Paper 4), and soil structural properties different from the Reference soil might have been more apparent at this depth. At 0.16 m depth there was, however, both a trend for a larger $\varepsilon_{<30\mu m}$ and $\varepsilon_{\text{a-blocked}}$ for 2+2 H, than for the Reference (p-value 0.052 and 0.246, respectively). This indicates that, without a change in $\rho_b$, a larger number of small pores and blocked air-filled pore space developed at the cost of macropores that might have been partially disrupted during wheeling. These are processes related to distortion rather than compression, and indicate that the effect of shearing from horizontal stresses was larger than the effect of compaction from normal vertical stress (Berisso et al., 2013).

In Foulumgaard B, a high risk of soil deformation at 0.10 m depth was anticipated for the driven tyre (DP 41.6 kN). However, no differences in $k_a$-Darcy or $\varepsilon_{\text{a-eff}}$ appeared from initial analysis (Table 8, p-values 0.057 and 0.28). Instead, $PO$ was significantly reduced for the towed tractor, whereas the driven tractor showed no significant differences from the towed tractor or the Reference (Table 8). It may also be relevant, in future studies, to study the soil response at several soil depths, and also to include a thorough analysis of the soil strength.

The results of these studies emphasise the need for more experimental work on a more comprehensive understanding of the stress distribution during traffic, the propagation of especially horizontal stresses into the soil profile and the stress-strain relationship. It is of critical importance to understand the processes that initiate soil deformation in order to propose effective mitigation measures that lessen the negative impact of traffic on soil functions.

Table 8: Soil structural properties at 0.1 m depth, at -100 hPa matric potential in response to traction (Foulumgaard B). Different letters indicate a significant difference between the Reference, towed and driven (p-value < 0.05).

<table>
<thead>
<tr>
<th>p-value</th>
<th>$\rho_{\text{wet}},$ Mg m$^{-3}$</th>
<th>$k_a$-Darcy, $\mu m^2$</th>
<th>$\varepsilon_{\text{a-eff}},$ m$^3$ m$^{-3}$</th>
<th>$PO,$ $\mu m^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reference (N = 36)</td>
<td>1.67 ± 0.08</td>
<td>15.8</td>
<td>0.29 ± 0.05</td>
<td>50.1 b</td>
</tr>
<tr>
<td>Towed (N = 36)</td>
<td>1.69 ± 0.08</td>
<td>6.8</td>
<td>0.28 ± 0.04</td>
<td>21.4 a</td>
</tr>
<tr>
<td>Driven (41.3 kN, N = 18)</td>
<td>1.71 ± 0.06</td>
<td>8.6</td>
<td>0.27 ± 0.03</td>
<td>21.8 ab</td>
</tr>
<tr>
<td>p-value</td>
<td>ns</td>
<td>ns</td>
<td>ns</td>
<td>*</td>
</tr>
<tr>
<td>6.1 kN (N = 9)</td>
<td>1.65</td>
<td>137.8</td>
<td>0.29 ± 0.03</td>
<td>475.1</td>
</tr>
<tr>
<td>21.4 kN (N = 9)</td>
<td>1.62</td>
<td>16.7</td>
<td>0.32 ± 0.02</td>
<td>53.0</td>
</tr>
</tbody>
</table>

N = number of soil cores; $\rho_{\text{wet}}$ = wet bulk density; $k_a$-Darcy = Darcian air permeability; $\varepsilon_{\text{a-eff}}$ = fraction of effective air-filled porosity; $PO$ = pore organisation. ° presented as geometric mean; ± = standard deviation. Significance: ns = p-value > 0.05, * = p-value < 0.05.
5 Effects of repeated wheeling

A first wheel pass generally increases the soil strength of the near-surface soil layer. Repeated wheeling then takes place on a more rigid soil surface than the first wheeling. This may increase soil stress. The effect of repeated single wheeling on soil contact stress and on soil structural properties was studied for a trailer rear tyre (dynamic wheel load, \( F_{\text{dynamic}} \), 5.6 ± 0.6 Mg) in Foulumgaard A (Papers 3 and 4), and the effect of repeated wheeling on soil stress was studied for the soil stress measurements in Ladoux and Foulumgaard A. Significant effects of repeated wheeling were limited to the soil structural response, which was better explained by a linear instead of a logarithmic fit (Manuscript 4).

5.1 Effect on contact area characteristics and soil stress

For three repeated single wheeling events, no significant differences of the tyre-soil contact area and distribution of vertical stress (\( \sigma_z \)) therein were found (Paper 3). There were, though, some tendencies worth mentioning: the squareness of the contact area (\( n \)) indicated a squarer shape (p-value 0.099) for the third wheeling (\( n = 3.0 \)) than for the first and second (\( n = 2.6 \)). Although there were no trends for \( F_{\text{dynamic}} \) and the measured contact area (\( A_{\text{num}} \)) individually (p-values 0.393 and 0.733, respectively), there was a trend of an increasing mean ground pressure (\( p_{\text{mean}} \)) with an increasing number of wheeling (95, 102 and 105 kPa, p-value 0.066). Lastly, the parameter describing the distribution of \( \sigma_z \) in the contact area across the tyre (\( \beta \)) increased with an increasing number of wheeling (1.24, 1.53 and 1.61, p-value 0.113). Generally, the first pass has the largest impact on the soil near the surface (Lamandé et al., 2015; Pytka, 2005; Way et al., 1995). This may explain why the largest differences in \( p_{\text{mean}} \) and \( \beta \) were observed between the first and second wheeling; the first wheeling was on loose, rotovated soil and the second wheeling was in the wheel track from the first.

Stress measured in the soil profile may increase due to the near surface soil deformation; a decrease of the tyre-soil contact area changes the stress distribution and the formation of a wheel rut leads to a decrease of the distance between the soil surface and the stress sensors in the soil (Naderi-Boldaji et al., 2018; Pytka, 2005; Wiermann et al., 1999). In the studies presented in this dissertation, no significant effect of repeated wheeling on the stress measurements was found. In the Ladoux experiment, the effect of the replicate measurements (rear tyres in Fig. 32) on the maximum Bolling probe inclusion pressure (\( p_{\text{r-max}} \)) yielded p-values ≤ 0.326–0.584 for the front and ≤ 0.326–1 for the rear tyres. In the Foulumgaard A experiment (Fig. 33), the effect of replicate measurements (\( N = 6–9 \)) on the vertical and horizontal stress (\( \sigma_x \) and \( \sigma_z \)) yielded p-values of 0.86 and 0.92, and 0.168–0.996, respectively.
5.2 Soil response to repeated wheeling

Several studies have shown that soil response in terms of penetration resistance and bulk density to repeated wheeling was well explained by a logarithmic function (Håkansson and Reeder (1994) and references therein) with the majority of the deformation happening during the first wheeling. In Foulumgaard A, however, repeated wheeling caused very little soil structural deformation within the first three passes of the passive trailer wheel (Paper 4, configurations 0+1 H1, 0+1 H2 and 0+1 H3). After the sixth wheeling (0+1 H6), penetration resistance (PR) at 0.19–0.24 m depth dry bulk density (ρb) was significantly increased compared with the Reference, while the fraction of effective air-filled porosity (εa-eff) was significantly reduced. No significant differences were found in the volume of small pores (ε<30µm), blocked air-filled pore space (εa-blocked), Darcian air permeability (kDarcy) or pore organisation (PO, specific air permeability) between the Reference and the configurations with wheeling (Paper 4). This indicates that the soil was seriously densified after six wheelings, yet not to the extent that functional pore space had diminished.
The soil structural deformation was for several characteristics well-described by a linear function of the number of wheelings; \( PR \) increased by 0.09 MPa, \( \rho_b \) by 0.02 Mg m\(^{-3}\) (\( R^2 = 0.56 \)) and \( \varepsilon_{a-eff} \) decreased by 0.01 m\(^3\) m\(^{-3}\) for each additional wheeling (\( R^2 = 0.80, 0.56 \) and 0.68, respectively; \( PR \) and \( \rho_b \) in Paper 4, \( \varepsilon_{a-eff} \) unpublished data). All soil structural characteristics were less well explained by the logarithm of the number of wheelings (data not shown, \( R^2 = 0.070–0.568 \)). The different responses, linear or logarithmic, may be related to the soil stiffness prior to the first wheeling. The different studies presented in Håkansson and Reeder (1994) were performed on disturbed soil. In a disturbed – tilled or dug – soil, the soil strength is low, which allows compression during the first pass(es). In an undisturbed soil, on the other hand, the soil is generally denser and stronger than in a disturbed soil. The initial strong densification that takes place in a disturbed soil might then not take place in an undisturbed soil; hence soil structural deformation might then follow a linear instead of a logarithmic fit.

Despite the linear relation, significant differences were found between \( 0+1 \) \( H_1 \) and \( 0+1 \) \( H_6 \) where no differences were found between the Reference and \( 0+1 \) \( H_6 \) (\( \varepsilon_{a-blocked}, k_a-Darcy \) and \( PO \), Paper 4). Although the differences may be related to stochastics of the field experiment, it may also be caused by vibration from shock effects from driving on an uneven surface (Soane...
et al., 1981b). The first wheeling may have actually disrupted the structure of the soil. Unexpected results like this were also found in the Ladoux experiment, although for a driven tyre, where air permeability \((k_a)\) at 0.3 m depth was significantly increased after one pass of the tractor with the largest tyre-soil contact area and most even vertical contact stress distribution of the tyres included in that experiment (\textbf{Paper 1, Section 3.2}).

As a consequence of the six repeated wheelings in \(o+1 H_6\), the degree of compactness (\(DC\), Håkansson, 1990) increased from 88.1 % for the Reference to 94.1 % (Table 9). For many crops, a \(DC\) in the range 84–87 % is considered the optimum for plant growth (Naderi-boldaji and Keller, 2016), and a higher \(DC\) is associated with poorer soil physical quality. This means that the \(o+1 H_6\) may have had a serious impact on crop productivity. Håkansson (2005) reported the optimal \(DC\) in the 0.5–0.25 m soil layer for crop yield for a range of crops on autumn-ploughed soils based on Swedish field trials and the estimated yield reduction for non-optimal \(DCs\). According to these data, yield reduction of a spring sown barley may be limited to < 5 % in 40 % of the cases for \(DC = 94\) %. For autumn sown rape, however, the yield reduction may be expected to be > 15 % in 90 % of the cases where \(DC = 94\) % (Håkansson, 2005).

Table 9: Measured bulk density (\(\rho_b\)) and estimated degree of compactness (\(DC\)) in response to repeated wheeling (Foulumgaard A).

<table>
<thead>
<tr>
<th>N wheeling</th>
<th>Reference</th>
<th>(o+1 H_1)</th>
<th>(o+1 H_2)</th>
<th>(o+1 H_3)</th>
<th>(o+1 H_6)</th>
</tr>
</thead>
<tbody>
<tr>
<td>(\rho_b), Mg m(^{-3})</td>
<td>1.47</td>
<td>1.41</td>
<td>1.45</td>
<td>1.43</td>
<td>1.57</td>
</tr>
<tr>
<td>(DC), %</td>
<td>88.1 ± 4.5</td>
<td>84.7 ± 3.9</td>
<td>86.9± 6.6</td>
<td>85.5 ± 3</td>
<td>94.1 ± 2.8</td>
</tr>
</tbody>
</table>
6 Uncertainties in soil compaction-studies

Despite decades of soil compaction research, results from field-compaction events may still be unexpected. This was also the case in the experiments presented in this dissertation. In the Ladoux experiment, a very limited effect of traffic on soil structure was observed and air permeability \( k_a \) even increased after a pass with the tractor tyres with the largest contact area, despite that the vertical stress \( \sigma_z \) exceeding the confined precompression stress \( \sigma_{pc} \) (Chapter 3, Paper 1). In the Foulumgaard A experiment, the soil structural characteristics after a pass with the tractor-trailer in the standard steering mode with a high drawbar pull \( DP, 9.1 \) kN) did not differ significantly from the Reference whereas the tractor alone in the offset steering mode with the same level of \( DP \) did (Chapter 4, Paper 4). In the Foulumgaard B experiment, however, soil structural properties did not differ significantly between the Reference and a pass with the driven tractor with a high \( DP \) (~41.6 kN) (Chapter 4). Moreover, a single pass of the passive trailer wheel seemed to disturb the soil structure without compressing it in the Foulumgaard A experiment (Chapter 5, Paper 4).

The expectations of compaction-events are based on the risk of compaction, which is estimated by a comparison of the stresses applied and soil strength. Next, the effects of compaction events are quantified by comparing the characteristics of the compacted soil with those of the soil prior to compaction. In this dissertation, the quantified effects were mainly soil structural characteristics, but soil mechanical characteristics or soil functions like crop growth and drainage can also be used. Unexpected results of compaction events may therefore have several causes, as there are uncertainties associated with measurements and calculations of both soil stress and soil characteristics, as well as due to the limited understanding of stress-strain relationships.

6.1 Deviation between measured and true stresses

Uncertainties in quantification of stresses arise from the difficulties in measuring the true stresses. The use of stress sensors means the soil is disturbed prior to the stress measurements during wheeling and this may affect propagation of stress into the soil. For a given soil texture, stress propagates deeper the less aggregated and the less dense the soil layers are (Horn et al., 2003). Installing sensors, however carefully done, may also disturb the soil immediately surrounding the sensors. Even a disturbed zone of 1–2 mm around a sensor may yield different stress measurements from undisturbed conditions. Generally, weaker zones lead to underestimations and stronger zones lead to overestimations (Kirby, 1999).

Moreover, stress sensors are of different material to the soil into which they are installed, and the difference in the stiffness of soil and stress sensors may lead to measured stresses that differ from the true stresses. This is complicated by the fact that the soil stiffness may change during traffic, but, generally, stress sensors that are softer than soil may underestimate
stresses, whereas stress sensors with greater stiffness may overestimate stresses. However, for
large differences in stiffness, the ratio of measured to true stress becomes constant and
therefore the effect of stiffness becomes negligible for high soil-sensor stiffness (< 0.5, is
recommended) (de Lima and Keller, 2021; Weiler and Kulhawy, 1982). Apart from the density
of the sensor, the measurement is influenced by the shape and size of the sensor used. For
example, stresses are generally overestimated for sensors with a large height:diameter ratio
and in instances were right-angled corners are located near the load cells within the sensors
(Kirby, 1999; Lamandé et al., 2015).

Soil disturbance during installation of the sensors is greater for some methods than for others.
The installation of the Bolling probes for measurements of mean normal stress ($\sigma_m$) in the soil
(Section 2.2.2) and the transducer housings for measurements of vertical and horizontal stress
($\sigma_z$ and $\sigma_x$) in the soil profile (Section 2.2.4) caused minimal soil disturbance: only where the
sensors were installed was the soil removed. Soil disturbance may also be accepted and be used
on purpose by creating a uniform driveway, like was done for the vertical contact stress
measurements with the load cells glued to a blanket (Section 2.2.3). In some cases, for example
for measurements of $\sigma_z$ in the contact area (Section 2.2.3), it is difficult to install stress sensors
near the surface in an undisturbed soil. In Foulumgaard A, the stress sensors were installed
with minimal disturbance for stress measurements at 0.4 m depth (Paper 3), but
measurements were actually made between 0.29 and 0.45 m depth; the hollow steel pipes that
were used to drill the hole for the sensors slightly changed direction in the process. If this
method is used for near-surface stresses, one risks installing the sensors too close to the soil
surface. The method decided upon for measurements of $\sigma_z$ in the contact area in Foulumgaard
B (fitting the transducer housings in a trench from the soil surface, Section 2.2.3) meant that
the lower half of the piston was in contact with minimally disturbed soil, whereas soil had to
be restored for contact with the upper part of the piston, as the transducer housings were of
cylindrical shape. If the sensor surfaces on which measurements were made had been flat, the
pistons could have been in full contact with undisturbed soil, but probably the transducer
housings would have had right-angled corners.

The stress measurements presented in Chapter 4 and 5 of this dissertation were corrected for
potential inaccuracies (Sections 2.2.3 and 2.2.4) between measured and true stresses based on
the deviation as measured by Lamandé et al. (2015). The correction factor used differed for the
two types of stress sensors employed, but was similar for measurements near the surface and
in the upper subsoil when the same type of sensor was used. Moreover, the same correction
factor was used for measurements of $\sigma_z$ and $\sigma_x$, i.e., a similar deviation of the measured from
the true stresses was assumed for both stress components. The corrected stresses may still be
different from the true stresses, but despite possible deviations, comparisons between wheels
are generally accepted. However, de Lima & Keller (2021) found, by finite element modelling,
that the deviation of measurements from true stress is also influenced by the depth at which measurements are made and the size of the loaded area, especially at shallow depths.

### 6.2 Capturing the stress state beneath a passing vehicle

The complex stress state beneath a passing tyre makes soil compaction studies even more complicated. Stresses have different directions and the magnitudes are dynamic. Several studies measured stresses under tyres in different directions simultaneously, using six-faced stress sensors (e.g. Bailey et al., 1996; Pytka, 2009, 2005; Pytka et al., 2006; Pytka and Konstankiewicz, 2002; Way et al., 1996). Although stress derivatives such as the octahedral and normal stress can be calculated from the measurements, the direction of the stresses on the six faces is unknown. Moreover, these sensors have to be buried in soil and obtaining a good contact between soil and sensor may still be difficult given the shape of the sensor. The deviation of the measured from true stresses may also differ between the different faces of the sensor, meaning that derived stresses may be inaccurate in magnitude and cannot be discussed relative to each other (Kirby, 1999). With Bolling probes, measurements of $\sigma_m$ are direct, rather than calculated. However, the directions of the three principal stresses that make up $\sigma_m$ are also unknown, and in the Ladoux experiment the position of the tyres relative to the peak measurement were also unknown. It may have been beneficial, and it may be in future studies, to use a laser-sensor on the soil surface for identification of the tyres’ axles relative to the peak stresses, as was done for measurements of $\sigma_z$ and $\sigma_x$ in the Foulumgaard A and B experiments.

Measurements of $\sigma_z$ generally show a single peak near the wheel’s axle (Sections 4.1 and 4.2.2), but the measurements of $\sigma_x$ showed a lopsided double-peak around the axles (Section 4.2.2). This was especially clear in Foulumgaard A (**Paper 3**), with a smaller peak in front of the axles and a higher peak behind the axles (**Paper 3**). The different magnitudes of the peaks were unexpected, but also observed by Ding et al. (under review). However, Ding et al. (under review) found opposite curves, that is, a higher peak in front of and a smaller peak behind the axle of a combine harvester. The two experiments took place on the same experimental site and on the same stress sensor installations, one week apart. It was thought that the opposite driving direction (**Fig. 34**) may have caused the differences. For the tractor in this dissertation, the low peak in front of the axles represented measurements of the piston being pushed into the soil in front of the transducer housing whereas the high peak behind the axles represented a more direct transmission of stresses onto the load cell embedded in the transducer housings. The opposite was thus the case in the experiment by Ding et al. (under review).
To test this hypothesis, the stress sensors for horizontal stress measurements were installed with the load cells facing opposite horizontal directions in Foulumgaard B (Sections 2.2.3 and 4.2.2). Although the double-peak was much more pronounced in Foulumgaard A than in Foulumgaard B, a smaller peak was observed in front of the axle and a larger behind the axle for both installations for measurements of horizontal stress and for both configurations (the towed and driven tractor). Hence, the driving direction in Foulumgaard A may not have affected the curvature of the stress measurements after all (Chapter 4).

In Foulumgaard B, a substantial soil deformation was observed on a few occasions when digging out the stress sensors after measurements of the driven tractor (Fig. 35). The deformation was especially pronounced for the last battery of transducer housings the driven tractor passed: 4–12 cm backwards in the driving direction. The deformation was limited, 0–2 cm, for the installation for vertical stress measurements (the battery in the middle), and none was observed for the installation that was first to be passed. Due to these deformations, part of the horizontal stresses could not have been transmitted to the load cells energy was lost into movement (of the stress sensors). In effect, these measurements will then have yielded an underestimation of the level of stress.

Figure 34: Illustration of the directions of travel in relation to the position of the load cells in Foulumgaard A (Paper 3, Chapter 4) and Ding et al. (under review).

Figure 35: Soil deformation observed after a single pass of the driven tractor in three blocks (Foulumgaard B). The deformation was considerable for the last installation passed (4–12 cm backwards in the driving direction) and small for the installation in the middle (0–2 cm backwards in the driving direction).
One hypothesis was that these observations reflected differences in soil strength. The driving direction in the experimental area was perpendicular to the driving direction of field operations, and while this reduced the risk of different soil strengths around sensors within one installation, the three different installations within a plot may then have been installed in soils with different strengths. Vane shear strength was therefore measured along three transects in the Reference plots in the driving direction, but no significant differences were found (data not shown). Provisional analysis of the maximum stresses for the different installations (Sections 2.2.4, 2.4 and 4.2.2) showed that the $\sigma_x$ stresses were significantly highest for the installation for which the deformation was observed (driven, $\sigma_x$-out), even though the $DP$ was not higher in the parts of the plots where these sensors were installed (Fig. 36).

![Figure 36](image.png)

**Figure 36:** Two individual measurements of drawbar pull ($DP$) for the driven tractor (Foulumgaard B). The vertical dashed lines indicate the outer edges of the areas where soil cores were sampled (the first ~1.5 m between the dashed lines) and where the stress measurements were made (the last ~2 m between the dashed lines).

### 6.3 Concepts of soil strength and compaction

According to the concept of precompression stress equals a soils strength against compression the maximum normal stress a soil has been exposed to in the past (Casagrande, 1936). As long as the stress imparted to the soil does not exceed its precompression stress, soil is expected to respond elastically; soil structural and mechanical characteristics after a compaction event are not substantially different from before the compaction event. For stresses higher than precompression stress, soil response is expected to be plastic, hence soil characteristics are expected to change considerably during the compaction event (Lebert and Horn, 1991). In the Ladoux experiment, estimations of the risk of compaction based on this comparison yielded a high risk, yet the assessed soil structural properties were not degraded (Paper 1, Chapter 3). Differences between expected deformation, based on the relation between stress and precompression stress, and measured deformation were also reported by, among others, Arvidsson and Keller (2004) and Schjønning and Lamandé (2018).
The use of precompression stress in soil compaction studies has then also been questioned (e.g. Keller et al., 2012; Peth et al., 2010; Schjønning et al., 2016a). Part of the discrepancies between the on the precompression stress based expected and observed deformation may be that the concept of precompression stress does not account for traction, shear stresses or the effect of multiple wheeling. Moreover, the precompression stress was defined in tests where the load strain-controlled velocity of 1 mm min⁻¹, which means that the load was applied much slower than during field traffic What is more, the concept of precompression stress assumes an exact level of normal stress as the boundary between elastic and plastic soil response, whereas it may actually be a more gradual process due to the complex architecture of a soil (Keller et al., 2004; Lamandé et al., 2017; Rücknagel et al., 2007). According to Hemmat et al. (2009), the precompression stress reflects a transition between elastic and plastic deformation. A gradual deformation of the soil structure was also observed with increasing number of wheeling (Paper 4, Chapter 5), which was especially pronounced for penetration resistance (PR) and bulk density, but not so clear (and after six wheelings not significantly different from the Reference) for the characteristics that inform about soil pore organisation.

Finally, in the studies presented in this dissertation, both soil mechanical and soil structural properties were measured in the laboratory on 100-cm³ soil cores of 3.84 cm height. Especially the assessment of soil mechanical properties might be influenced by the fact that the soil is taken out of its natural confined environment and instead is confined in a steel cylinder ring. Aggregates and bonds between aggregates may have been disrupted and instead, there are friction forces in play between soil and cylinder ring (de Lima and Keller, 2019). Although a number of replicate cores were sampled, it provides only a narrow insight into the soil response. Berisso et al. (2013) showed how the compaction effects differ across the wheel track for a passive tyre, due to differences in the stress state in the contact area across the tyre. In the studies included in this dissertation, analysis of soil structural properties was included to relate to soil stress measurements and calculations, which were (in Ladoux and Foulumgaard A) made under the centreline of the tyres. In Foulumgaard B, soil cores were also sampled under the centreline of tyres because a significant effect of traction on soil structural properties was observed under the centreline in Foulumgaard A. Besides differences in soil response across the tyre, the soil response may also be different at different depths. In Foulumgaard A, for example, PR showed significant differences from the Reference in the soil layer below the depth of sampling for both configurations with a high drawbar pull (DP) and for the configuration with six repeated wheel passes (Paper 4).

6.4 Evaluation of soil properties
Classifications and limits of parameters of soil response can provide perspective to the measurements. In this dissertation, for example, references are made to the evaluation of the rate of \( k_e \) by Fish and Koppi (1994), to the (lower) limit of \( k_a \) as suggested by Ball et al. (1988),
to thresholds for PR (Bengough et al., 2011; Dexter, 1987) and to the compaction index (CI) as introduced by Håkansson (1990). The evaluation of soil properties according to such limits should, however, not be done without consideration of differences in methodology and the state of the soil (e.g., top- subsoil, whether or not recently tilled).

For example, values of $k_a$ will be different for measurements at different pressure gradients. In the studies presented in this dissertation, two types of $k_a$ were measured as suggested by Schjønning and Koppelgaard (2017): Darcian air permeability ($k_{a-Darcy}$) and apparent air permeability ($k_{a-App}$). Values for $k_{a-Darcy}$ are generally larger than $k_{a-App}$ and the difference becomes larger at higher levels of $k_a$. The lower limit of $k_a$ of 1 µm² (Ball et al., 1988) indicates the minimum value for permeable soil with regard to transport of water and air. Depending on the soil function evaluated, the minimum desired $k_a$ may also take different values in different soil layers, for example depending on where the roots concentrate. For PR, a limit of 2 MPa was used to indicate severe impacts on root growth (Bengough et al., 2011; Dexter, 1987). However, the presence of continuous macropores provides pathways of least resistance for root growth (Colombi et al., 2017) and a certain PR may then not be a severe problem for root growth. Finally, different crops have different root systems with different penetration abilities (Place et al., 2008; Pulido-Moncada et al., 2020), which is generally disregarded when evaluating the state of soil and the impacts of compaction.
7 Conclusion

The overall objective of this dissertation was to deepen our understanding of key processes of soil structure deformation after traffic, with a particular focus on tyre-soil interactions as affected by tyre evolution, traction and repeated wheeling. It was shown that machinery using **tyres with a large contact area and low tyre inflation pressure, limited traction and limited number of wheeling contribute to limit the risk of soil compaction.** Three field compaction experiments were performed, which yielded the following highlights:

- Newer tyres (in design) had a better vertical contact stress distribution and lower mean normal soil stress even in the subsoil due to a larger contact area and reduced tyre inflation pressures (**Chapter 3, Papers 1 and 2**);
- The impact of the different tyres on soil structure was very minimally, with the only difference an increase in air permeability for the newest tyre (**Chapter 3, Paper 1**).

- Traction increased the tyre-soil contact area as the area became squarer (**Chapter 4, Paper 3**);
- The distribution of vertical contact stresses improved under the influence of traction, leading to lower mean ground pressure and lower vertical peak stresses for higher traction despite an increase in the dynamic wheel load (**Chapter 4, Paper 3**);
- Traction influences the magnitude of horizontal contact stress increases and changes the ratio between the loading time in front of and behind a tyre's axle (**Chapter 4**);
- No effect of traction was found on horizontal soil stress measured in the upper subsoil, but horizontal stress increased with wheel load for towed (trailer) tyres (**Chapter 4, Paper 3**).

- No significant effect of repeated wheeling of a towed tyre was found on the tyre soil contact characteristics (**Chapter 5, Paper 3**);
- No significant effect of repeated wheeling of driven tyres was found on mean normal and vertical soil stress (**Chapter 5**).

- Soil structural response in the topsoil to traction varied: whereas deformation increased significantly with traction in the first experiment (**Chapter 4, Paper 4**), no effect was found in the second experiment (**Chapter 4**);
- Soil structural response indicated a gradual deformation and a linear regression could be established with increasing number of wheeling passes (**Chapter 5, Paper 4**).
8 Perspectives

The results of this PhD project show that machinery with tyres with a large contact area and low inflation pressure, limited traction and, preferably, limited number of wheel passes limits the risk of soil structural deformation. These recommendations should be considered in addition to keeping wheel loads limited and timing field operations for when conditions are suitable. Higher wheel loads not only causes vertical stresses to propagate deeper into the soil, but also require higher tyre inflation pressures and, if higher for the towed wheels, require higher levels of traction [for the driven wheels]. Timing of field operations remains of major importance because of the change in soil strength at different water contents.

One technology that ought to be promoted is CTIS (Central Tyre Inflation System). Potentially, tyre inflation pressure may even be regulated on-the-go, taking into account the dynamic wheel load due to loading or unloading in the field, and thereby CTIS can reduce driving with over- or underinflated tyres.

There is a need for more measurements of tyre-soil interaction for tyres with different levels of traction, since traction greatly influenced tyre behaviour and contact characteristics in the studies presented. The relation between drawbar pull and contact area characteristics potentially allows more accurate predictions of tyre-soil interaction.

More measurements of horizontal stresses are needed to put the studies presented in this dissertation into perspective. It is recommended to collect measurements near the surface as well as in the soil profile for both tyres without and with traction to study the relation with other stress components as well as the propagation of the stresses into the soil.

Finally, a better understanding of the stress-strain relationship is needed to predict the risk of compaction more accurately. Soil strength and mechanical properties other than the precompression stress might bring a better understanding of the relationship. The relation between soil strength against compression and against shearing should be tested for different levels of vertical and horizontal stress, keeping in mind that traction reduced the risk of compaction from vertical stresses.
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Supporting papers

Paper 1

The contribution of tyre evolution to the reduction of soil compaction risks

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The contribution of tyre evolution to the reduction of soil compaction risks

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Mean normal stress measurements
Vertical soil stress

ABSTRACT

The use of today's heavy machinery in agriculture poses a great risk to soil in the form of compaction. Subsoil compaction has been found to persist for decades, thus reducing the risk is extremely important. The stress distribution in the contact area between the tyre and the soil is of primary importance for the propagation of stress in the soil. The characteristics of the tyre therefore affect soil stress. The objective of this study was to compare effects of five generations of tyres (introduced from before the 1970s to 2018) on soil stress and soil structure, including two standard narrow tyres and three larger low-aspect-ratio tyres. Wheel loads of 2900 and 4300Mg were chosen for the front and rear axles respectively, and the load-rated inflation pressure ranged from 240 to 60kPa. The contact stress distribution was estimated using the FRIDA model and was used as input for calculation of the vertical stress through the soil profile. Mean normal stress and physical properties were quantified in a field experiment on a clay soil in Clermont-Ferrand, France. The results show that for a given wheel load, the tyre-evolution reduced soil stress when the development included an increase in the tyre-soil contact area and an associated decrease in the tyre inflation pressure. FRIDA model calculations indicated a reduction in soil stress for newer tyres due to a more even contact stress distribution, and were confirmed by the mean normal stress measurements. Although the difference in soil stress between the various tyres decreased with depth, a significant reduction was measured even at 0.6m depth beneath the centreline of both front and rear tyres. We found only a very limited effect of the traffic on the dry bulk density and air permeability at 0.3m depth below the centre of the tyres.

1. Introduction

The heavy agricultural machinery used for many field operations in modern agriculture poses a considerable risk to the soil through the degradation of physical, chemical and biological soil functioning by compaction. Its consequences are discussed extensively in the literature (e.g. Alblas et al., 1994; Soane and van Ouwerkerk, 1995; Arvidsson and Håkansson, 2014; Edwards et al., 2016). Tillage can effectively loosen compaction in the topsoil but often had a limited lasting effect in the subsoil (Schneider et al., 2017). A loosened subsoil often becomes recompacted within a few years and the subsoil structure may then be even less favourable than before (Håkansson, 2005). Alleviation of subsoil compaction by natural processes is a slow process (Håkansson and Reeder, 1994), and subsoil compaction has been found to persist for decades (e.g. Berisso et al., 2012; Schjønning et al., 2013). This makes reduction of the risk of soil compaction extremely important. This risk is governed by the capacity of the soil to resist stress (i.e. soil strength) and by the stress induced, \( \sigma \). The maximum soil strength is often defined by its precompression stress, \( \sigma_{pc} \), which is the strength against compression and an expression of the maximum stress any soil has been exposed to in the past (Casagrande, 1936). As long as the stress induced does not exceed the precompression stress, soil is expected to remain elastic, and soil physical properties after the stress event should be similar to those before the event. Exceeding the precompression stress is expected to result in plastic deformation that changes soil physical properties considerably (Lebert and Horn, 1991).

Limiting the risk of soil compaction requires control of the stress level induced, but the development for many field operations has been...
towards heavier and more cost-effective machinery. Schjønning et al. (2012) suggested the ‘50-50 rule’ as a rough but practical guideline for minimising soil compaction. Based on earlier recommendations, the authors proposed that for stresses in the soil profile to remain tolerable “At water contents around field capacity, traffic on soil should not exert vertical stresses in excess of 50kPa at depths >50 cm”, where field capacity is taken at the commonly used matric potential of −100hPa. The use of wider tyres and lower inflation pressures at a given load creates a larger tyre-soil contact area, A, which allows a reduction of the maximum stress in the contact area, σpc (e.g. Lamandé and Schjønning, 2011). The use of larger machines with larger tyres and higher wheel loads has, however, increased the risk of exceeding the proposed threshold for sustainable traffic and thus the risk of soil compaction (Schjønning et al., 2015a).

An example of the relation between increased wheel load, increased tyre size, and the effect on vertical stress, σz (calculated using the Terramino® model) was given by Schjønning et al. (2015a): from 1958 to 2009, the load of a loaded self-propelled combine harvester increased from 4.3 Mg to 24.9 Mg. While tyre volume increased from 0.169 m³ to 1.617 m³, the maximum contact stress increased from about 175 kPa to 220 kPa and the mean ground pressure from around 75 kPa to 110 kPa. Vertical stress at the depth of 0.5 m, σz-0.5 increased from approximately 40kPa in 1958 to nearly 125kPa in 2009 – exceeding the recommendations of Schjønning et al. (2012) by a large margin.

The increase in tyre size in the example of Schjønning et al. (2015a) could thus not offset the increase in load. Deeper in the soil profile, the stress relates primarily to wheel load (Lamandé et al., 2007; Lamandé and Schjønning, 2011). Nevertheless, the level of stress in the topsoil is critical for the stresses reaching the subsoil, and the level of stress in the subsoil therefore a function of tyre-soil contact stress. Optimisation of the contact stress distribution is thus crucial for reducing the risks of both topsoil and subsoil compaction.

Newer technologies and designs by tyre manufacturers may help optimise the stress distribution in the contact area between the tyre and the soil. Initially, the improvements to tractor tyres focussed on increasing their functionality. For example, Kising and Göhlich (1989) refer to tyre developments aimed to reduce vibrational behaviour resulting from increase of the speed on roads. The introduction of the radial tractor tyre as an alternative to the diagonal tractor tyres in the 1970s was the first step in increasing tyre flexibility. Diagonal tyres are constructed with ply cords arranged at an angle, creating a diagonally layered pattern where the tyre sidewall and tyre tread act as one. In radial tyres, the ply cords radiate from the one end of the tyre sidewall to the other end, and the tyre sidewall and tyre tread move independently compared to the diagonal tyre. Nowadays, many tyres are constructed with advancing flexion technologies that allow them to carry high loads at rather low inflation pressures (Schjønning et al., 2012). The objective of this study was to quantify the effects of the evolution in agricultural tyres on the stress distribution in soil and on soil physical properties. It was hypothesised that newer tyres with more advanced flexion technology allowing lower inflation pressures at similar loads, reduce soil stress in the upper part of the soil and consequently have less negative impacts on soil structure.

### 2. Materials and methods

#### 2.1. Experimental site

The experimental site forms part of the Ladoux Michelin Technology Centre (45°51’28.3″N 3°07’24.4″E) and is situated in the Limagne rift valley, which is an elongated tectonic depression in the Hercynian crystalline Massif Central, France. The soil at the experimental site is classified as a Chernozem according to the WRB (FAO, 1998) system, and developed on calcareous Oligocene fluvo-lacustrine sediments. The soil in the experimental field was well drained. The characteristics of the soil are presented in Table 1.

At the experimental site, a wheeling experiment with a tractor was conducted with five different generations of tyres (i.e. 10 tyres). The fieldwork was done in March 2018 at a soil water content slightly drier than field capacity (−100 hPa). The arable field had not been ploughed since 2012, but only been tilled to 0.10-0.15 m depth using a disc harrow. Since the harvest of wheat in 2017 (produced for the last five years), the field had been left undisturbed. Initial bulk density, ρb, and volumetric soil water content, θ, precompression stress, σpc, Young’s modulus, E, and Poisson’s ratio, ν, were measured on 100-cm² soil cores from undisturbed soil (for more details on the measurements of pre-compression stress, Young’s modulus, and Poisson’s ratio, see section 2.6). The remaining properties mentioned in Table 1 were analysed on bulk samples from the undisturbed soil. These samples were first air-dried, then crushed and sieved to 2 mm. The particle density was determined by displacement of water in a pycnometer. The size distribution of primary particle classes was determined using the hydrometer method for clay (<2 μm) and silt (2-50 μm) content, and the sieve method for mineral particles (>63 μm) (Gee and Or, 2002). The hydrometer method was applied after soil organic matter was removed from the samples with H2O2 (Jensen et al., 2017) and after CaCO3 was removed from the samples with hydrochloric acid to prevent disturbances of particle dispersion.

#### 2.2. Experimental design

The experiment was designed around five generations of tyres (Table 2), and replicated in four blocks. Each block was divided into seven lanes (Fig. 1). In each middle lane, fluid inclusion probes (Berli et al., 2006; Bolling, 1987) were installed to simultaneously measure mean normal stress, σmn at three depths (0.2, 0.4, and 0.6 m) at the centreline and at 0.3 m lateral distance from the centreline of the wheel rut. We made three measurements for each tyre (i.e. one tyre type but both front and rear tyres) in each block (i.e. 4 blocks * 5 sets * 7 lanes = 140 measurements per block).
3 measurements = 60 in total), with the 15 passes within a block in a complete randomised order. The six remaining lanes within each block were used for soil sampling (Fig. 1). These lanes were randomly assigned to a single pass of a tractor with the tyres as specified in Table 2 or as a lane without experimental traffic as the control. The driving speed aimed for in all lanes was 0.83 m s⁻¹.

The five sets of tyres included in the field experiment represent four stages in the agricultural tyre evolution from the diagonal technology to the most recent product of flexion technology (Table 2). In the experiment, the diagonal tyres were represented by the tyre Bias. The first stage of the tyre evolution included in this study was the introduction of the radial technology in the 1970s, here represented by the tyre AgriBib (designed in the late 1990s). The radial technology resulted in the tyre footprint having a constant width and a more homogeneous distribution of stresses in the tyre-soil contact area, a further reduction of the tyre inflation pressure at a given load (Vervaet, personal communication, 2018). The front tyre of CerexBib has slightly different dimensions from the other two low aspect ratio tyres because not all dimensions are available for this tyre. The tyre chosen had dimensions as close to those of the other two low-aspect-ratio front tyres as possible. EvoBib is a product of the most recent technology, commercially launched in 2018. The tyre has a “2-in-1 technology” that allows a complete change of tyre shape between road and field by the activation of a pressure change (i.e. the tyre is built for use with a central tyre inflation system): by lowering the inflation pressure, the shoulders of the tyre participate into the tyre-soil contact area. This increases both the length and the width of the tyre-soil contact area in comparison with tyres of similar dimensions (e.g. EvoBib), and thereby allows a further reduction of the tyre inflation pressure at a given load (Vervaet, personal communication, 2018). For example, it facilitated a reduction in the recommended inflation pressure at 10 km h⁻¹ of 40% for the front wheel in comparison with AxioBib.

In this paper, we measured the mean normal stresses of these five generations sets of tyres at wheel loads of 2.9 Mg and 4.3 Mg for the front and rear tyres respectively. These wheel loads are considered moderate in comparison to loads on modern agricultural machinery, which can be up to 6 Mg for articulated tractors and even 15 Mg for self-propelled harvesters (Schijfennings et al., 2015a; Verein Deutscher Ingenieure, 2014). Regarding the smaller tyres, Bias and AgriBib, the loads tested are higher than what the tyres originally were designed for. Both sets of tyres are however still widely used today, and wheel loads might also exceed those they were designed for. The inflation pressures (ranging from 240 to 60 kPa, Table 2) were load-recommended at a

### Table 2

<table>
<thead>
<tr>
<th>Tyre</th>
<th>Type</th>
<th>Flexion</th>
<th>Specification</th>
<th>(W_{\text{tyre}})</th>
<th>(\Theta_{\text{tyre}})</th>
<th>(F_{\text{wheel}})</th>
<th>(P_{\text{tyre}})</th>
<th>(V_{\text{tyre}})</th>
<th>(P_{\text{tyre-rec}})</th>
</tr>
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<tbody>
<tr>
<td><strong>Front</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bias</td>
<td>D</td>
<td>–</td>
<td>16.9:28</td>
<td>429</td>
<td>1435</td>
<td>2.9</td>
<td>240</td>
<td>0.36</td>
<td>150</td>
</tr>
<tr>
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<td>R</td>
<td>–</td>
<td>16.9 R28</td>
<td>450</td>
<td>1427</td>
<td>2.9</td>
<td>240</td>
<td>0.39</td>
<td>150</td>
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<td>R</td>
<td>IF</td>
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<td>2.9</td>
<td>80</td>
<td>0.64</td>
<td>100</td>
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<td>IF, CFO</td>
<td>620/70 R30</td>
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<td>0.65</td>
<td>120</td>
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<td>VF</td>
<td>600/70 R30</td>
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<td>1607</td>
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<td>0.82</td>
<td>60</td>
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<td></td>
<td></td>
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<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bias</td>
<td>D</td>
<td>–</td>
<td>20.8:38</td>
<td>528</td>
<td>1840</td>
<td>4.3</td>
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<td>0.71</td>
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<td>–</td>
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<tr>
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<td>IF</td>
<td>710/70 R42</td>
<td>742</td>
<td>2062</td>
<td>4.3</td>
<td>80</td>
<td>1.29</td>
<td>60</td>
</tr>
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<td>CerexBib&lt;br/b</td>
<td>R</td>
<td>IF, CFO</td>
<td>710/70 R42</td>
<td>715</td>
<td>2078</td>
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</tr>
<tr>
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<td>VF</td>
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<td>2082</td>
<td>4.3</td>
<td>60</td>
<td>1.33</td>
<td>60</td>
</tr>
</tbody>
</table>

\(a\) Alliance tyre; \(b\) Michelin tyre; D, diagonal tyre; R, radial tyre; IF, increased flexion; CFO, Cyclical Field Operation; VF, Very High Flexion; \(W_{\text{tyre}}\), wheel load; \(P_{\text{tyre}}\), tyre inflation pressure; \(V_{\text{tyre}}\), tyre volume (FRIDA-calculated); \(P_{\text{tyre-rec}}\), tyre inflation pressure as recommended by the manufacturer for the wheel load and speed of 10 km h⁻¹.

In this paper, we measured the mean normal stresses of these five generations sets of tyres at wheel loads of 2.9 Mg and 4.3 Mg for the front and rear tyres respectively. These wheel loads are considered moderate in comparison to loads on modern agricultural machinery, which can be up to 6 Mg for articulated tractors and even 15 Mg for self-propelled harvesters (Schijfennings et al., 2015a; Verein Deutscher Ingenieure, 2014). Regarding the smaller tyres, Bias and AgriBib, the loads tested are higher than what the tyres originally were designed for. Both sets of tyres are however still widely used today, and wheel loads might also exceed those they were designed for. The inflation pressures (ranging from 240 to 60 kPa, Table 2) were load-recommended at a

![Fig. 1. Example of the design of a single block where the middle lane was used for measurements of mean normal stress beneath the centreline and at 0.3 m lateral distance (Y) from the centreline of the rear wheel rut, at three depths as indicated by the black, grey, and white circles. The six remaining lanes were used for soil sampling (indicated by X) of soil without experimental traffic and after a single pass of each tyre (randomised). Figure not to scale.](image-url)
maximum speed of 65 km h⁻¹ for road usage, representing the situations when the inflation pressure is not adjusted from road to field. However, there are no recommendations for CerexBib at this (low) load, and EvoBib requires adjustment of its inflation pressure between road and field configuration to make use of its 2-in-1 technology. Tyre volume, \( V_{pys} \), was calculated based on tyre dimensions according to Schjønning et al. (2015b).

2.3. Calculations of vertical contact stress distribution and vertical soil stress propagation

The distributions of vertical stress, \( \sigma_z \), in the tyre-soil contact area were estimated from the loading characteristics as described by Schjønning et al. (2015b, Eq. 18). We used the tyre dimensions, static loaded radius, inflation pressure characteristics (actual and load-recommended inflation pressure for traffic at 10 km h⁻¹) and wheel load to estimate the parameters of the FRIDA model (Schjønning et al., 2008) for the tyre-soil contact area, \( A \), and contact stress distribution. The FRIDA model describes the shape of the tyre-soil contact area with a super ellipse, which includes three parameters, \( a, b, \) and \( n \), where \( a \) and \( b \) are the half-length of the minor and major axes, respectively, and \( n \) is the squareness of the super ellipse. The FRIDA model combines a power law and a decay function to represent the stress distribution in the driving direction and across the tyre. These two functions are assigned the shape parameters \( a \) and \( b \), respectively. Please consult Keller (2005) and Schjønning et al. (2008) for more details about the FRIDA model.

In addition to the 10 tyres used in the field experiment, we made the estimations for theoretical tyres as well, named Evo+. For Evo+, the stress distribution across the tyre was optimised to minimise stress level on the soil profile: the shape parameter \( b \) was set to 2 (as calculated to be optimal by Schjønning et al., 2008). For each tyre, the stress distribution in the tyre-soil contact area as estimated from the loading characteristics using FRIDA was then used as input to the analytical Söhne (1953) model for calculations of vertical stress in the soil profile. The Söhne summation procedure is based on the Boussinesq (1885) solution for the problem of the load transfer from a concentrated force to an isotropic half space medium, with a concentration factor of 5 to account for the elastoplastic behaviour of the soil for the experimental conditions (Söhne, 1953).

2.4. In-situ measurements of mean normal stress

Bolling probes (Berli et al., 2006; Bolling, 1987) were used to measure mean normal stresses, \( \sigma_{m} \), for front and rear axles at three depths (0.2, 0.4, and 0.6 m) and at two positions (beneath the centreline and at 0.3 m lateral distance from the centreline of the wheel rut). The position at 0.3 m lateral distance from the centreline of the wheel rut was near the edge of the tyre shoulders for CerexBib, AxioBib and EvoBib (front and rear). For the smaller tyres Bias and AgriBib, the lateral distance between these Bolling probes and the tyre shoulders was approximately 0.075 m and 0.04 m for the front and rear wheels, respectively. The Bolling probes were inserted at different angles through a carefully drilled hole to obtain the measurements at different depths. The probes were filled with water, connected with a data bus, and subjected to a pressure of circa 100 kPa to assure good soil contact. Please consult Keller et al. (2016) for more details. The measurements were recorded every 0.004 s. The mean normal stress was then derived from the maximum measured inclusion pressure, \( P_{l\text{-max}} \), and a proportionality coefficient, \( k_\phi \), (Eq. 2) — a method adapted from Berli et al. (2006) and Naderi-Boldaji et al. (2018). The coefficient \( k_\phi \) is an empirical factor introduced by Bolling (1987) and is mainly a function of Poisson’s ratio, \( v \). Poisson’s ratio was calculated for soil cores sampled from 0.1, 0.3, and 0.6 m depth (Table 1) from compression tests (see section 2.6), and used to obtain the mean normal stress from the maximum measured inclusion pressure at 0.2, 0.4, and 0.6 m.

\[
\sigma_{m} = P_{l\text{-max}} k_\phi \approx P_{l\text{-max}} \frac{1 + v}{3(1 - v)}.
\]

2.5. Soil core sampling

Minimally disturbed soil cores (100 cm³, 34.82 mm high, 60 mm inner diameter) were sampled for measurements of the soil’s mechanical properties (precompression stress, \( \sigma_{pc} \), Young’s modulus, \( E \), and Poisson’s ratio, \( v \)) and soil structural properties (air permeability, \( k_a \), bulk density, \( \rho_b \), volumetric soil water content, \( \Theta \), and porosity, \( c \)). For the soil mechanical properties, a total of 80 cores samples were sampled from a small area in the four lanes without experimental traffic at 0.1 m (n = 9 * 1 lane * 4 blocks), 0.3 m (n = 9 * 1 lane * 4 blocks) and 0.6 m depth (n = 2 * 1 lane * 4 blocks) from below the soil surface. The samples for soil structural properties were taken from 0.3 m depth from below the soil surface below the centreline of one wheel rut of each set of tyres (in a transect along the driving direction) and from the lane without experimental traffic for the control (n = 3 * 6 lanes * 4 blocks). During the experiment, the samples were stored near the experimental site. The samples were tightly for transportation, then stored in a 2 °C climate room until further usage.

2.6. Measurements of soil mechanical properties

Uniaxial confined and unconfined compression tests (UCCT and UUCT, respectively) were performed on field-moist samples to derive the soil (confined) precompression stress (UCCT), Poisson’s ratio (UCCT and UUCT), and Young’s Modulus (UUCT). The compression tests were done using the 5969 Dual Column Tabletop Testing System (INSTRON®, Norwood, Massachusetts, United States of America) with a strain-controlled piston velocity of 1 mm min⁻¹, in principle as described by Koolen (1974). In the UCCT, the samples in their steel cylinders were loaded to 1000 kPa, then unloaded for 15 min, and reloaded to 1200 kPa. The stress-strain relationships of the UCCT were used to derive the soil precompression stress and Poisson’s ratio (Table 1). The precompression stress was determined based on the method developed by Lamandé et al. (2017). The load was converted to stress and log10-transformed, and the displacement was converted to strain. The dataset was limited to the first loading, and made monotone for load over time (i.e. load does not decrease over time) and for strain over load (i.e. strain does not reduce with increasing load). A polynomial (Eq. 2, where \( b \) is in kPa) was fitted to each subset of 23 pairs of stress-strain values of the UCCT-data. The maximum positive B-coefficient indicates the maximum increase in strain and the corresponding stress-level precompression stress of each individual sample.

\[
\text{strain} = A\log_{10} b = B (\log_{10}\sigma)^2
\]

Poisson’s ratio (Eq. 3) was determined based on the work of Eggers et al. (2006), combining the slope of the reloading part of the UCCT and Young’s modulus (Eq. 4). Again, the load was converted to stress and log10-transformed, and the displacement converted to strain. The dataset was now limited to the reloading range from 40 kPa (to exclude initial friction) to 1000 kPa (the maximum load of the first loading).

\[
v = \frac{1}{2} \left[ 1 + \frac{1}{3} \left( 1 - \frac{d E}{d \varepsilon} \right) \left( 1 - \frac{d E}{d \varepsilon} \right)^{0.5} \right] - 1
\]

Young’s Modulus (Table 1) was derived from the stress-strain relationship of the UCCT. In these tests, the soil sample was removed from the cylinder core by placing it on a piston with a radius slightly smaller than that of the cylinder (59.0 mm versus 60.3 mm) and by pushing the cylinder carefully downwards. The unconﬁned sample was then placed on a plate beneath the piston. A piece of greaseproof paper was placed on top of the sample to prevent it sticking to the piston.
The FRIDA parameters of tyre-soil contact stress and the level of vertical stress at 0.5 m depth for each of the 10 tyres used in the field experiment, and the theoretical, optimised tyre Evo+ (similar to EvoBib, except for the shape parameter $\beta$).

<table>
<thead>
<tr>
<th>Tyre</th>
<th>$A$</th>
<th>$\text{MGP}$</th>
<th>$\sigma_{\text{max}}$</th>
<th>$\alpha$</th>
<th>$\beta$</th>
<th>$\sigma_{\alpha,0.5}$</th>
<th>ratio $\sigma_{\alpha,0.4}/\sigma_{\alpha,0.4}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Front</td>
<td>0.22</td>
<td>129</td>
<td>335</td>
<td>1.69</td>
<td>0.44</td>
<td>72</td>
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</tr>
<tr>
<td>Evo+</td>
<td>0.47</td>
<td>61</td>
<td>104</td>
<td>2.14</td>
<td>2.00</td>
<td>49</td>
<td>-</td>
</tr>
<tr>
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<td>66</td>
<td>107</td>
<td>2.68</td>
<td>2.00</td>
<td>62</td>
<td>-</td>
</tr>
</tbody>
</table>

$A$, tyre-soil contact area; $\text{MGP}$, mean ground pressure; $\sigma_{\text{max}}$, maximum stress in the tyre-soil contact area; $\alpha$, shape parameter describing the distribution of vertical stress in the tyre-soil contact area along the centreline of the tyre in the driving direction; $\beta$, shape parameter describing the distribution of vertical stress in the tyre-soil contact area along the centreline of the axle across the driving direction; $\sigma_{\alpha,0.5}$, vertical stress at 0.5 m depth beneath the centreline of the tyre; ratio $\sigma_{\alpha,0.4}/\sigma_{\alpha,0.4}$, ratio of measured mean normal stress to calculated vertical stress at 0.4 m depth beneath the centreline of the tyre.

### 2.7. Measurements of soil structural properties

For measurements of air permeability, the $100$-cm$^3$ minimally disturbed soil cores were equilibrated to $100$ kPa matric potential using sand tables, by slowly wetting the soil cores to saturation to remove entrapped air and then draining them to the selected matric potential. The methodology for measurements of air permeability is based on the Forchheimer approach as introduced and described by Schjønning and Koppelgaard (2017). In short, the volumetric air flow rate through the soil in the steel cylinder is recorded at four pressure differences: 5, 2, 1, and 0.5 kPa. These measurements yield both apparent air permeability, $k_{\text{App}}$, and Darcy air permeability, $k_{\text{D}}$. Apparent air permeability accounts for laminar flow conditions and equals the volumetric air flow rate at a pressure head of 5 kPa, while Darcy air permeability accounts for the nonlinear relation between flow and pressure gradient as suggested by Forchheimer (1901). The ratio of apparent air permeability to Darcy air permeability, $k_{\text{App}}/k_{\text{D}}$, provides an indication of the tortuosity of the soil pores (the pores connected to the surfaces). A low ratio indicates less tortuosity, i.e., less turbulent air flow through the soil sample (Schjønning et al., 2013). The soil cores were weighed before the measurements, and the soil around the inner edge of the steel cylinder was gently pressed with the rounded back of a knife to minimise excessive air leakage. After the measurements, the soil cores were dried in the oven at 105°C for 48 h and weighed again for calculations of dry bulk density, $\rho_b$, volumetric soil water content, $\Theta$, and porosity. Air-filled porosity, $\varepsilon_a$, was calculated as the difference between the volume of the soil core, the volume of the solids (calculated from dry bulk density and particle density) and the volumetric soil water content over the core volume.

### 2.8. Statistics

The mean normal stress measurements for all combinations of tyre position (front and rear axle) and probe position (beneath the centreline and at 0.3 m lateral distance from the wheel rut), except beneath the centre of the rear axle, were not normally distributed and not homoscedastic. Therefore, all mean normal stress measurements were log-transformed prior to the statistical analysis. Differences in mean normal stress at a given probe position between tyres at the same tyre position were tested using a non-parametric Kruskal-Wallis test (degree of freedom of 4). The post-hoc analysis was then performed using the Conover-Iman test of the conover.test R package (R Core Team, 2017), version 1.1.5, with the Holm-Sidak adjustment method, where the null-hypothesis (mean normal stress is similar) was rejected when the p-value was equal to or smaller than $\lambda/2$, where $\lambda = 0.05$. The non-parametric Kruskal-Wallis test was also used to test differences in the ratio of measured mean normal stress to calculated vertical stress at a given probe position (degree of freedom of 4).

Both apparent air permeability and Darcy air permeability measurements followed a Gamma distribution. For each, one outlier was removed from the dataset, AxioBib block 3, with a value of 214% of the median for apparent air permeability and 6489% of the median for Darcy air permeability. Differences in apparent air permeability, Darcy air permeability and the ratio of apparent air permeability to Darcy air permeability were then tested using a mixed model with tyre as the main effect and the interaction of tyre and block as a random effect. The GroupClusterEffects function of the pairwiseComparisons R package, version 1.1.4.7 was used (R Core Team, 2017).

### 3. Results

#### 3.1. Calculated vertical contact stress distribution and vertical soil stress propagation

The FRIDA-calculated parameters (tyre-soil contact area, A, mean ground pressure, MGP, maximum contact stress, $\sigma_{\text{max}}$, shape parameters for the stress distribution at the tyre-soil interface in and across the driving direction, $\alpha$ and $\beta$) differed only to a small extent between Bias and AgriBib for both tyre positions (front and rear) (Table 3). The vertical stress at 0.5 m depth, $\sigma_{\alpha,0.5}$, was therefore nearly similar for these tyres at the two tyre positions. There was an increase in the tyre-soil contact area and a decrease of the mean ground pressure and maximum contact stress for AxioBib, CerexBib, and EvoBib in comparison with Bias and AgriBib, for both tyre positions. The shape parameters $\alpha$ and $\beta$ also increased, and consequently the vertical stress at 0.5 m depth decreased in comparison with Bias and AgriBib.

For the larger tyres, there were strong similarities between AxioBib and EvoBib at the front position. These two tyres had a larger tyre-soil contact area, a lower mean ground pressure and maximum contact stress, and higher shape parameters $\alpha$ and $\beta$ than CerexBib. Consequently, the vertical stress at 0.5 m depth beneath the front position was lower for AxioBib and EvaBib than for CerexBib. At the rear position, the FRIDA-calculated parameters were nearly similar for AxioBib and CerexBib, but they differed from EvoBib which had a larger tyre-soil contact area, lower mean ground pressure and maximum contact stress, and the shape parameters $\alpha$ and $\beta$ higher. Consequently, the vertical stress at 0.5 m depth beneath the rear position was lower for EvoBib than for AxioBib and CerexBib. For Evo+, the only difference from EvoBib at both tyre positions was a higher shape parameter $\beta$ for Evo+. The vertical stress at 0.5 m depth was nearly similar for the two tyres at the rear and front axle. Fig. 2 presents the vertical stress distribution in the tyre-soil interface (in 3D) and the vertical stress in the soil (in 2D) of the rear tyres. Contact stresses for Bias and AgriBib were characterised by a high maximum contact stress beneath the centre of the wheel track. Contact stresses were more evenly distributed for AxioBib, CerexBib and EvoBib, but only EvoBib and Evo+ were...
Fig. 2. FRIDA calculations of the vertical stress distribution in the contact area (3D) and calculated vertical soil stress (2D) for the tyres at the rear position as used in the field experiment and the theoretical tyre Evo+ (in which shape parameter $\beta = 2$).
characterised by a dual peak stress distribution, meaning that the vertical stress beneath the shoulders of the tyre was higher in comparison with the vertical stress at the centre of the tyre. For the front axle, such distribution was calculated for AxioBib, EvoBib, and Evo+ (data not shown).

3.2. Measured mean normal stress

The measured mean normal stresses, \( \sigma_{mn} \), were similar for the standard small tyres Bias and AgriBib for both tyre positions and probe positions at the three depths (0.2, 0.4, and 0.6 m, Fig. 3). For AxioBib and CerexBib, mean normal stress values were similar beneath the centreline of the wheel rut for both tyre positions at all depths, but they were lower than for Bias and AgriBib at 0.2 and 0.4 m depth (both tyre positions) and lower for AgriBib at 0.6 m depth for the rear tyre position. For EvoBib, the mean normal stress beneath the centreline of the wheel rut was lower than for Bias and AgriBib at all depths at both tyre positions. Moreover, the mean normal stress beneath the centreline of the wheel rut was lower for the EvoBib than for the CerexBib front tyres, but only at 0.2 m depth. For the rear tyres, a significant reduction in mean normal stress was also measured beneath the centreline of the wheel rut for EvoBib compared with both AxioBib and CerexBib at 0.2 m depth. At 0.4 m depth, the difference was not significant between EvoBib and AxioBib, but there was a trend towards it (p-value 0.0329 > \( \lambda/2 \)). There were no significant differences between the ratio of measured mean normal stress to calculated vertical stress, \( \sigma_m/\sigma_z \), beneath the centreline of the tyres (Table 2, p-value = 0.8665 for the front axle, and p-value = 0.6708 for the rear axle).

For the mean normal stress measured at 0.3 m lateral distance from the centreline of the wheel rut (i.e. near the edge of the shoulders for AxioBib, CerexBib, and EvoBib), but at 0.075 m and 0.04 m lateral distance from the edge of the shoulders for Bias and AgriBib for the front and rear, respectively), significant differences were only found at 0.2 m depth. Here, beneath the front tyres, mean normal stress was lowest for AgriBib, although not significantly different from Bias, and highest for EvoBib, although not significantly different from AxioBib and CerexBib. Beneath the rear tyres, mean normal stress at 0.3 m lateral distance from the wheel rut was lowest for Bias and AgriBib (extra lateral distance +0.04 m) and highest for CerexBib.

3.3. Soil structural properties

Table 4 presents the soil structural characteristics at 0.3 m depth from soil without experimental traffic and from soil after a single pass of each set of tyres. Values for bulk density, \( \rho_b \), apparent air permeability, \( k_a \), and Darcy air permeability, \( k_a-D \), were low even for the control soil. Bulk density and air-filled porosity, \( \varepsilon_a \), were not significantly affected by the single passes. Darcy air permeability was significantly higher for EvoBib than for the Control (p-value 0.044). The

<table>
<thead>
<tr>
<th>Lanes</th>
<th>( \rho_b ) (g cm(^{-3}))</th>
<th>( \varepsilon_a ) (m(^3) m(^{-3}))</th>
<th>( k_a ) (( \mu )m(^2))</th>
<th>( k_a-D ) (( \mu )m(^2))</th>
<th>( k_a )/( k_a-D ) Ratio</th>
</tr>
</thead>
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<tr>
<td>Bias</td>
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<td>0.15</td>
<td>0.95</td>
<td>1.16</td>
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<td>1.95</td>
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</tr>
<tr>
<td>Control</td>
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<td>0.15</td>
<td>0.64</td>
<td>0.79</td>
<td>0.86</td>
</tr>
</tbody>
</table>

\( \rho_b \), dry bulk density; \( \varepsilon_a \) mass-balance total air-filled porosity; \( k_a \), Apparent air permeability at 5 hPa; \( k_a-D \), Darcy air permeability. Different letters behind the value indicate significant differences between the treatments.

[Fig. 3. Measured mean normal stress, \( \sigma_m \), beneath both tyre positions, the front axle (A, B) and rear axle (C, D) at the two Bolling probe positions, beneath the centreline of the wheel rut (A, C) and at 0.3 m from the centreline of the wheel rut (B, D). Each point is the median of 12 values. NB: in B and D the measurements were made near the edge of the shoulders for AxioBib, CerexBib and EvoBib, but at 0.075 and 0.04 m lateral distance from the edge of the shoulders for Bias and AgriBib (front and rear, respectively).]
difference was not significant for apparent air permeability but the trend was similar (p-value 0.080). The ratio of air permeability, \( k_{app}/k_D \), was significantly lower for EvoBib than for the Control (p-value 0.036).

4. Discussion

4.1. The relation between calculated vertical soil stress and measured mean normal stress

Calculated vertical stresses, \( \sigma_z \), beneath the centreline of the tyres were higher than measured normal stresses, \( \sigma_n \), for all tyres and depths – as expected since the mean normal stress is the mean of the major, intermediate, and minor principal stress while vertical stresses is the major principal stress only. Since we do not know the direction or magnitude for each of the three principal stresses separately, we cannot compare the stress levels directly, but we can analyse the ratio of the measured mean normal stress to the calculated vertical stress, \( \sigma_z/\sigma_n \), at a given depth. The ratio was not significantly different between tyres at a given depth beneath the centreline, which indicates that the vertical stress reflects the mean normal stress the same way for all tyres.

4.2. Reduction of soil stress due to tyre evolution

The expected reductions of soil stress for newer tyres due to a better contact stress distribution, as indicated by the FRIDA calculations, were to a large extent confirmed by the measured mean normal stresses. The most substantial reductions of stress were realised in the upper part of the soil. Here, the stresses are controlled by the magnitude and distribution of stress at the tyre-soil interface (Schjønning et al., 2008).

The contact stress distribution was worst for Bias and AgriBib, and best for EvoBib which was the only actual rear tyre with a dual-peak stress distribution, which is an indication of good tyre deflection (Schjønning et al., 2012) and has been shown to minimise the stress impact in the soil profile (Schjønning et al., 2008). Even though the effect of newer tyres on reducing soil stress diminished with depth, the results still showed considerable reduction of soil stress for newer tyres deeper in the soil profile. These results suggest that the statement that for the subsoil (in this statement: 200–600 mm) any attempt to select tyres for the purpose of minimising compaction would be unsuccessful and only axle weight can limit soil compaction (Botta et al., 2002) should be more nuanced. Instead, at a specific load, an improvement of the tyre-soil contact stress distribution can help reduce soil stress in the upper part of the soil beneath the tyre, which in turn influences the stress level deeper in the soil (Schjønning et al., 2008). This can be very important for the zone just below the regularly tilled layer, where a plough pan often forms. The effect of a plough pan on soil stress propagation may only be very limited, unless the difference in soil stiffness is very high (Keller et al., 2014). The reduction of soil stress can thus also be very relevant for soils with a plough pan.

It is important to remember that due to the different widths of the tyres, the measurements of mean normal stress at 0.3 m lateral distance from the centreline of the tyre were made near the edge of shoulders of the six larger tyres, while the measurements for Bias and AgriBib were made at approximately 0.075 and 0.04 m from the edge of the shoulders of the front and rear tyres, respectively. This could explain the lower stresses for the smaller tyres at 0.2 m depth for both the front and the rear axle: the stress (for the smaller tyres) did not reach that far laterally. The increased mean normal stress for the two smaller standard tyres at 0.2 m to 0.4 m depth was related to the propagation of stress through the soil, which can be seen in Fig. 2 (2D). Although not significant, the mean normal stress at 0.2 m depth and 0.3 m lateral distance from the centreline increased from AxioBib to EvoBib, which might be the result of the higher stresses beneath the shoulders than beneath the centreline of the tyre. Such ‘dual-peak’ stress distribution was indicated for the EvoBib tyres by the FRIDA model.

4.3. Tyre dimension and inflation pressure are essential

Our results show that the improvement of the tyre-soil contact stress distribution and reduction of soil stress essentially relate to the tyre dimensions (width and diameter) and the actual inflation pressure of the tyre. For example, no differences in the soil contact stress distribution and vertical soil stress between Bias and AgriBib were revealed by the FRIDA calculations, as the model calculations are based on tyre dimensions, load, and inflation pressure, and not on tyre construction (diagonal vs. radial). Yet, no differences of mean normal stress were measured either, which confirms again the observations from the simulated stresses. The biggest improvement in contact stress distribution was achieved in the first development stage of the radial tractor tyres, i.e. from AgriBib to AxioBib, and only the introduction of the wider, lower-aspect-ratio tyres allowing traffic at much lower inflation pressures (~75%) resulted in large reductions of the mean normal stress beneath the centreline of the front and rear tyres. Even newer tyres contributed relatively little to the reduction of soil stress deeper in the soil profile. For the rear tyres, for example, an improvement in the tyre-soil contact stress distribution and associated reduction of soil stress from AxioBib to EvoBib (~20 kPa inflation pressure) was expected from the FRIDA model – though smaller than the improvement when moving from AgriBib to AxioBib. The measured mean normal stress for EvoBib was also lower than for AxioBib, but only at 0.2 m depth (adjusted p-value = 0.0026) and the reduction in the mean normal stress was not as large as in the move from AgriBib to AxioBib: 13 kPa (15%) versus 59 kPa (41%). At 0.4 m depth, the reduction was only 4 kPa (7%), i.e. negligible, when moving from AxioBib to EvoBib, while it was 27 kPa (34%) from AgriBib to AxioBib. These results indicate the need to continue the development of tyres with a large contact area and very low inflation pressures when aiming at a further reduction of soil stress.

4.4. Future perspective for tyre construction for sustainable traffic in agricultural fields

Regarding the effects of the tyres on soil stress, only the three larger low-aspect-ratio front tyres approached the guideline for sustainable traffic at soil water content around field capacity as recommedned by Schjønning et al. (2012). For none of the tyres included in the field experiment did the results of the FRIDA-calculated vertical stress stay below the recommended limit of 50 kPa at 0.5 m depth. Even the theoretically optimised tyre, Evo+ (\( \beta = 2 \)), had only a limited effect on the stress distribution at the tyre-soil interface and at the stress levels in the soil profile in comparison to EvoBib. The dual-peak stress distribution at the tyre-soil interface was more pronounced for Evo+ than for EvoBib, but the effect on soil stress was limited to the upper parts of the soil profile. At the depth of 0.5 m, only the front axle of Evo+ could stay within the recommended limit of 50 kPa, while the rear tyre of Evo+ exceeded this level by 12 kPa. These results show that further development of tyre technology and design is necessary in order to reduce soil stress, i.e. the risk of soil compaction, especially considering the effect on wheel loads of the increasing size and weight of agricultural machinery.

The theoretical optimisation of the stress distribution of vertical stress across the driving direction in this study was obtained by changing only the static loaded radius of EvoBib (as part of the tyre deflection), while keeping the dimensions and inflation pressures, but it is not the only solution. Besides, the distribution of vertical stress in the driving direction can be improved by optimising shape parameter \( \alpha \). This can be done by creating a longer tyre-soil contact area. Optimised shape parameters should be translated into a functional design but should not compromise other tyre functions such as traction, durability and comfort. The practical and legal possibilities of increasing tyre dimensions, which will be necessary for further reductions in tyre inflation pressure, should also be investigated.

Another solution to the reduction of soil stress in the soil profile is by reducing the wheel load through an increase in the number of
wheels. However, different wheel arrangements will affect the distribution of stress in the soil differently. For example, dual wheels at a tyre position act as separate wheels with respect to soil stress (Keller and Arvidsson, 2004). If the dual wheels are thus used to decrease the (initial) wheel load, the associated reduction of tyre inflation pressure will reduce the risk of compaction in the topsoil and upper subsoil – yet the potential area of compaction becomes larger (Keller and Arvidsson, 2004). Extra wheels when put in a standard tandem configuration can also reduce the risk of soil compaction beneath a single wheel, but the number of wheel passes through the same track increases. Multiple wheel passes on a track have been shown to increase soil deformation, especially in the topsoil (Naderi-Boldaji et al., 2018; Pulido-Moncada et al., 2019). Naderi-Boldaji et al. (2018) showed that the greater rut depth from multiple wheel passes resulted in higher mean normal soil stress. Yet the increasing rut depth alone could not explain the increase in soil stress. The authors suggest that other factors like soil strength must have contributed, and conclude that further study is required to understand stress propagation as affected by repeated wheel passes. Pulido-Moncada et al. (2019) hypothesize about the impact of traction on soil deformation in the subsoil. The authors found a negligible effect of four years of repeated annual traffic with a self-propelled tricycle-like slurry spreader with a wheel load of 12 Mg, whereas a more traditional tractor-trailer combination with wheel loads of 8 Mg (and therefore expected higher traction) clearly impacted the soil from around 0.25 m to around 0.7 m depth. The effects of multiple passes and traction on soil deformation are thus not fully understood, and possible solutions to the protection of soil functioning by different wheel arrangements need to be further explored.

4.5. Stress-strain relationship

The effect of soil stress induced by the experimental traffic on the soil structural properties at 0.3 m depth below the centreline of the wheel track were very limited, in spite of what could have been expected. Exceedance of the recommended limit for sustainable agricultural traffic at field capacity (Schjønning et al., 2012) indicated namely a risk of soil deformation. Moreover, the measured compressive strength of the soil at 0.3 m depth (as expressed by the precompression strength of the Control) was exceeded by the calculated vertical stresses. This indicated that the soil would not respond elastic, i.e. that the soil would be compacted by the experimental traffic (Lebert and Horn, 1991). However, we found only a very limited effect of traffic on the dry bulk density, \( \rho_b \), and also on air permeability at 0.3 m depth below the centreline of the wheel track.

The discrepancy between expected and measured deformation questions the relevance of applying the concept could relate to the relevance of applying the concept of precompression stress to soil deformation caused by traffic. The concept cannot account for traction, shear stresses or the effect of multiple wheeling. Although Arvidsson and Keller (2004) and Schjønning and Lamandé (2018) indicated an underestimation of the risk of soil deformation when comparing precompression stress and vertical stress, they implicitly raise awareness of considering other soil mechanical properties than precompression stress. In the present study, the relatively low Young’s modulus (Table 1) indicates that the soil had a low stiffness but was rather easily compressed under axial loading (e.g. Kirby, 1994). The Poisson’s ratio was relatively high (Table 1), indicating expansion in the lateral direction under loading (e.g. Das, 2008), and a high elasticity of the soil. These soil mechanical parameters suggest that the soil had a relatively high resilience, i.e. could recover from the stresses induced.

The dry bulk density before the experimental traffic was low (\( \rho_b = 1.14 \text{ g cm}^{-3} \) at 0.3 m depth), indicating a high porosity of the soil. Air-filled porosity, \( \varepsilon_{af} \), was above the generally applied lower critical limits for plant growth, i.e. 10% (Wesseling and van Wijk, 1957) and 12–15% (Grable and Siemer, 1968), and the stress measurements took place at a water content slightly lower than field capacity. Surprisingly, the air permeability before the experimental traffic was extremely low with regard to total and air-filled porosity, as it was close to or below the limit of 1 μm² suggested for impermeable soil by Ball et al. (1988). These results indicate that air-filled macropores were present but disconnected and/or tortuous. Despite some significant differences for Darcy air permeability, \( k_{D,av} \), we need to be careful with the interpretation of the results. The absolute differences were small, and the general level of Darcy air permeability was low. Yet, the results show that a single pass of a tractor with a large tyre-soil contact area and a more even contact stress distribution (EvoBib) could somehow increase air permeability for these soil conditions at 0.3 m depth. A theory could be that the more even distribution of traction forces on a large contact area led to some cracking of the soil and produced continuous macropores beneath the centreline of the tyre. The lower ratio of Darcy air permeability to apparent air permeability, \( k_{D,Apv}/k_{D,av} \) for EvoBib than for the Control indicate an increase in air velocity with an increase in pressure gradient (Schjønning and Koppelgaard, 2017) and therefore indicates again that more continuous air-filled macropores were present after the pass of the tractor equipped with EvoBib.

5. Conclusion

This study showed that the evolution in tyre construction has helped reduce soil compaction risks at a specific wheel load through the development of designs that allow an expansion of the tyre-soil contact area combined with a reduction in tyre inflation pressure. The expected reduction in soil stress for newer tyres due to a more even contact stress distribution, as indicated by the FRIDA calculations, were confirmed by the mean normal stress measurements. For tyres of similar dimensions and inflation pressures but of different construction, no differences of mean normal stress were measured. This indicates that the soil stress primarily related to the width, length, and inflation pressure of the tyre at a specific load, and not to the specific tyre construction like diagonal vs radial or whether or not a tyre is reinforced with metallic belts. Although the differences in soil stress beneath the tested tyres decreased with depth, significant differences were recorded even at 0.6 m depth beneath the centre of the tyres. These results indicate that tyre design might further help reduce the risk of soil compaction at a specific load if it allows for further reductions of the tyre inflation pressure. No effect of a single pass was found on bulk density, but the tyre with the larges tyre-soil contact area and most even contact stress distribution could somehow increase air permeability for these soil conditions at 0.3 m depth.

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References


Short communication

Construction of modern wide, low-inflation pressure tyres per se does not affect soil stress

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ABSTRACT

The interaction between rolling gear and soil is complex, but most important for the stress distribution in the soil profile. We explored the effect of three types of wide, low-inflation pressure tyres with similar dimensions on mean normal stress throughout the soil profile. We first tested the hypothesis that the stress is not affected by specific tyre construction. Second, we tested the benefit of lowering the tyre inflation pressure to a minimum for the tyre with the lowest recommended inflation pressure. Finally, we tested the effect of tyres with similar tractive potential at different wheel loads, i.e. with a different weight-pull ratio. Stress measurements were made with Bolling probes at six positions simultaneously: both beneath the centreline (centre) and at 0.3 m lateral distance (+0.3 m) of the centreline of the wheel track, at 0.2, 0.4, and 0.6 m depth. The results revealed a very limited effect of tyre construction on mean normal stress. No differences were measured beneath the centre, and the differences at +0.3 m were found only at 0.2 m depth for the tyres at the rear axle. The effect of minimising tyre inflation pressure was limited to the upper parts of the soil profile for the measurements beneath the centre of the tyre (significant at 0.2 m depth and a trend at 0.4 m depth). Finally, our study did not reveal significant benefit of tyres with a lower wheel load while potentially having similar tractive performance, although the reduction of wheel load and associated lower inflation pressure potentially reduce stress in both top- and subsoil.

The results emphasize that in order to reduce soil stress, tyre design and use should allow for a large contact area and low inflation pressure.

1. Introduction

The interaction between rolling gear and soil is complex, but most important for the stress distribution at the contact area and in the soil profile. Tyre characteristics play therefore a major role in relation to soil compaction. In 1994, Tijink summarised inflation pressure, wheel load, design (among which dimension and deflection), and slip as factors that could be managed to reduce the impact of a single pass on soil structure.

The tyre inflation pressure is of primary importance for stress distribution at the tyre-soil contact area and for the stress in the upper part of the soil profile (Lamandé and Schjønning, 2011). For a given tyre and wheel load, a lower inflation pressure generally increases the contact area. This decreases both the mean ground pressure and the magnitude of the peak stress in the soil profile (Schjønning et al., 2008). The benefit of reducing tyre inflation pressure is limited in the subsoil, where stress is more closely related to wheel load (Lamandé et al., 2007). Given the increase of wheel loads over the past decades, increased levels of compaction are now found throughout the soil profile (e.g. Brus and van den Akker, 2018; Schneider and Don, 2019).

Tyre design is first of all relevant because of a tyres’ dimension; a larger tyre decreases the mean ground pressure for a given load. Wider tyres allow for a reduction of the tyre inflation pressure at a given wheel load, as they have a higher load carrying capacity (Perdok and Arts, 1987). Such tyres are especially beneficial in combination with a Central Tyre Inflation System (CTIS) that allows for adjustments of the inflation pressure to the load and speed, e.g. between traffic on the road and in the field. Tyre deflection depends on the load, inflation pressure...
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Construction of modern wide, low-inflation pressure tyres per se does not affect soil stress

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and carcass stiffness (Tijink, 1994). In relation to soil stress, a larger deflection improves the stress distribution in the contact area across the tyre, but might not influence the distribution in the driving direction (Schjønning et al., 2015).

Although wheel slip is needed to develop traction, it is desirable to keep slip as low as possible to maintain soil structure (Tijink, 1994). About 10 % slip is optimal in relation to traction efficiency: the fraction of torque action on the axle that is converted to drawbar pull. Typically, this ratio (output: input) is around 0.4 (Gee-Clough et al., 1982; Pichlmaier and Honzek, 2011).

Reducing wheel loads and increasing the contact area can contribute substantially to reduce the soil stress for a single wheeling, but the effect of specific tyre construction of similar dimensions might be very limited. Ten Damme et al. (2019) found no significant difference in mean normal stress between two sets of narrow tyres of similar dimensions, diagonal vs. radial, when tested at similar wheel loads and similar inflation pressure. Yet, tyre design can improve a vehicles weight-pull ratio, meaning that the wheel load can be reduced to generate a given tractive force (Gee-Clough, 1980).

In this study, we explored effects of tyre construction on mean normal soil stress in both top- and subsoil. We tested the following three hypotheses using three sets (i.e. front and rear) of wide, low-inflation pressure tyres: 1) Mean normal stress in the soil profile is not affected by the specific construction of tyres of similar dimensions at similar wheel load and inflation pressure; 2) Further lowering of the inflation pressure of wide, low-inflation pressure tyres reduces soil stress in the upper part of the soil profile, and; 3) An improved weight-pull ratio, i.e. similar tractive potential but with reduced wheel load and inflation pressure, helps reducing soil stress.

### 2. Materials & methods

#### 2.1. The experimental site

The measurements of mean normal soil stress took place in a field traffic-experiment at a site part of the Ladoux Michelin Technology Centre (45°51’28.3”N 3°07’24.4”E) in March 2018. The arable field was left undisturbed since the harvest of wheat in 2017, and the soil water content at the time of the experiment was slightly less than field capacity. The soil is a silty clay loam and classified as a Chernozem according to the WRB (FAO, 1998) system. We refer to Ten Damme et al. (2019) for more details on the textural, chemical, mechanical, and structural characteristics of the soil. 2.2 The treatments

The tyres presented in this study (AxioBib, CerexBib, and EvoBib) are similar to those in Ten Damme et al. (2019), yet with inflation pressures and loads to test our three hypotheses (Table 1). The tyres are of similar dimensions (only the front tyre CerexBib is larger than the front tyres AxioBib and EvoBib) but of different construction: AxioBib and CerexBib are similar wide, low inflation pressure tyres but CerexBib is reinforced with metallic belts, and EvoBib is equipped with the ability to completely change the tyre shape by lowering the shoulders of the tyres to the soil surface when the inflation pressure is reduced. The tyres’ soil contact area and mean ground pressure (Table 1) were calculated with the FRIDA model (Schjønning et al., 2008) hence based on tyre dimensions, static loaded radius, wheel load, and a ratio between the actual and load-recommended inflation pressure for traffic at 10 km h⁻¹.

To test for the effect of tyre construction (hypothesis 1), the three sets of tyres were tested at equal wheel load (2.9 Mg front, 4.3 Mg rear) and inflation pressure (80 kPa). This inflation pressure was recommended at 10 km h⁻¹ for AxioBib. For CerexBib it meant a reduction of 60 kPa, and for EvoBib an increase of 20 kPa in comparison to the recommended inflation pressure by the manufacturer. To test for the effect of reducing tyre inflation pressure to a minimum (hypothesis 2), EvoBib was inflated to 80, 60, and 40 kPa (with 60 kPa being recommended by the manufacturer). Lastly, we tested EvoBib with an inflation pressure of 60 kPa but with 20 % less load to test the effect of wheel loads for tyres with the same tractive potential, i.e. with a different weight-pull ratio (hypothesis 3). Namely, according to the tyre manufacturer, the net traction ratio of EvoBib could go over 50 % at 10 % slip, while typical values are around 40 % at 10 % slip. This means that EvoBib can potentially generate the same level of traction as the AxioBib (Michelin, 2018) with a 20 % load reduction and 25 % inflation pressure reduction (Table 1).

<table>
<thead>
<tr>
<th>Hypothesis</th>
<th>Treatment</th>
<th>Name</th>
<th>Dimension</th>
<th>$F_{\text{ Load}}\text{ Mg}$</th>
<th>$P_{\text{ tyre}}\text{ kPa}$</th>
<th>$A\text{ m}^2$</th>
<th>$MGP\text{ kPa}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Front 1: Construction</td>
<td>Axio80</td>
<td>AxioBib</td>
<td>600/70 R30, IF</td>
<td>2.9</td>
<td>80</td>
<td>0.44</td>
<td>64</td>
</tr>
<tr>
<td>Cerex80</td>
<td>CerexBib</td>
<td>620/70 R30, IF, CFO</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Evo80</td>
<td>EvoBib</td>
<td>600/70 R30, VF</td>
<td>2.9</td>
<td>80</td>
<td>0.41</td>
<td>69</td>
<td></td>
</tr>
<tr>
<td>2: Inflation pressure</td>
<td>Evo80</td>
<td>EvoBib</td>
<td>600/70 R30, VF</td>
<td>2.9</td>
<td>80</td>
<td>0.41</td>
<td>69</td>
</tr>
<tr>
<td>Evo80*</td>
<td>EvoBib</td>
<td>600/70 R30, VF</td>
<td>2.9</td>
<td>80</td>
<td>0.47</td>
<td>61</td>
<td></td>
</tr>
<tr>
<td>3: Tractive potential</td>
<td>Evo80Evo80RL</td>
<td>EvoBib</td>
<td>600/70 R30, VF</td>
<td>2.3</td>
<td>60</td>
<td>0.45</td>
<td>51</td>
</tr>
</tbody>
</table>

| Rear 1: Construction | Axio80 | AxioBib | 710/70 R42, IF | 4.3 | 80 | 0.54 | 78 |
| Cerex80 | CerexBib | 710/70 R42, IF, CFO | | | | |
| Evo80 | EvoBib | 710/70 R42, VF | 4.3 | 80 | 0.56 | 75 |
| 2: Inflation pressure | Evo80 | EvoBib | 710/70 R42, VF | 4.3 | 80 | 0.56 | 75 |
| Evo80* | EvoBib | 710/70 R42, VF | 2.3 | 60 | 0.45 | 51 |
| 3: Tractive potential | Evo80Evo80RL | EvoBib | 710/70 R42, VF | 3.5 | 60 | 0.52 | 66 |
| Axio80* | AxioBib | 710/70 R42, IF | 4.3 | 80 | 0.54 | 78 |

* Treatments presented in Ten Damme et al. (2019).

* Calculations could not be performed as the ratio of actual and recommended inflation pressure (80 kPa and 140 kPa respectively) was out of range.

IF, increased flexion; CFO, Cyclical Field Operation; VF, Very High Flexion; $F_{\text{ Load}}$, wheel load; $P_{\text{ tyre}}$, tyre inflation pressure; $A$, calculated tyre-soil contact area; $MGP$, calculated mean ground pressure.
The measurements was 0.83 m s−1.

Table 2

Median of maximum measured mean normal stress (kPa) for the three sets of tyres used to test for the effect of tyre construction. N = 12 for each probe position for Axio80 and N = 9 for each probe position for Cerex80 and Evo80.

<table>
<thead>
<tr>
<th>Probe position (placement and depth)</th>
<th>Tyre</th>
<th>Centre</th>
<th>+0.3 m</th>
</tr>
</thead>
<tbody>
<tr>
<td>Axio80</td>
<td>82</td>
<td>46</td>
<td>16</td>
</tr>
<tr>
<td>Cerex80</td>
<td>98</td>
<td>50</td>
<td>17</td>
</tr>
<tr>
<td>Evo80</td>
<td>99</td>
<td>48</td>
<td>17</td>
</tr>
<tr>
<td>p-value</td>
<td>0.668</td>
<td>0.779</td>
<td>0.981</td>
</tr>
</tbody>
</table>

Table 3

The null-hypothesis (mean normal stress is not significantly lower for the tyres at the rear axle). Only at 0.2 m depth, at +0.3 m of the front wheels (Table 2). Only at 0.2 m depth, at +0.3 m beneath the rear wheels the mean normal stress was significantly lower for Axio80 (−16 % to −21 %, p-value 0.024). The differences between Axio80 and Cerex80 were solely due to the tyre construction, since CerexBib is a duplicate of AxioBib only with reinforced sidewalls to carry high loads, i.e. not intended for use at low inflation pressure as tested [load-recommended is 120 kPa (Ten Damme et al., 2019)]. This under-inflation is reflected by the fact that the mean normal stresses at +0.3 m were higher for CerexBib than for AxioBib.

3. Results and discussion

3.1. The effect of tyre construction on mean normal soil stress

No significant effect of tyre construction on mean normal stress was found at any depth beneath the centre of both front and rear wheels, nor at +0.3 m of the front wheels (Table 2). Only at 0.2 m depth, at +0.3 m beneath the rear wheels the mean normal stress was significantly lower for Axio80 (−16 % to −21 %, p-value 0.024). The differences between Axio80 and Cerex80 were solely due to the tyre construction, since CerexBib is a duplicate of AxioBib only with reinforced sidewalls to carry high loads, i.e. not intended for use at low inflation pressure as tested [load-recommended is 120 kPa (Ten Damme et al., 2019)]. This under-inflation is reflected by the fact that the mean normal stresses at +0.3 m were higher for CerexBib than for AxioBib.

Peak stresses near the edge, although vertical, were reported by both Raper et al. (1995a) and Schjønning et al. (2008) for under-inflated tyres. The difference between Axio80 and Evo80 was explained by a combination of tyre construction and the position of the Bolling probes at 0.3 m from the centreline of the wheel track in relation to the contact area of tyres: EvoBib is of similar dimensions as AxioBib and CerexBib (Table 1) but at the inflation pressure tested, the shoulders of the tyre were much wider and the shoulders of the tyre were much wider in the soil profile (Table 2). Although the differences were not significant, it does support the general assumption that stress in the subsoil is of similar dimensions as AxioBib and CerexBib. Hence, the measurements at +0.3 m of the front wheels (Table 2) were not comparable. Beneath the centre, no significant differences between the front- and rear tyre were found (analysis not shown). This indicated an effect of proportionality: the smaller load at the front allowed for a tyre of smaller dimensions, which then resulted in similar soil stress. Note that the mean normal stress tended to be higher for the rear axle (i.e. with higher load) deeper in the soil profile (Table 2). Although the differences were not significant, it does support the general assumption that stress in the subsoil relates to wheel load (Arvidsson and Keller, 2007; Lamandé et al., 2007).

3.2. The effect of tyre inflation pressure on mean normal soil stress

The tyre inflation pressure of EvoBib affected the mean normal stress only beneath the centre of the tyres; the front and rear tyres were of different dimensions, hence the measurements at +0.3 m were not comparable. Beneath the centre, no significant differences between the front- and rear tyre were found (analysis not shown). This indicated an effect of proportionality: the smaller load at the front allowed for a tyre of smaller dimensions, which then resulted in similar soil stress. Note that the mean normal stress tended to be higher for the rear axle (i.e. with higher load) deeper in the soil profile (Table 2). Although the differences were not significant, it does support the general assumption that stress in the subsoil relates to wheel load (Arvidsson and Keller, 2007; Lamandé et al., 2007).

In each block, the arithmetic mean of the mean normal stress was calculated for each probe position (centre and +0.3 m, at 0.2, 0.4, and 0.6 m depth) and treatment (the front and rear separately). The four resulting values for each probe position of each treatment were considered replicates. These were used as input data to test for differences in mean normal stress between the medians of the treatments at a given probe position using the non-parametric Kruskal-Wallis test. We performed the Conover-Iman test on the conover.test R package (R Core Team, 2017), version 1.1.5, with the Holm-Sidak adjustment method as the post-hoc analysis, where the null-hypothesis (mean normal stress is similar at a given probe position between treatments) was rejected when the p-value was equal to or smaller than λ/2, with λ = 0.05.
Given that only the inflation pressure differed between the three treatments, the results support the findings that inflation pressure influences soil stress in the upper part of the soil profile (Arvidsson and Keller, 2007; Schjønning et al., 2012). The depth of this ‘upper part’ might be situation-dependent. For example, Arvidsson and Keller (2007) mentioned “very little influence” of inflation pressure on soil stress at a depth of 0.3 m, whereas our results indicated a strong trend of highest mean normal stress for Evo80 at 0.4 m depth (rear axle, p-value = 0.069). According to Raper et al. (1995a, 1995b) and Schjønning et al. (2008), a decrease of the tyre inflation pressure increases the length but not the width of the contact area. This could be valid for EvoBib as well, knowing that the shoulders supported the contact area at all the three levels of inflation pressure. This might explain the differences beneath the centre but not at +0.3 m of the tyres (Fig. 1); the effect of the increase in length from decreasing inflation pressure on the stress distribution in the tyre-soil contact area is most pronounced closer to the centre of the tyre. Raper et al. (1995a, 1995b) also reported significant increase of tyre-soil interface stress with increasing inflation pressure near the centre of the tyre, and none near the edge of the tyre.

### 3.2. The effect of reduced wheel load for tyres with similar tractive potential on mean normal soil stress

The specific construction of EvoBib allowed a reduction of approximately 20 % of the wheel load and 25 % of the inflation pressure in comparison with AxioBib (Evo60RL and Axio80, Table 1) while having potentially similar tractive properties. The reductions were expected to have led to lower vertical soil stress throughout the soil profile (Arvidsson and Keller, 2007; Schjønning et al., 2012) and therefore lower mean normal stress. Although mean normal stress was generally 10–14 % lower for Evo60RL beneath the centre, no significant differences were measured between the treatments at any depth beneath the centre of the tyres, and the trend supporting the expectations was weak (p-values > 0.15, Table 3). The differences at +0.3 m were even smaller (Table 3).

Assuming that the vertical stress indeed was lower for Evo60RL, implies that stresses from horizontal directions must have been higher in comparison to Axio80 – given that the mean normal stress was not significantly different. This would be unexpected if the tractive forces actually were similar, but the level of traction was not recorded during the experiment (and no extra pulling force was added to the treatments, section 2.3). These results indicate a current knowledge gap in our understanding of the interactions between tyre and soil.

One aspect, other than traction, that could be of interest is the effect of the length of the tyre-soil contact area on soil stress. This area might have been larger for Evo60RL due to its lower tyre inflation pressure. According to Söhnes (1953) summation procedure, an increase in length for a given width would mean that the vertical stress at a given point in the soil profile includes more point loads. It might be possible that this has cancelled out the benefit of the reduced load at 0.4 and 0.6 m depth.

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**Fig. 1.** Median of maximum measured mean normal stress (kPa) for EvoBib at an inflation pressure of 40, 60, and 80 kPa. N = 12 for each probe position for Evo40, and N = 9 for each probe position for Evo60 and Evo80. Different letters behind the symbol indicate differences between the tyres at a given probe position at a significance level of 2.5 %. Treatment presented in Ten Damme et al. (2019).
3.4 Perspectives across the characteristics of wide, low inflation pressure tyres

The specific construction of tyres had only a very limited impact on mean normal stress, as discussed in section 3.1. Previously, Ten Damme et al. (2019) found no effect of tyre construction on mean normal stress for two types of smaller, standard tyres of similar dimensions (diagonal of the wheel track + 0.3 m): stresses were 16–20 % lower for the rear axle at 0.2 m depth at 0.3 m lateral distance from the centreline normal stress in the soil profile. The only differences were measured at 0.2 m depth beneath the centre of the rear tyre (p-value 0.069). A further reduction to 40 kPa reduced the stress at 0.2 m depth beneath the centre of the rear tyres. No other differences were found, hence the benefit of very low inflation pressure seems to be limited to the upper part of the soil profile. Finally, we measured no significant effect for tyres with the same tractive potential at different wheel loads, even though the improved weight-pull ratio of EvoBib allowed for a reduction of 20 % of the wheel load and 25 % of the inflation pressure in comparison with AxioBib. This potentially reduces soil stress, but we found only indications of lower mean normal stress beneath the centre of EvoBib (10–14 %, p-values > 0.15).

These results imply that tyre dimension and inflation pressure are of primary importance in relation to soil stress, rather than specific tyre construction. In order to reduce the risk of soil deformation, design and use of tyres should thus allow for large contact areas and low tyre inflation pressures. Systems as CTIS can then also be extremely beneficial in relation to the protection of soil structure.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

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3.3. Discussion on methodology

The interpretation of the results, hence the recommendations for tyre manufacturers and users, are complicated by the fact that the ratio between the three principal stresses that contribute to mean normal stress as measured with the Bolling probes are unknown. The direction of soil stress is of great importance for the nature of soil deformation, i.e. whether compaction or distortion might occur (Berisso et al., 2013). Moreover, the fact that soil can resist more shear stress when exposed to higher normal stress (Coulomb, 1776), makes the ratio between the principal stresses very important when considering the actual risk of soil stress on causing deformation of soil structure. Yet, normal stress can lead to compaction if it exceeds the soil’s compressive strength (Lebert and Horn, 1991).

4. Conclusion

The specific construction of three sets of wide, low inflation pressure tyres of similar dimension had only a very limited effect on mean normal stress in the soil profile. The only differences were measured at the rear axle at 0.2 m depth at 0.3 m lateral distance from the centreline of the wheel track (+ 0.3 m): stresses were 16–20 % lower for AxioBib than for CerexBib and EvoBib. These differences could be related to an under-inflated CerexBib (80 kPa when 120 kPa was recommended), and to the larger width of EvoBib which meant that the measurements at + 0.3 m were influenced by a larger part of the contact area.

The reduction of the tyre inflation pressure of EvoBib from 80 kPa to 60 kPa (the recommended inflation pressure) did significantly reduce stress at 0.2 m depth beneath the centre of both front and rear tyres, and tended to reduce the stress at 0.4 m depth beneath the centre of the rear tyre (p-value 0.069). A further reduction to 40 kPa reduced the stress at 0.2 m depth beneath the centre of the rear tyres. No other differences were found, hence the benefit of very low inflation pressure seems to be limited to the upper part of the soil profile. Finally, we measured no significant effect for tyres with the same tractive potential at different wheel loads, even though the improved weight-pull ratio of EvoBib allowed for a reduction of 20 % of the wheel load and 25 % of the inflation pressure in comparison with AxioBib. This potentially reduces soil stress, but we found only indications of lower mean normal stress beneath the centre of EvoBib (10–14 %, p-values > 0.15).

These results imply that tyre dimension and inflation pressure are of primary importance in relation to soil stress, rather than specific tyre construction. In order to reduce the risk of soil deformation, design and use of tyres should thus allow for large contact areas and low tyre inflation pressures. Systems as CTIS can then also be extremely beneficial in relation to the protection of soil structure.

References

Paper 3

Traction and repeated wheeling – effects on contact area characteristics and stresses in the upper subsoil

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Traction and repeated wheeling – effects on contact area characteristics and stresses in the upper subsoil

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Keywords horizontal and vertical soil stress; vertical contact stress; driven and towed tyres; subsoil compaction risk.
Abstract

Reducing wheel loads has long been the key advice to reduce the risk of subsoil deformation, but this disregards other machinery-soil interactions such as the effects of traction and repeated wheeling. We conducted a field experiment to disentangle the effect of traction (described as drawbar pull) and repeated wheeling on the contact area characteristics and stresses in the upper subsoil. Experimental traffic comprised a tractor (static load 11 Mg) with activated 4 WD towing a trailer (static load 17 Mg or 24 Mg) and took place on a sandy loam with stubble of oats at soil water content near field capacity. Measurements included drawbar pull, contact area and vertical contact stress, and horizontal (in the driving direction) and vertical stresses at ~0.36 m depth in an undisturbed soil profile. Drawbar pull was significantly higher (9.13 kN compared to 6.46 kN) for the high trailer load, but no differences were observed between the two steering modes. The contact area of the tractor’s rear tyres increased for the high drawbar pull but with no significant differences in length or width. The maximum vertical stress in the tractor rear tyre’s contact area then tended to be lower, despite the increase in the dynamic wheel load (from 3.5 Mg to 4.1 Mg). Whereas high drawbar pull improved the stress distribution in the driving direction, the effect across the tyre was complicated. We found evidence of different tyre-soil interaction for tyres with and without traction. No significant effect of repeated wheeling with a single towed tyre (5.5 Mg) on the contact area characteristics were found. For the towed tyres, horizontal soil stress increased linearly with vertical soil stress, and we suggest that this increase is intrinsic to the soil (at these experimental conditions). Traction does then influence the ratio of horizontal to vertical stress. The results confirm the importance of considering dynamic aspects of field traffic such as traction and dynamic wheel load.
1. Introduction

The risk of soil compaction depends on the strength of soil to resist induced stresses. Multiple models exist that calculate the risk of compaction by comparison of stress and strength. Many of these models, such as SOCOMO (Van den Akker, 2004), SoilFlex (Keller et al., 2007), and Terranimo (Stettler et al., 2014), are based on the pseudo-analytical continuum concept of Söhne (1953), which in turn is based on the Boussinesq (1885) solution for stress propagation. An implication of the summation procedure of the Söhne model approach is that in the subsoil, wheel load is the dominant factor determining vertical stress. This has been validated in numerous field studies (e.g. Arvidsson and Keller, 2007; Lamandé et al., 2007; Lamandé and Schjønning, 2011a). Reducing wheel loads has therefore for many years been the key recommendation to reduce the risk of subsoil deformation. Yet some recent investigations have revealed that other machinery-soil interactions might be of critical importance for the stress distribution and the risk of soil deformation.

For example, Schjønning et al. (2016) and Pulido-Moncada et al. (2019) showed only minor effects on subsoil properties for a ~12 Mg wheel load applied by a tricycle-like, self-propelled slurry spreader, while a 6 Mg and 8 Mg wheel load was found to induce significant impacts on subsoil properties for a traditional tractor-trailer combination. Their experiment did not allow decisive conclusions on cause-effects, although a considerable difference in tyre inflation pressures may have contributed. The observations were ascribed either to repeated wheeling from a single pass of the tractor-trailer combination, or to the traction needed to pull the machinery across the field.

The effect of repeated wheeling on soil stress and tyre-soil interaction has been the subject of several studies. Pytka (2005) and Naderi-Boldaji et al. (2018) found an increase in principal soil stresses and mean normal stress, respectively, with increasing machinery passes. Bakker and Davis (1995) visualised the increased impact of five consecutive tractor passes (8.5 Mg, rear tyre 28.5 R 38, 180 kPa) compared to a single pass of the tractor on wheel rut formation and soil deformation below the wheel rut, in
conditions that represented cultivation on a well trafficable soil with a moist subsoil. Repeated wheeling often takes place on a more rigid soil surface than the first wheel passing, due to increase in surface soil strength following the pass of the first wheel. As a consequence, the tyre-soil contact area can be smaller for successive wheeling of similar tyres (Way et al., 1995). This can lead to higher soil stresses, especially at shallow depths (Wiermann et al., 1999). Yet the studies of repeated wheeling mentioned here, and many other studies of the effect of repeated wheeling on soil compaction, were performed with a tractor, i.e., with two wheels passing in the same wheel track during a single pass.

The effect of traction and drawbar forces on horizontal stresses are not taken into account in the Söhne model as used in many soil compaction models (De Pue and Cornelis, 2019). Both the SOCOMO and SoilFlex models did attempt to include horizontal soil stress for driven tyres. Yet De Pue et al. (2020) found only limited effects of traction on horizontal stress using the Söhne model, which contradicts the results of similar simulations using a discrete element models. These deviating results are partly because the effect of traction on stress distribution beneath tyres lacks understanding. Traction induces shear stresses in the soil beneath a driven wheel, which lead to the hypothesis that traction will have a significant effect on the stress field and hence on soil deformation and distortion, as also stated by Schjønning et al. (2016) and Pulido-Moncada et al. (2019). Pytka et al. (2006) found increase in stress (measured in six directions) in a disturbed upper subsoil under driven tyres with increasing traction, yet higher traction was achieved by reducing tyre inflation pressure, which means no decisive conclusions on cause-effect can be made.

The main purpose of this paper was to evaluate the effect of driven and towed tyres on the vertical stress distribution at the contact area and on vertical and horizontal in the upper part of the subsoil. To reach this purpose, we first tested the hypothesis that driving with a trailer in offset steering mode (offsetting trailer tyres so that they pass outside of the tractor’s wheel track) for a given load increases the drawbar pull in comparison with driving with a trailer in standard steering mode (wheels driving in the tractor
tracks), and the hypothesis that the drawbar pull increased with higher towed load for a given steering mode. Second, we tested the hypothesis that both the level of drawbar pull on driven tyres and repeated wheeling of towed tyres affect the contact area and the distribution of vertical stress therein. Third, we tested the hypothesis that horizontal stress in the driving direction in the soil profile increases with increasing level of drawbar pull.

2. Material and methods

2.1 Experimental site and soil

A wheeling experiment was performed on a slightly sloping arable field with stubble of oats at Research Centre Foulum, Denmark. The soil is a sandy loam, typically classified as a Luvic Umbrisol according to the WRB classification system (Food and Agriculture Organization of the United Nations, 2015). Textural data for the plough layer were taken from Abdollahi et al. (2014), who analysed a range of soil properties on the neighbouring field, viz: 9.0 % clay (<2 µm), 24 % silt (2–63 µm), and 67 % sand (63–200 µm).

The field was irrigated a few days prior to the experiment to be able to perform the experiment at a soil water content just below field capacity. Dry bulk density and volumetric soil water content were measured for 100-cm³ soil cores (inner diameter 60.5 mm, 34.82 mm high) from reference soil, i.e., without traffic, at 0.15 and 0.4 m depth, and were, respectively, 1.47 ± 0.07 Mg m⁻³ and 1.52 ± 0.07 Mg m⁻³ for dry bulk density, and 0.30 ± 0.02 cm³ cm⁻³ (saturation about 70 %) and 0.29 ± 0.02 cm³ cm⁻³ (saturation about 64 %) for volumetric soil water content. At the time of the experiment, the soil matric potential at 0.15 m depth was then slightly less negative than -100 hPa, as the volumetric soil water content was 0.28 ± 0.02 cm³ cm⁻³ for the soil cores after equilibration to a matric potential of -100 hPa in the laboratory.

The precompression stress (131 ± 50 kPa, median = 130) and Young’s modulus (median = 2470 kPa) were measured on the 100-cm³ soil cores from 0.4 m depth at the water regime prevailing at sampling. The
cores were subjected to uniaxial compression tests using the 5969 Dual Column Tabletop Testing System (INSTRON®, Norwood, MA, USA). The confined compression tests were performed in principle as described by Koolen (1974). The cores were loaded to 1000 kPa with a strain-controlled piston velocity of 1 mm min\(^{-1}\) (Schjønning, 1991; Schjønning and Lamandé, 2018). The precompression stress was then determined from the stress-strain relationship based on the method developed by Lamandé et al. (2017).

Young’s modulus was derived from unconfined compression tests, in which each sample was first loaded to 17 kPa, then unloaded for three minutes, and reloaded to 33 kPa. The Young’s Modulus was determined as the slope from the stress-strain relationship of the reloading curve (Fig. S1) based on Eggers et al. (2006).

### 2.2 The machinery

A T7, 270 hp New Holland tractor with a total weight of 11 Mg was used to tow a trailer (Fig. 1) with a total weight of either 17 Mg (L, low) or 24 Mg (H, high). No load was transferred from the trailer to the tractor. The tractor was equipped with standard wide, low-inflation-pressure tyres: 600/65R28 on the front and 650/75R38 on the rear axles. These were inflated to the pressure recommended by the tyre manufacturer for the static wheel loads used in our experiment for a speed of up to 10 km h\(^{-1}\) (Table 1).

The standard 4WD with locked differential was activated to ensure traction on all wheels during traffic in the experimental plots. The velocity was controlled by GNSS (Global Navigation Satellite System) and set to 0.83 ms\(^{-1}\) when driving in experimental plots.

The trailer was equipped with wide, low-inflation-pressure tyres in the dimensions 710/50R26.5 170D on all wheels, which also were inflated to the manufacturer-rated pressure for the specific static wheel loads for a speed of up to 10 km h\(^{-1}\) (Table 1). The concept trailer could switch between standard and offset steering mode (Fig. 1). The standard configuration refers to the mode where the trailer tyres pass in the same tracks as the tractor tyres. In the offset configuration, the front axle of the trailer was shifted 700 mm to the left and the rear axle was shifted 700 mm to the right (Fig. 1), so that the trailer tyres passed...
on soil outside the tractor tyres’ tracks. There was nevertheless a small overlap of approximately 0.28 m for the wheel tracks of the trailer’s and tractor’s rear tyres.

Fig. 1. Left: In the offset steering mode, the axles of the trailer were shifted. The overlap between the right rear wheels of the tractor and trailer was approximately 0.28 m. Right: A drawbar was mounted between the tractor and the trailer for measurements of drawbar pull.

Table 1. Wheel loads and tyre inflation pressures applied.

2.3 Vehicle configurations and experimental design

Eight combinations of steering mode, wheel load, and number of machinery passes were tested (Table 2). The label for each different combination was made up of the number of driven tractor wheels + the number of towed trailer wheels passing in the same wheel track, with either the low (L) or high (H) load on the trailer, and with the number of machinery passes (N) as subscript.

The experimental site was divided into three blocks for replicate measurements (Fig 2). Each block was again divided into two areas: one for measurements of contact stress (for five configurations), and one for measurements of drawbar pull (for all eight configurations). Soil stress measurements (for two configurations) were made in the centre of the area used for drawbar pull measurements. The driving direction was always with the slope of the field – the elevation being highest in block 2 (highest elevation 55.0 m), and generally lowest in block 1 (lowest point 54.3 m), and the difference within a plot at most 0.3 m (over a length of 13.5 m).

Table 1. Specifications of the configurations of the tractor-trailer (top), and the measurements that were made for the different configurations (bottom).

Fig. 2. Layout of the experimental field. The number in brackets indicates the number of configurations for the measurements (see Table 2). Plots marked NA are without experimental traffic and not part of this study. The three tractors drawn in Block 2 indicate the three positions on the plots for which the drawbar pull was calculated for each pass in relation to the slope of the field.

2.4 Measurements and calculations

2.4.1 Drawbar pull
In this study, the traction is described in terms of drawbar pull (kN), which was measured when driving in the experimental plots by load cells that were built on a frame and mounted between the tractor and trailer (Fig. 1). Drawbar pull was recorded with a frequency of 0.2 kHz using three load cells on three joints (lift arms and top linkage), and the total drawbar pull was calculated as the sum of the three load cell measurements.

The topography of the field meant we could not compare the drawbar pull between plots as they were measured; we first had to take the slope of the field into account. We used the digital elevation model DK-DEM/Terrain (© The Danish Agency for Data Supply and Efficiency) with a 0.4 m raster in ArcGIS 10.4.1 to estimate the slope of the field (%) beneath the trailer for three fixed positions in each plot (with the trailer’s rear axle at the entrance, and at 5 m and 10 m in the driving direction, as indicated by the tractors in block 2 in Fig. 2). For each plot, we calculated the average drawbar pull over ~0.32 s [the time it took for the tractor to drive 0.4 m forwards] around the same three fixed positions, i.e., taking into account the estimated slope of the field.

2.4.2 Contact area and vertical stress distribution at the soil-tyre interface

Measurements of the tyre-soil contact area and the vertical stress distribution were made for the configurations 2+2 L₁, 2+2 H₁, and 0+1 H₁, 0+1 H₂ and 0+1 H₃ at three different positions (the measurements of the configurations 0+1 H₂ and 0+1 H₃ were made by immediately repeating the passes of the 0+1 H₁ configuration). We followed the approach described by, e.g., Schjønning et al. (2008). Seventeen stress transducer housings (each 50 mm in diameter and 32 mm height) glued to a rubber blanket were placed in a fitted trench in the undisturbed soil layer just below 0.10 m rotovated soil, ensuring the top of transducer housings to be at 0.10 m. The soil around the transducer housings was repacked by hand to approximately similar densities as the non-tilled soil. Ten cm of rotovated soil was then loosely restored on top to cover the sensors. Each transducer housing contained a load cell (DS
Europe and X-SENSORS, Series BC-302) that was connected to a data-logger. Measurements were made at 1 kHz. A laser sensor kept track of the exact position of the passing vehicle relative to the load cells to correlate the two data-acquisition systems. Please consult Schjønning et al. (2008) for further details about the measuring method.

2.4.2.1 Calculations of vertical stress at the tyre-soil contact area

Raw stress measurements need correction to account for potentially inaccurate measurements due to differences in stiffness between the transducer housings and the surrounding soil. Previously, corrections have been made with the static weighbridge wheel load measurements, $F_{\text{static}}$ (Mg). By this, the correct vertical stress is found by multiplying with a ‘load factor’ $F_{\text{static}}/F_{\text{app}}$, where $F_{\text{app}}$ (Mg) is the integral of the measured stress over the contact area (Schjønning et al., 2008). In the present study, we calculated the dynamic wheel load, $F_{\text{dynamic}}$ (Mg, Table 1), during traffic as $F_{\text{dynamic}} = 0.82 \times F_{\text{app}}$, based on Lamandé et al. (2015) who reported an 18 % overestimation from the true vertical stresses from the stress transducers used for the tyre-soil contact measurements. The corrected maximum measured vertical stress in the contact area is denoted $p_{\text{peak}}$ (kPa).

The tyre-soil contact area was calculated numerically based on the load cell readings with stresses exceeding 10 kPa (as an expression of tyre contact with the soil), $A_{\text{num}}$ ($m^2$). The mean ground pressure in the tyre-soil contact area, $p_{\text{mean}}$ (kPa), was then calculated as $F_{\text{dynamic}}/A_{\text{num}}$. Additionally, we calculated $A_{\text{num}}$, $F_{\text{dynamic}}$ and $p_{\text{mean}}$ also for the contact areas forward and rearward of the tyres’ axles.

The FRIDA model (Schjønning et al., 2008) was fitted to the measured contact vertical stresses to describe the tyre-soil contact and the contact stress distribution. It includes a super-ellipse model to describe the shape of the contact area (Hallonborg, 1996). The half length and width of the contact area are denoted $a$ and $b$, respectively. The super-ellipse parameter, $n$ is then used as an indicator of the shape of the contact area. The tyre-soil contact area, $A_{\text{ellip}}$ ($m^2$), was calculated from these three
parameters. The FRIDA parameters $\alpha$ and $\beta$ describe the stress distribution in the longitudinal and lateral directions, respectively, and the model-fitted maximum vertical stress in the contact area is denoted $p_{\text{max}}$ (kPa).

2.4.3 Measurements of vertical and horizontal stress in the soil profile

Measurements of vertical and longitudinal (in the driving direction) horizontal soil stresses ($\sigma_z$ and $\sigma_x$, respectively) beneath the centreline of the wheel track were made in minimally disturbed soil profile as described below (section 2.4.3.1). This was done for the two configurations with standard steering, $2+2\ L$ and $2+2\ H$ (Table 2). The measurements were first made for $2+2\ L$, and then on the same installation for $2+2\ H$. The sensors used were load cells (DS Europe and X-SENSORS, Series BC-302) embedded in cylindrical steel transducer housings 52 mm in diameter and 80 mm in height. The housings had a piston with a diameter of 20 mm that transmitted the load to the load cell inside. Please consult Lamandé et al. (2007) for a detailed description of the sensors. The data acquisition was similar to the measurements of contact stress: each load cell was connected to the data-logger, and measurements were made with a frequency of 1 kHz. The laser sensor connected to same data-logging system kept track of the exact position of the passing vehicle relative to the load cells.

2.4.3.1 Installation of the soil stress sensors

The installation of the sensors in the soil profile was done with minimal soil disturbance and followed a similar procedure as in Lamandé et al. (2007) and Lamandé and Schjønning (2011b). Pits were dug to a depth of 1.1 m, and horizontal holes were made for insertion of the transducer housings. A hydraulic jack was used to push a stainless steel soil corer (54 mm outer diameter, 50 mm inner diameter) into the soil at approximately 0.4 m depth. In each pit, two holes were made in each of which two sensors were installed at both sides of the aimed tyre centre: one hole for measurements of $\sigma_z$ [two pistons facing
upward], and one hole for measurements of $\sigma_x$ [two pistons facing forward in the driving direction]. The wedging system of the transducer housings was activated to ensure contact between the soil and the sensors (see Lamandé et al., 2007 for details). The actual depth of the sensors below the soil surface was measured when the sensors were taken out of the ground.

2.4.3.2 Calculations of the soil stresses

The $\sigma_z$-measurements showed a single peak very near to the centre of each axle, while the $\sigma_x$-measurements were characterised by two different peaks for each axle: a smaller forward and a larger rearward of the axles (Fig. 3). We derived the maximum $\sigma_z$ and the maximum forward and rearward $\sigma_x$ for each axle and each pass, and calculated the average for each peak ($N = 6$ per axle per configuration for $\sigma_z$, $N = 9$ per axle per configuration for $\sigma_x$). These average stresses were corrected as $\sigma = 1.07 * \sigma$ in order to account for an 7 % underestimation due to the difference in stiffness between the soil and transducer housing (Lamandé et al., 2015). Prior to these calculations, we subjected the (raw) data of $\sigma_x$ to the smooth spline function from the R (R Core Team, 2017) package Stats, version 3.4.3, with the smoothing parameter ‘spar’ set to 0.4 to reduce the noise. The data of $\sigma_z$ in block 1 were excluded because of a poor contact between the sensors and the soil. The same was the case for data of one of the sensors for $\sigma_x$ in block 3 that was not functioning properly.

Fig. 3. An example of vertical ($\sigma_z$, green) and longitudinal horizontal ($\sigma_x$, orange) stress measurements (left and right axes respectively) beneath the centreline of the wheel track. The vertical dashed lines indicate the positions of the four axles. The close-up on the right is of the trailer’s front axle.

2.6 Statistical analysis

An ANCOVA analysis was run in R (R core team, 2017) to determine the effect of the configurations on the drawbar pull, corrected for the effect of the slope of the field, during the first passes on each plot. A post-hoc pairwise comparison was performed with a Bonferroni adjustment. We used a similar analysis
to determine the effect of repeated wheeling on the drawbar pull, but considered only the configurations in offset steering mode with the high load where the tractor-trailer combination passed two, three, or six times (i.e., configurations $0+1 H_2$, $0+1 H_3$ and $0+1 H_6$).

We tested for differences in the characteristics of the area and stress distribution at the tyre-soil interface as affected by configurations, as well as differences between the contact areas forward and rearward of the tyres’ axles, using the non-parametric Kruskal-Wallis test. In cases of significant differences ($p$-value < 0.05), a post-hoc analysis was performed with the Conover-Iman test of the Conover.test R package (R core team, 2017) and the Bonferroni adjustment method.

We tested for differences in maximum soil stresses (vertical and horizontal) as well as for difference in the ratio of horizontal to vertical stress for each axle of the configurations $2+2 L$ and $2+2 H$ with the gls-function of the nlme-package, version 3.1–142 (R Core team, 2017). The configuration, repeated vehicle-passes (1–3), and their interaction were used as main effects. A correlation between numbers of wheeling in each block (1–12, four per pass) was included to account for the potential effect of repeated wheeling on the stress measurements.

### 3. Results and discussion

**Fig. 4.** The drawbar pull for first passes for each of the four configurations (standard and offset, low and high wheel load) in relation to the slope of the field between the axles of the trailer. Different letters at the end of each regression indicate significant differences in the drawbar pull between the configurations ($p$-value < 0.05).

#### 3.1 Drawbar pull as affected by topography, vehicle configuration, and repeated wheeling

The slope of the experimental area influenced the drawbar pull linearly for all four configurations of machinery included (**Fig. 4**, standard and offset steering mode, low and high wheel load). The regression slopes were parallel ($p$-value 0.462), indicating that the increase in drawbar pull with increasing slope was
similar for the different configurations of machinery. On average, the drawbar pull increased by 0.57 kN for each %-unit increase in slope.

The intercepts were significantly different for the two configurations with a low load as compared to high load (p-value < 0.001), but we found no effect of the steering mode for a given wheel load (p-value = 0.209 for low wheel load, and p-value = 0.902 for the high wheel load). The drawbar pull was significantly greater (about 2.7 kN) for the configurations with the high trailer wheel load (p-value < 0.001, means of 6.46 and 9.13 kN for the low and high wheel loads, respectively), and was independent of the effect of the slope and steering mode. It is generally well documented that wheel load has a large effect on the rolling resistance (e.g. Hetherington and Littleton, 1978; Taghavifar and Mardani, 2013), leading to a higher drawbar pull with increasing towed loads. Our results suggest that the soil deformation below the trailer tyres was as large on the untrafficked stubble as it was when passing in the wheel tracks from the tractor, and that the rolling resistance therefore resulted from the wheel load rather than the steering mode.

McBride et al. (2000) reported a drawbar pull of ~14 kN for a tractor pulling a ~24 Mg slurry spreader that was equipped with high flotation tyres at a high inflation pressure (238 kPa) on a tandem axle. The drawbar pull for the high load configurations in our study was lower (9 kN). This difference might reflect the effect of a tyre with a high inflation pressure on soil rolling resistance when driving on a wet soil. The measurements in the McBride et al. (2000) study were taken on a conventionally tilled silt loam soil with soybean residues with a degree of saturation of about 77 %.

The drawbar pull for the offset steering mode with the high wheel load slowly decreased with increasing number of wheeling (Fig. 5). A significant decrease was observed after the third and the sixth wheeling (~18 % and -29 % from the first wheeling, respectively). These results indicated that the rolling resistance decreased with the expected increase in soil density at the tyre-soil contact interface (i.e., the wheel rut) and are in line with those of Kurjenluoma et al. (2009), who reported a higher coefficient of rolling
resistance for firmer soils (based on a cone index at 0–0.15 m depth). The relatively small differences between each successive pass in drawbar pull could be explained by the relative modest soil deformation at the soil surface, as the wheel rut was fairly shallow: only 0.03–0.05 m in the plots where the vertical and horizontal soil stress measurements were taken following the measurements with four wheel passes in the same wheel track on an initially undisturbed soil surface.

The drawbar pull as affected by increasing number of passes, presented as means at a slope of 0.36 %-unit. The data included is limited to the configuration in the offset steering mode with high load and minimum two passes on the same plot (configurations 0+1 H, 0+1 H3 and 0+1 H6). Different letters indicate significant difference (p-value < 0.05)

3.2 Contact area and vertical stress distribution at the soil-tyre interface

3.2.1 Effect of traction

For the tractor front tyres, the measured contact area, \(A_{num}\), was significantly smaller (-14 %, p-value 0.0495) for 2+2 H than for 2+2 L (Table 3). A smaller contact area at a similar wheel load would lead to a higher mean ground pressure, \(p_{mean}\), yet \(F_{dynamic}\) was slightly lower for the tractor’s front tyre for 2+2 H than for 2+2 L, and cancelled out this effect on \(p_{mean}\). No significant differences of the characteristics of the contact area and the vertical stress distribution therein were found for the tractor’s front tyres for the two configurations (Table 3).

For the tractor’s rear tyres, the squareness of the contact area, \(n\), differed significantly between the two configurations (Table 3). For 2+2 L the contact area was in the shape of an ellipse \((n = 2.00)\), while it was more rectangular for 2+2 H \((n = 2.65; \text{Table 3})\) (Schjønning et al., 2015, 2006). This change of squareness of the tyre-soil contact was likely to be the main explanation for the significantly higher \(A_{num}\) for 2+2 H than for 2+2 L. Indeed, neither the half-length, \(a\), nor the half-width, \(b\), of the contact area differed significantly between the two configurations. Although tyres are expected to expand in the longitudinal direction, for example when subjected to a higher wheel load and/or lower tyre inflation pressures...
our measurements indicate that traction affects the squareness of the tyre-soil contact area.

For the tractor’s rear tyres, the larger $A_{num}$ for 2+2 H than for 2+2 L cancelled out an effect of the slightly (although not significant) larger $F_{dynamic}$ on $p_{mean}$ for the tractor’s rear tyres. The calculated contact area, $A_{ellip}$, was, as $A_{num}$, significantly larger for 2+2 H than for 2+2 L. The measured maximum vertical stress, $p_{peak}$, tended to be lower beneath the tractor’s rear tyre for 2+2 H (-19 %, 172 kPa compared to 213 kPa, Table 3; p-value 0.513 due to one low outlier for 2+2 L, Fig. S2), despite $F_{dynamic}$ being 16 % higher for 2+2 H than for 2+2 L (p-value 0.123). Differences in the model-fitted maximum vertical stress in the contact area, $p_{max}$, between the two configurations were not tested significant (p-value > 0.5).

The parameters describing the distribution of vertical stress at the tyre-soil interface for the tractor’s rear tyres differed significantly between the two configurations (Table 3): the shape parameter describing the ability of a tyre to distribute vertical stress in the longitudinal direction, $\alpha$, was significantly higher for 2+2 H, while the shape parameter describing the distribution of vertical stress in the lateral direction, $\beta$, was significantly lower for 2+2 H (p-value 0.0495). The stress distribution is more even for higher values of $\alpha$, which results in lower maximum stresses at the tyre-soil contact (Schjønning et al., 2008). Our results then clearly indicated an improvement in the distribution in the longitudinal direction with an increase in traction. Across the tyre, values of $\beta < 1$ reflect a stress distribution with a single-peak, while $\beta > 1$ reflect a double-peak distribution. Schjønning et al. (2008) showed that the optimum in terms of stress distribution occurs for $\beta \sim 1.9$. The average $\beta$ for 2+2 H ($\bar{\beta} = 1.31$) was closer to the optimum than the average $\beta$ for 2+2 L ($\bar{\beta} = 2.81$, Table 3). It is – though – not perfectly clear which configuration provided the best stress distribution.

A closer look at the replicate measurements for the rear tractor tyre indicated a consistent tyre performance across replicates for 2+2 L, while it was quite variable for 2+2 H. Fig. 6 shows the measured and FRIDA-fitted stress distribution for the replicates with the median $\beta$ estimate for each configuration.
The two additional replicates for both configurations can be found in the Supplementary materials, Fig. S2. Despite the statistically significant different δ-values for the configurations (Table 3), the appearance of peak stresses across the tyre is much more variable across replicates for 2+2 H than 2+2 L (Fig. 6 and Fig. S2). This may be interpreted as an effect of traction on the way the tyre ‘works’ during wheeling. For all replicate 2+2 H tests, the measurements indicate stress peaks located quite randomly across the tyre. This is in contrast to 2+2 L, where all three measurements display a clear double-peak stress distribution across the tyre for all three replicates (Fig. S2), the peaks are situated approximately at the same distance from the centre of the tyre. Our results thus show that high traction – at least for low-pressure tyres – probably induces a dynamic stress distribution that is difficult to describe with the FRIDA model.

The FRIDA-fitted stress distribution in Fig. 6 reflect the implicit assumption of symmetry in the longitudinal as well as in the lateral direction of the FRIDA model (Hallonborg, 1996; Schjønning et al., 2008). Yet further analysis of the measured data revealed that the assumption of symmetry in the longitudinal direction (forward and rearward of the axles) did not apply to the driven tractor tyres (Table 4, upper part). Both $A_{num}$ and $F_{dynamic}$ were significantly larger rearward of the axles (except for $F_{dynamic}$ for the tractor’s front axle, for which the p-value = 0.067). This means that for tyres with traction, the main part of the dynamic load is transferred to the soil in the rearward part of the tyre. Tyre deflection accounts for this, increasing the area of contact between the tyre rubber and the soil. In effect, $p_{mean}$ did not differ significantly between the first and second halves of the contact area of the driven tyres.

The relative distribution of $A_{num}$ and $F_{dynamic}$ in the contact area of the driven tyres differs from that of towed tyres, which is further discussed in section 3.2.2, and may be of critical importance in understanding the tyre-soil interaction of driven tyres. The net effect of traction on the contact area and the stress distribution therein is difficult to interpret, and more studies are needed. In our study, the tractor rear tyres of both the configurations had traction, and it is reasonable to anticipate that the
difference in the vertical stress distribution in the contact area is even larger for a given tyre with and without traction.

S2. Measured (left columns) and FRIDA-calculated (right columns) vertical stress distribution at the tyre-soil interface for the three replicate tractor rear tyre as affected by traction: 2+2 L (left) and 2+2 H (right). α, β = shape parameter describing the distribution of vertical stress in the tyre-soil contact area along the centreline of the tyre in the longitudinal and lateral direction, respectively. The replicates marked with * make Fig. 6 in the main text.

Fig. 6. Measured (A and B) and FRIDA-calculated (C and D) vertical stress distribution at the tyre-soil interface for the tractor’s rear tyre as affected by traction: 2+2 L (A and C) and 2+2 H (B and D). The plots show two individual tests selected as the ones with median β (shape parameter describing the distribution of vertical stress in the tyre-soil contact area along the centreline of the tyre in the lateral direction) within both configurations. Please find similar plots for the remaining replicate tests in the Supplementary materials.

Table 4. Characteristics of the contact area for the tyre segments, forward and rearward of the axle. Different letters indicate significant difference between the two segments of the tyre for the given configuration (p-value < 0.05).

3.2.2 Effect of repeated wheeling

We found no significant effect of repeated wheeling of a passive tyre on any of the characteristics of the contact area and the vertical stress distribution therein (Table 5), although consistent trends were found for increasing n (p-value 0.099), \( p_{\text{mean}} \) (p-value 0.066), and \( \beta \) (p-value 0.113) with an increasing number of wheeling.

Table 5. Characteristics of the contact area and the vertical stress distribution at the tyre-soil interface of the towed tyre, as affected by repeated wheeling.

The differences for \( p_{\text{mean}} \) and \( \beta \) were largest between \( 0+1 \ H_1 \) and \( 0+1 \ H_2 \), i.e., between the first and second wheeling of the towed trailer wheel. This could be explained by the fact that the first wheeling took place on the loose, rotavated soil surface, which was created as part of the installation procedure, while the repeated wheeling obviously occurred in a wheel track. Other studies have also observed that the first pass causes the largest near-surface deformation (Pytka, 2005) and creates a more rigid soil surface in the form of a wheel rut (Way et al., 1995). Lamandé et al. (2015) found a significant decrease of the thickness of a rotavated soil layer from the first to the second wheeling of a single, passive trailer wheel, while no differences were found afterwards for up to ten wheeling. The difference in the
looseness of the soil surface can lead to a reduction of the tyre-soil contact area and consequently alters the stress distributions at the surface and lead to higher, more concentrated stresses (Wiermann et al., 1999).

Still, the trends we observed were consistent throughout the three repeated wheeling events, but not significantly different (Table 5). This indicates that the rotovation did not affect our estimate of contact area on this soil. This might be explained by the interaction of ground- and tyre stiffness. In our field experiment, the ground stiffness was relatively high (reflected by the shallow wheel rut where soil stress measurements were made), while tyre stiffness was relatively low due to the low tyre inflation pressures. As a result of this interaction, deformation is expected to be larger for the tyre than for the soil. The opposite, i.e., deformation of the soil, is expected when tyre stiffness is higher than soil stiffness (Botta et al., 2009).

For the towed tyre, we noted a general trend of markedly higher $F_{\text{dynamic}}$ and $A_{\text{num}}$ forward than rearward of the tyre’s axle ($\sim$0.60 and $\sim$0.40, respectively, Table 4), yet significant difference was only found for $A_{\text{num}}$ for $0+1 H_3$. Though, $p_{\text{mean}}$ was significantly higher forward than rearward of the tyre’s axle for $0+1 H_1$.

We found no significant effect between the configurations on the characteristics of the contact area for the parts of the tyre forwards or rearwards of the axle (data not shown). The contrasting distribution of $F_{\text{dynamic}}$ and $A_{\text{num}}$ forward and rearward of the tyres’ axles for driven and towed tyres is remarkable: for the driven tyres the tyre segment behind the axle was larger and carried more of the wheel load, while the opposite was found for the towed tyres. This indicates a fundamentally different tyre-soil interaction for tyres with and without traction. Analyses of contact area data for towed tyres by Lamandé and Schjønning (2008) and Schjønning et al. (2008, 2006) did not reveal significant differences between forward and rearward sections, meaning that the assumed symmetrical super-ellipse model fitted their towed tyres well.
Differences in the tyre-soil interaction between tyres with and without traction have previously been documented, for example by Schjønning et al. (2015). The authors found a longer tyre contact area for tyres without traction and with a tyre volume similar to traction tyres, and they suggested that this resulted from construction differences in tyre width and aspect ratio – although the authors noted that their results might reflect other differences between the two types of tyre. Several studies have successfully fitted the FRIDA model to measured data (Lamandé and Schjønning, 2018, 2011b, 2008; Schjønning et al., 2015, 2008, 2006), but those studies only involved tyres being towed. Our results strongly call for further studies of the area and the stress distribution in the tyre-soil interface, especially for driven tyres, i.e., with traction.

3.3 Vertical and horizontal soil stresses in the upper subsoil

The maximum vertical and horizontal soil stresses measured in the upper subsoil, $\sigma_z$ and $\sigma_x$, respectively, are presented in Fig. 7. Note that $\sigma_x$ is the higher of the two peaks measured, i.e., the peak to the rear of the axles (Fig. 3). In our experiment, the sensors used for measuring $\sigma_x$ were all installed with the piston facing forward in the longitudinal direction, and the driving direction over the sensors was similar for each pass. We hypothesise that the stresses in front of the axle (data not presented) were underestimated as it was a measurement of the sensor pistons being pushed onto the soil in front of the sensor, while soil was pushing onto the pistons in the case of the rearward stresses.

In contrast to Pytka (2005) and Naderi-Boldaji et al. (2018), we found no significant effect of multiple machinery-passes on the soil stresses (data not shown). Pytka (2005) measured soil stress in six different directions (Nichols et al., 1987) in a disturbed soil profile, and explained the increase in soil stress by an increasing soil strength during the first passes. Naderi-Boldaji et al. (2018) measured mean normal soil stress using cylindrical Bolling probes (Berli et al., 2006; Bolling, 1987) drilled in an undisturbed soil profile, and found that the stress generally increased with increasing rut depth. Both authors made
measurements at several depths, and found the effect most pronounced at 0.15 m and decreasing with depth. In our case, we measured at approximately 0.4 m depth, and we cannot exclude an effect of repeated wheeling on soil stress higher up in the soil profile.

For both $\sigma_z$ and $\sigma_x$ we found no significant difference between the configurations 2+2 L and 2+2 H for the tractor’s axles, but significantly higher stresses for the trailer’s axles for 2+2 H compared to 2+2 L (Fig. 7).

This is in accordance with the fact that vertical soil stress at depth is known to correlate well with wheel load (e.g. Lamandé et al., 2007), which was similar for the driven tractor tyres in the two configurations, while the wheel load was substantially higher for the towed tyres of configuration 2+2 H than for 2+2 L (Table 1, $F_{\text{dynamic}}$ 23 % for the front tyres, and 41 % for the rear tyres).

According to the Boussinesq (1885) solution for stress propagation, $\sigma_x$ and $\sigma_z$ would both increase proportionally to the wheel load (e.g. Davis and Selvadurai, 1996). This is exactly what we see for the towed tyres (Fig. 8 A). We then interpret that this proportional increase reflects the soil intrinsic ability to transmit stresses through the soil profile. For driven tyres, the ratio of $\sigma_x$ to $\sigma_z$ will be influenced by the wheel load but also by the traction forces acting on the soil (e.g. Koolen and Kuipers, 1983). Assuming the same soil stress propagation factor for driven and towed tyres implies identical slope of the $\sigma_x=f(\sigma_z)$ – relation for towed and driven tyres. The intercept of $\sigma_x=f(\sigma_z)$ would then be proportional to the traction forces applied to the soil by the driven tyres, and would be expected to be higher for the driven than for towed tyres. This was clear for the tractor front tyres, yet not for the tractor rear tyres (Fig. 8 B).

On average, the ratio of $\sigma_x$ to $\sigma_z$ was 0.07 (0.05–0.12, data not shown), which is rather low in comparison to the factor of 0.5 that was suggested by Van den Akker (2004) in the SOCOMO model for estimating $\sigma_x$ from $\sigma_z$. SOCOMO then assumes a similar propagation of $\sigma_x$ through the soil profile as for $\sigma_z$, but our results indicate that the propagation of $\sigma_x$ may be different for driven and towed tyres. We encourage more experimental research on specifically the horizontal stress component, both near the surface as
well as deeper in the soil profile, to improve our understanding of the distribution and propagation of \( \sigma_x \) for both driven and towed tyres.

Fig. 7. Maximum vertical (\( \sigma_z \)) and (rearward) horizontal (\( \sigma_x \)) stress measured beneath the centreline of the wheel track (at \(-0.39\) m and \(-0.33\) m depth, respectively), presented as means and standard deviations. \( F_{dynamic} \) = calculated dynamic wheel load. Significant differences between the two configurations for each axle are indicated with different letters (ns \( p \)-value > 0.05, **\* \( p \)-value \( \leq 0.001 \)).

Fig. 8. Relation between vertical and horizontal stress, \( \sigma_z \) and \( \sigma_x \), for each axle and configuration for each wheeling (A), and as the means and standard deviation for each axle and configuration (B). The regression in A is based on the towed tyres and the dashed lines in B indicate the expected slope for the driven tyres (similar to the slope for the towed tyres). Significant differences between the ratio of \( \sigma_x \) to \( \sigma_z \) for the driven tyres are indicated with different letters (\( p \)-value < 0.05).

4. Conclusion

With this study, we aimed to disentangle and quantify the effect of driven and towed tyres on the vertical stress distribution at the contact area and on vertical and horizontal in the upper part of the subsoil.

Traction, in terms of drawbar pull, increased with weight of the towed trailer. The higher drawbar pull significantly increased the contact area of the rear tractor tyres as the shape of the tyre’s contact area was more square rather than elliptical, but not longer. The larger contact area levelled out a traction-induced increase in the dynamic load of the rear tractor tyres, maintaining the mean ground pressure. Moreover, increased traction tended to decrease measured peak and modelled vertical stress in the contact area for the tractor’s rear tyre. Measured and modelled vertical contact stress distribution reflected a more complex stress pattern with increased traction. High traction also gave rise to asymmetry in the contact area, which was significantly larger rearward of the tractor’s tyres axles. The effect of repeated wheeling of a towed tyre on the contact area characteristics appeared to be modest.

While we found a wheel load-induced increase of both vertical and horizontal soil stress, we suggest that the ratio of horizontal to vertical stress is influenced by traction for the driven tyres. Our results confirm the importance of considering dynamic aspects of field traffic such as traction and dynamic wheel load in addition to the effects of tyre inflation and wheel load.
References


Fig. 1. Left: In the offset steering mode, the axles of the trailer were shifted. The overlap between the right rear wheels of the tractor and trailer was approximately 0.28 m. Right: A drawbar was mounted between the tractor and the trailer for measurements of drawbar pull.
**Fig. 2.** Layout of the experimental field. The number in brackets indicates the number of configurations for the measurements (see Table 2). Plots marked NA are without experimental traffic and not part of this study. The three tractors drawn in Block 2 indicate the three positions on the plots for which the drawbar pull was calculated for each pass in relation to the slope of the field.
**Fig. 3.** An example of vertical ($\sigma_z$, green) and longitudinal horizontal ($\sigma_x$, orange) stress measurements (left and right axes respectively) beneath the centreline of the wheel track. The vertical dashed lines indicate the positions of the four axles. The close-up on the right is of the trailer’s front axle.
Fig. 4. The drawbar pull for first passes for each of the four configurations (standard and offset, low and high wheel load) in relation to the slope of the field between the axles of the trailer. Different letters at the end of each regression indicate significant differences in the drawbar pull between the configurations (p-value < 0.05).
Fig. 5. The drawbar pull as affected by increasing number of passes, presented as means at a slope of 0.36 \%-unit. The data included is limited to the configuration in the offset steering mode with high load and minimum two passes on the same plot (configurations $0+1 H_2$, $0+1 H_3$ and $0+1 H_6$). Different letters indicate significant difference (p-value < 0.05)
Fig. 6. Measured (A and B) and FRIDA-calculated (C and D) vertical stress distribution at the tyre-soil interface for the tractor’s rear tyre as affected by traction: 2+2 L (A and C) and 2+2 H (B and D). The plots show two individual tests selected as the ones with median $\beta$ (shape parameter describing the distribution of vertical stress in the tyre-soil contact area along the centreline of the tyre in the lateral direction) within both configurations. Please find similar plots for the remaining replicate tests in the Supplementary materials.
Fig. 7. Maximum vertical (\(\sigma_z\)) and (rearward) horizontal (\(\sigma_x\)) stress measured beneath the centreline of the wheel track (at ~0.39 m and ~0.33 m depth, respectively), presented as means and standard deviations. \(F_{\text{dynamic}}\) = calculated dynamic wheel load. Significant differences between the two configurations for each axle are indicated with different letters (ns p-value > 0.05, *** p-value ≤ 0.001).
Fig. 8. Relation between vertical and horizontal stress, $\sigma_z$ and $\sigma_x$, for each axle and configuration for each wheeling (A), and as the means and standard deviation for each axle and configuration (B). The regression in A is based on the towed tyres and the dashed lines in B indicate the expected slope for the driven tyres (similar to the slope for the towed tyres). Significant differences between the ratio of $\sigma_x$ to $\sigma_z$ for the driven tyres are indicated with different letters ($p$-value $< 0.05$.)
S1. Stress-strain curves of a first- and reloading of an unconfined compression test on 100-cm³ soil cores from which the Young’s Modulus (E) is calculated.
Measured (left columns) and FRIDA-calculated (right columns) vertical stress distribution at the tyre-soil interface for the three replicate tractor rear tyre as affected by traction: 2+2 L (left) and 2+2 H (right). \( \alpha, \beta \) = shape parameter describing the distribution of vertical stress in the tyre-soil contact area along the centreline of the tyre in the longitudinal and lateral direction, respectively. The replicates marked with * make Fig. 5 in the main text.
Table 1. Wheel loads and tyre inflation pressures applied.

<table>
<thead>
<tr>
<th></th>
<th>Tractor</th>
<th></th>
<th>Trailer</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Front</td>
<td>Rear</td>
<td>Front</td>
<td>Rear</td>
</tr>
<tr>
<td>L, low load</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$F_{\text{static}}$ Mg</td>
<td>2.0</td>
<td>3.6</td>
<td>4.6</td>
<td>4.1</td>
</tr>
<tr>
<td>$F_{\text{dynamic}}$ Mg</td>
<td>1.4</td>
<td>3.5</td>
<td>4.2</td>
<td>3.8</td>
</tr>
<tr>
<td>$p_{\text{tire}}$ kPa</td>
<td>60</td>
<td>60</td>
<td>90</td>
<td>90</td>
</tr>
<tr>
<td>H, high load</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$F_{\text{static}}$ Mg</td>
<td>2.0</td>
<td>3.6</td>
<td>6.0</td>
<td>6.0</td>
</tr>
<tr>
<td>$F_{\text{dynamic}}$ Mg</td>
<td>1.2</td>
<td>4.1</td>
<td>5.2</td>
<td>5.5</td>
</tr>
<tr>
<td>$p_{\text{tire}}$ kPa</td>
<td>60</td>
<td>60</td>
<td>140</td>
<td>140</td>
</tr>
</tbody>
</table>

$F_{\text{static}}$ = static wheel load. $F_{\text{dynamic}}$ = calculated dynamic wheel load. $p_{\text{tire}}$ = tyre inflation pressure.

Table 2. Specifications of the configurations of the tractor-trailer (top), and the measurements that were made for the different configurations (bottom).

<table>
<thead>
<tr>
<th>Configuration</th>
<th>2+2 L</th>
<th>2+2 H</th>
<th>2+0 L H</th>
<th>0+1 H 1</th>
<th>0+1 H 2</th>
<th>0+1 H 3</th>
<th>0+1 H 6</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
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</tr>
<tr>
<td>Steering mode</td>
<td>Standard</td>
<td>Offset</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$N$ tyres Tractor passing</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>0</td>
<td>0</td>
<td>0</td>
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<tr>
<td>0</td>
<td>2</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>6</td>
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<tr>
<td>Number of passes</td>
<td>3</td>
<td>3</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>2</td>
<td>3</td>
</tr>
<tr>
<td>Measurements of</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Drawbar pull</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
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<tr>
<td>Contact stress</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
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<tr>
<td>Soil stress</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
</tr>
</tbody>
</table>

*Only one pass for the measurements of drawbar pull and contact stress.*
Table 3. Characteristics of the contact area and the vertical stress distribution at the tyre-soil interface for the driven tyres, as affected by the level of drawbar pull. Different letters indicate significant difference between the two configurations for the given tyre (p-value < 0.05).

<table>
<thead>
<tr>
<th>Axle</th>
<th>Conf.</th>
<th>Contact area</th>
<th>Stress</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>$F_{\text{dynamic}}$</td>
<td>$A_{\text{num}}$</td>
</tr>
<tr>
<td></td>
<td></td>
<td>[Mg]</td>
<td>[m$^2$]</td>
</tr>
<tr>
<td>Tractor front</td>
<td>2+2 L$_1$</td>
<td>1.4 ± 0.2</td>
<td>0.32</td>
</tr>
<tr>
<td></td>
<td>2+2 H$_1$</td>
<td>1.2 ± 0.2</td>
<td>0.29</td>
</tr>
<tr>
<td></td>
<td>p-value</td>
<td>ns</td>
<td>ns</td>
</tr>
<tr>
<td>Tractor rear</td>
<td>2+2 L$_1$</td>
<td>3.5 ± 0.3</td>
<td>0.55</td>
</tr>
<tr>
<td></td>
<td>2+2 H$_1$</td>
<td>4.1 ± 0.6</td>
<td>0.53</td>
</tr>
</tbody>
</table>

$F_{\text{dynamic}}$ = mean and standard deviation of the calculated dynamic wheel load. $a$, $b$ = half-length and half-width of the contact area respectively. $n$ = squareness of the contact area. $A_{\text{num}}$ = measured contact area. $A_{\text{clip}}$ = calculated contact area. $\mu_{\text{mean}}$ = mean ground pressure. $\sigma_{\text{peak}}$ = corrected measured maximum vertical stress in the contact area. $\alpha$, $\beta$ = shape parameter describing the distribution of vertical stress in the tyre-soil contact area along the centreline of the tyre in the longitudinal and lateral direction, respectively. $p_{\text{max}}$ = model-fitted maximum vertical stress in the contact area. Significance: $ns$ $P > 0.05$, * $P \leq 0.05$.

Table 4. Characteristics of the contact area for the tyre segments, forward and rearward of the axle. Different letters indicate significant difference between the two segments of the tyre for the given configuration (p-value < 0.05).

<table>
<thead>
<tr>
<th>Axle</th>
<th>Conf.</th>
<th>Contact area</th>
<th>Stress</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>$F_{\text{dynamic}}$</td>
<td>$A_{\text{num}}$</td>
</tr>
<tr>
<td></td>
<td></td>
<td>[Mg]</td>
<td>[m$^2$]</td>
</tr>
<tr>
<td>Tractor front</td>
<td>2+2 L$_1$</td>
<td>0.41 b</td>
<td>0.59 a</td>
</tr>
<tr>
<td></td>
<td>2+2 H$_1$</td>
<td>0.45</td>
<td>0.55</td>
</tr>
<tr>
<td>Tractor rear</td>
<td>2+2 L$_1$</td>
<td>0.46 b</td>
<td>0.54 a</td>
</tr>
<tr>
<td></td>
<td>2+2 H$_1$</td>
<td>0.44 b</td>
<td>0.56 a</td>
</tr>
<tr>
<td>Trailer rear</td>
<td>0+1 H$_1$</td>
<td>0.61</td>
<td>0.40</td>
</tr>
<tr>
<td></td>
<td>0+1 H$_2$</td>
<td>0.59</td>
<td>0.40</td>
</tr>
<tr>
<td></td>
<td>0+1 H$_3$</td>
<td>0.58</td>
<td>0.42</td>
</tr>
</tbody>
</table>

$A_{\text{num}}$ = measured contact area. $F_{\text{dynamic}}$ = calculated dynamic wheel load. $\mu_{\text{mean}}$ = mean ground pressure. $\sigma_{\text{peak}}$ = characteristic for the segment (first and second half) of the tyre. Significance: $ns$ $P > 0.05$, * $P \leq 0.05$.

Table 5. Characteristics of the contact area and the vertical stress distribution at the tyre-soil interface of the towed tyre, as affected by repeated wheeling.

<table>
<thead>
<tr>
<th>Axle</th>
<th>Conf.</th>
<th>Contact area</th>
<th>Stress</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>$F_{\text{dynamic}}$</td>
<td>$A_{\text{num}}$</td>
</tr>
<tr>
<td></td>
<td></td>
<td>[Mg]</td>
<td>[m$^2$]</td>
</tr>
<tr>
<td>Trailer rear</td>
<td>0+1 H$_1$</td>
<td>5.3 ± 0.4</td>
<td>0.40</td>
</tr>
<tr>
<td></td>
<td>0+1 H$_2$</td>
<td>5.8 ± 0.5</td>
<td>0.39</td>
</tr>
<tr>
<td></td>
<td>0+1 H$_3$</td>
<td>5.7 ± 0.8</td>
<td>0.38</td>
</tr>
<tr>
<td>p-value</td>
<td>ns</td>
<td>ns</td>
<td>ns</td>
</tr>
</tbody>
</table>

$F_{\text{dynamic}}$ = mean and standard deviation of the calculated dynamic wheel load. $a$, $b$ = half-length and half-width of the contact area, respectively. $n$ = squareness of the contact area. $A_{\text{num}}$ = measured contact area. $A_{\text{clip}}$ = calculated contact area. $\mu_{\text{mean}}$ = mean ground pressure. $\sigma_{\text{peak}}$ = corrected measured maximum vertical stress in the contact area. $\alpha$, $\beta$ = shape parameter describing the distribution of vertical stress in the tyre-soil contact area along the centreline of the tyre in the longitudinal and lateral direction, respectively. $p_{\text{max}}$ = model-fitted maximum vertical stress in the contact area. Significance: $ns$ $P > 0.05$. 
Soil structure response to field traffic: effects of traction and repeated wheeling

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Soil structure response to field traffic: effects of traction and repeated wheeling

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Keywords Soil compaction; soil functions; driven and towed wheels; pore organisation; penetration resistance
Abstract

Soil compaction caused by the use of heavy agriculture machinery in non-optimal soil conditions hampers crucial soil functions. Tyre inflation pressure and wheel load are well-known key drivers of compaction. The effects of traction and repeated wheeling are, however, not yet fully understood but may be of critical importance. We aimed to quantify the effects of traction and repeated wheeling on some soil structural properties independently in a compaction experiment conducted on a sandy loam at a soil water content near field capacity, using a tractor-trailer combination. The trailer was used in ‘standard’ and ‘offset’ steering modes, the latter referring to the mode in which measurements could be taken for the pass of a single towed and thereby passive trailer wheel (with one, two, three and six wheel passes).

Penetration resistance was measured to 0.71 m depth and 100-cm³ soil cores were sampled around 0.16 m depth. In the offset steering mode, the measurements were made in the tractor tracks to investigate the effect of traction and in the trailer’s wheel track to investigate the effect of repeated wheeling (at 6.0 Mg static wheel load). The measurements were also collected for the standard steering configuration with the high towed load and from reference plots. Measurements on the soil cores comprised bulk density, porosity, and air permeability. We found a clear effect of traction on deformation of some soil structural properties, with no significant effects of the low drawbar pull but with substantial effects of the high drawbar pull. Reductions in air permeability and specific permeability were significant (89 % and 83 %, respectively) and indicated a densification and homogenisation of the soil. The effect of repeated wheeling was gradual, and reasonably well explained by a linear fit to the number of wheel passes. First six passes with the passive wheel caused some soil structural properties to differ significantly from the reference soil, and resulted in approximately similar levels of bulk density, porosity, air permeability and specific permeability as the tractor with high drawbar pull. Still, the deformation was stronger for the single pass of the tractor with the high drawbar pull than for six repeated wheeling of the passive trailer wheel. These results highlight the substantial effect of traction on soil compaction. Yet, the mechanisms
causing this deformation remain speculative until the propagation of horizontal stress through the soil profile is better understood.

Nomenclature

\( \varepsilon_{<30\mu m} \) Fraction of volume of small pores (< 30 \( \mu m \))

\( \varepsilon_{a\text{-blocked}} \) Fraction of blocked air-filled pore space

\( \varepsilon_{eff} \) Fraction of effective pore space

\( F_{\text{wheel}} \) Static wheel load

\( F_{\text{static}} \) Dynamic wheel load

\( k_{D\text{-Darcy}} \) Darcian air-permeability

\( PO \) Pore organisation

\( PR \) Penetration resistance

\( \rho_b \) Dry bulk density

\( \rho_{\text{steel}} \) Steel density

\( v_{\text{pyc}} \) Pycnometer volume of solids and water

\( v_{\text{sample}} \) Sample volume, inner volume cylinder sampling ring

\( w_{\text{ring}} \) Weight cylinder sampling ring
1. Introduction

The use of heavy machinery in agriculture in non-optimal, often too wet, soil conditions carries a considerable risk of soil compaction (Edwards et al., 2016; Schjønning et al., 2015). Compaction changes the soil pore system, which can severely restrict root growth as well as transport of water and gas through the soil profile. The resulting effects of soil compaction, such as yield reduction, soil erosion, and flooding have been reported globally (Hamza and Anderson, 2005). In other words, crucial soil functions are hampered by soil compaction.

Soil compaction is used as a general term to describe the combined effects of different soil deformation processes of which compression and distortion are the most generally observed (Van den Akker, 2008). During compression, the soil volume decreases and the size of soil pores is reduced, particularly arterial macropores and marginal pores (Schjønning et al., 2013). Distortion of the soil pores can lead to disconnection between pores. These two processes are driven by different stress states: pure compression happens when the normal stresses are of equal magnitude, whereas distortion happens when the three normal stresses differ in magnitude (Dawidowski et al., 1990; Koolen and Kuipers, 1983).

The soil stress state beneath a wheel is complex during wheeling, as is shown by studies that employed six-faced soil stress transducers that measure stress in six different directions (e.g. Bailey et al., 1996; Pytka, 2009, 2005; Pytka et al., 2006; Pytka and Konstankiewicz, 2002; Way et al., 1996). Way et al. (1996) indicated that the orientation of the major principal stress changed during wheeling. Way et al. (2005) used a strain transducer installed at about 0.2 m depth to capture the movement of soil particles beneath the centreline of a tyre. The authors found a compression in the vertical direction, an elongation in the direction across the tyre, and an initial compression followed by elongation and again compression in the driving direction. Besides the complexity beneath the centreline of the tyre, Berisso et al. (2013) found evidence that assuming a homogeneous wheeling effect on soil pore system across a tyre is too simple, even for a tyre without traction.
The risk of soil compaction can be reduced by the adjusting drivers of soil stress. Mean ground pressure and peak stress in the soil profile are decreased by lowering the tyre inflation pressure for a given tyre and load (Arvidsson and Keller, 2007; Bailey et al., 1996; van den Akker et al., 1994). Likewise, soil stress is lower for tyres that are designed to allow an expansion of the tyre-soil contact area, which generally also are tyres that allow for low tyre inflation pressures, regardless of the specific construction of a tyre (Ten Damme et al., 2020, 2019). The effect of a larger contact area at low inflation pressure becomes, however, more limited the deeper the stress propagates down the soil profile, because deeper in the soil profile stress is closely correlated with wheel load instead (Arvidsson and Keller, 2007; Lamandé and Schjønning, 2011; Smith and Dickson, 1990).

Despite the knowledge of these key drivers (tyre inflation pressure and wheel load) of the risk of soil compaction, Danish compaction trials (Pulido-Moncada et al., 2019; Schjønning et al., 2016) have revealed surprising results. In the Danish trials, a larger deformation in the subsoil was predicted with a 12-Mg wheel load than with a 6- and 8-Mg wheel load, where the 12-Mg wheel load was a self-propelled three-wheeler without repeated wheeling and the 6- and 8-Mg wheel load were a traditional tractor-slurry spreader, i.e., with repeated wheeling as it passed with several axles. Yet, penetration resistance in the upper subsoil significantly increased in the order 0-Mg (i.e., the reference), 12-Mg and 6-Mg wheel load. Also, cereal grain yield was significantly lowest for the 6-Mg wheel load, with no differences between the 0-Mg and 12-Mg wheel loads. (Schjønning et al., 2016). Pulido-Moncada et al. (2019) examined the structure of the subsoil (> 0.5 m depth) two years after these trials were stopped, and found significantly reduced subsoil structural quality beneath the 8-Mg wheel load, while no distinct signs of subsoil compaction were found for the 12-Mg wheel load. Although a difference in tyre inflation pressures between the configurations may have been a contributing factor, the results highlight the need for a better understanding of effects of traction (needed to pull a trailer across the field) and repeated wheeling (during a single pass of the traditional tractor-trailer combination) on soil deformation.
Few studies have focussed on the relative effects of traction and repeated wheeling on soil stress or soil structure. Pytka et al. (2006) measured higher stresses (measured in six directions) for higher levels of traction, yet differences were achieved by changing tyre inflation pressure of the driven tyre. Kirby (1989) showed, by model evaluation, that shear stress may be found at depths 1.5–2 times the tyre width in a profile of uniform strength. According to Koolen et al. (1992), the effect of traction vanishes rapidly with depth. More recently, Ten Damme et al. (under review) found that the tyre-soil contact area was larger for high compared to low traction at a given static wheel load. The distribution of vertical stress in the contact area also differed: in the driving direction the distribution was more even for the higher traction, but the effect of traction on the vertical stress distribution across the tyre was complicated and reflected a change of tyre behaviour at the tyre-soil interface (Ten Damme et al., under review).

What is more, many field-traffic studies are performed with machinery where multiple wheels pass in the same wheel track, i.e., with the rear passing in the front’s wheel track. The different interaction between the front and rear wheel with the soil is called the multi-pass effect (Battiato and Diserens, 2013). In effect, the effect of a single wheel pass remains unclear. Multiple wheeling generally leads to greater soil deformation. Olsen (1994) suggested that several short-term loadings could have a bigger impact on soil compaction than a relative long stress experience. Seehusen et al. (2019) highlighted that repeated wheeling with a small wheel load might indeed be more harmful than a single wheeling with a higher wheel load. Schjønning and Rasmussen (1994) found an increased penetration resistance and a decreased crop yield after four rather than a single pass of a dump-truck. Håkansson and Reeder (1994) and references therein reported that the first of multiple tractor-passes accounted for the majority of soil structural deformation (mainly in the form of increased dry bulk density). Tolon-Becerra et al. (2011) observed increased penetration resistance and dry bulk density, and a decrease in crop yield with increased number of tractor passes. Yet in these studies, the effects of traction and repeated wheeling were not separated due to the wheels being propelled and the multi-pass effect. Thus, no decisive conclusions on cause-effects for soil deformation can be drawn.
Processes leading to soil deformation are thus not fully understood. The aim of our study was therefore to test the effects of traction and of repeated wheeling on soil structure independently of each other. It was hypothesised that soil structural deformation would be larger at higher levels of traction, as the three principal normal stresses would have different magnitudes, and at an increased number of wheel passes.

2. Material and methods

2.1 Soil and experimental site

A field compaction experiment was performed using a tractor-trailer combination at Research Centre Foulum, Denmark (56°29"N, 9°34"E), in June 2018. The experimental site was part of an arable, sandy loam field with cereal stubble that was sown in spring 2017. The field is generally ploughed to ~0.22 m depth. The plough layer was characterized by 9.0 % clay (<2 µm), 24 % silt (2–63 µm), and 67 % sand (63–200 µm), according to Abdollahi et al. (2014), who had analysed a neighbouring field. At the time of the experiment, the soil matric potential at 0.15 m depth was slightly less negative than -100 hPa, which was impacted by irrigation a few days prior to the experiment. The volumetric water content at 0.15 m depth was 0.30 ± 0.02 cm$^3$ cm$^{-3}$, compared to 0.28 ± 0.02 cm$^3$ cm$^{-3}$ after equilibration to a matric potential of -100 hPa. Dry bulk density at 0.15 m depth was 1.47 ± 0.07 Mg m$^{-3}$. Experimental traffic followed by measurements of penetration resistance and soil core sampling were done in eight plots in three replicate blocks (Fig. 1).

Fig. 1. Layout of the experimental field. The grey area in the centre of each block was used for measurements of soil stress (Ten Damme et al., accepted). The configurations other than the reference are built-up as $x+yZ_N$, where $x =$ number of tractor wheels and $y =$ number of trailer wheels passing in the wheel track where measurements are collected, $Z =$ low (L) or high (H) load, and $N =$ number of passes. Further specification of the different configuration are given in Table 2.

2.2 The machinery
A 270 horsepower tractor with a total static weight of 11 Mg was used in combination with a two-axle transport trailer with a total weight of either 17 or 24 Mg. The wheel loads measured on a weighbridge \( F_{\text{static}} \) for the tractor and the trailer are presented in Table 1. For each wheel, we derived the dynamic wheel load \( F_{\text{dynamic}} \) by correcting the integral of the measured vertical contact stresses (Ten Damme et al., accepted) during wheeling with a factor of 0.82 to account for potentially inaccurate measurements due to differences in the stiffness of the stress sensors and the soil (Lamandé et al., 2015).

Both the tractor and trailer were equipped with wide, low-aspect ratio tyres: the tractor with 600/65R28 on the front and 650/75R38 on the rear, and the trailer with 710/50 R26.5 170D TL. All tyres were inflated to the pressures recommended by the tyre manufacturers for the specific wheel loads for a speed of up to 10 km h\(^{-1}\) (Table 1). To ensure full traction, the tractors standard 4WD with locked differential was activated. We aimed at a controlled driving speed of 0.83 ms\(^{-1}\) during wheeling using the GNSS (Global Navigation Satellite System) of the tractor.

Table 1. Tyre specification, static and dynamic wheel loads (Mg) and tyre inflation pressure (kPa) (Table is adapted from Ten Damme et al., accepted).

Fig. 2. Conceptual drawing of the tractor-trailer combination, explaining the two steering modes of the trailer: standard and offset on the top and bottom, respectively. The red points indicate where penetration resistance was measured and soil cores were sampled [for the configurations with experimental traffic]. Figure not to scale.

The trailer was towed in a standard and in an offset steering mode (Fig. 2). In the standard steering mode, the towed trailer wheels passed in the wheel track made by the tractor wheels. Activating the offset steering mode shifted the trailers front and rear axles 700 mm to the left and right, respectively, so that the centre of the trailer wheels was passing soil that had not been wheeled by another wheel (Fig. 2). There was, however, an overlap between the tractor and trailer wheel tracks. For the tractor and trailer rear wheels the overlap was 0.28 m.

A requirement for the hypothesis of this study to be tested was the use of different levels of traction, here described as drawbar pull. Drawbar pull was recorded at a frequency of 0.2 kHz by three load cells on three joints (lift arms and top linkage) mounted between the tractor and trailer. The total drawbar pull
was calculated as the sum of the three load cell measurements. The drawbar pull was significantly higher, about 2.7 kN, for the configurations with the high trailer wheel load as compared to the configurations with the low trailer wheel load (means of 9.1 kN and 6.5 kN, respectively), whereas we found no differences between the two steering modes (standard and offset) at a given (low or high) trailer wheel load (Ten Damme et al., accepted).

2.3 Vehicle configurations

The seven test configurations with experimental traffic (Table 2) and a reference, i.e., without experimental traffic, were randomised over the eight plots within each of the three blocks (Fig. 1). The labels for the different test configurations were made up of the number of tractor wheels + the number of towed trailer wheels impacting the same wheel track, with either the low (L) or high (H) load on the trailer, and with the number of passes (N) as subscript (Table 2). For example, 2+0 L$_1$ refers to the configuration where we focussed on the wheel track of the tractor alone, and where the towed trailer was thus in offset position with the low load with just a single pass, resulting in 2*1 wheels impacting the plot. The configuration 0+1 H$_3$ is then focussed on the wheel track made by the single trailer wheel (right rear wheel in offset position) with the high trailer wheel load and three repeated passes on the plot, i.e., one wheel passing the plots three times (1*3). The configurations with traffic are also part of Ten Damme et al. (accepted) who presented measurements of drawbar pull, contact area and vertical contact stress, and vertical and horizontal soil stresses for tractor-trailer combination.

Table 2. Specifications of the experimental traffic for each of the configurations.

2.4 Measurements and calculations

2.4.1 Penetration resistance

Penetration resistance (MPa), $PR$, was measured with a cone penetrometer with a cone-diameter of
20.27 mm (angle of cone 30°) designed and described by Olsen (1988), just after the experimental traffic.

The PR was automatically recorded at a 10-mm interval to a depth of 0.71 m, penetrating at a speed of 30 mm s\(^{-1}\). In each plot (configuration * block), 9–12 replicate recordings were taken. For each plot and each depth, the geometric mean of the replicate recordings was calculated. A PR of 2 MPa was used as an indication of severe compaction-effects (Bengough et al., 2011; Dexter, 1987).

2.4.2 Soil porosity and air permeability

In each plot, four minimally disturbed 100-cm\(^3\) soil samples in steel cylinders (60.5 mm inner diameter, 34.82 mm high, N = 12 per configuration) were taken for analysis of some soil structural properties with their upper surface at 0.15 m depth. In the following these are simply referred to as “the samples and some soil structural properties around 0.16 m depth”. In the plots with experimental traffic, the samples were taken below the centreline of the wheel tracks (as indicated by the red dots in Fig. 2). We measured porosity (m\(^3\) m\(^{-3}\), \(\varepsilon\)), air permeability (\(\mu m^2\)), \(k_a\), and soil water content (m\(^3\) m\(^{-3}\)) after equilibration to a matric potential of -100 hPa (where pores < 30 \(\mu m\) are not drained), and dry bulk density (Mg m\(^{-3}\)), \(\rho_b\).

The soil water content at -100 hPa matric potential equals the volume of small pores (< 30 \(\mu m\)), \(\varepsilon_{<30\mu m}\).

Equilibration of the soil samples was done by placing the cores on a sand table, slowly wetting them to saturation to remove entrapped air, and then draining them to -100 hPa.

The air pycnometer was used for estimating the effective porosity fraction, \(\varepsilon_{eff}\), i.e., the air-filled pores connected to a surface of the soil sample. The air pycnometer principle uses Boyle’s Ideal Gas Law, which states that pressure times volume is constant for a given mass of gas at a given temperature. The pycnometer measured volume (of solids, water, and blocked pores), \(v_{pyc}\), was converted to \(\varepsilon_{eff}\) for each soil core by accounting for the volume of the steel cylinder ring (with steel density, \(\rho_{steel}\), of 8.1 g cm\(^{-3}\) and the weight of the ring, \(w_{ring}\), and the volume of the soil sample, \(v_{sample}\) (Eq. 1):
\[ \varepsilon_{\text{eff}} = \frac{v_{\text{sample}} - (v_{\text{pyc}} - \omega_{\text{ring}}/\rho_{\text{steel}})}{v_{\text{sample}}} \quad \text{ (Eq. 1)} \]

Subtracting \( \varepsilon_{\text{eff}} \) from the balance-based air-filled porosity yielded the estimated blocked porosity, \( \varepsilon_{\text{a-blocked}} \), i.e., the estimated fraction of remote air-filled pores.

The Darcian air permeability, \( k_{\text{a-Darcy}} \), was measured by the Forchheimer approach as introduced and described by Schjønning and Koppelgaard (2017). In short, the volumetric airflow rate through the soil in the steel cylinder is recorded at four pressure differences: 5, 2, 1, and 0.5 hPa. The \( k_{\text{a-Darcy}} \) is then calculated based on the air flow at an infinitesimal pressure gradient. The \( k_{\text{a-Darcy}} \) in combination with \( \varepsilon_{\text{eff}} \) yields the specific permeability, which is a measure of pore geometry and labelled pore organisation, \( \text{PO} \) (Eq. 2), as suggested by Groenevelt et al. (1984).

\[ \text{PO} = \frac{k_{\text{a-Darcy}}}{\varepsilon_{\text{eff}}} \quad \text{ (Eq. 2)} \]

Prior to the permeability measurements, the soil around the inner edge of the steel cylinder was gently pressed with the rounded back of a peeling knife to minimise excessive air leakage.

2.5 Statistical analysis

The effect of the configurations on \( PR \) was tested for each cm-increment between 0.05–0.71 m depth. We used a linear mixed-effect model, the \textit{lme} function of the \textit{nlme}-package, version 3.1–142 (R Core Team, 2017), with configuration as fixed effect and plot (the interaction of configuration and block) within block as random effects. For significance, a multiple comparison (Tukey’s test) was carried out to determine the differences in the means of \( PR \) for the configurations at a given depth at the 5 % significance level. Additionally, we used the \textit{lme} function to test the fixed effects of configuration, depth, and the interaction of configuration and depth on \( PR \) in and around the depth of soil coring (0.15–0.19 m and 0.10–0.20 m). Plot was used as random effect, and the data was treated as repeated measurements with the autocorrelation structure \text{CorAR1} for depth within plot.
One of the 100-cm³ soil cores was excluded from the dataset due to a sampling error. Another soil sample was excluded due to an extraordinarily high porosity, which probably derived from a high root density in the core. These two soil samples, both from the Reference, were excluded in all analyses. For $k_{\text{a-Darcy}}$, one soil core from 0+1 H₁ was lost due to a technicality. Five other soil cores (one from 2+2 H₁, three from 2+0 H₁, and one from 0+1 H₃) were too loose to turn on their side which was needed for measurements in the pycnometer.

Negative values for $\varepsilon_{\text{a-blocked}}$ were set to 0.001 prior to statistical analysis. The $\varepsilon_{\text{a-blocked}}, k_{\text{a-Darcy}}$ and PO were log10-transformed to obtain normal distribution and homogeneous variance. The \textit{lme} function of the \texttt{nlme}-package, version 3.1–142 (R Core Team, 2017) was used to test for differences with configuration as a fixed effect and block as random effect. The same \textit{lme}-analysis was also performed on the Reference, 2+2 H₁, 2+0 L₁ and 2+0 H₁, but with drawbar pull added as a continuous variable. In case of significant difference (at the 5 \% significance level), we completed a pairwise comparisons with the \textit{lsmean}-function of the \texttt{lsmeans} package, version 2.30–0 (R Core team, 2017).

### 3. Results

#### 3.1 Penetration resistance

The PR was significantly higher for 2+2 H₁ than for the Reference at the 0.21–0.25 m depth and this trend is visible in Fig. 3 A for the entire upper part of the soil profile, down to 0.30 m depth. The PR for the Reference exceeded 2 MPa around 0.28 m depth, whereas it exceeded 2 MPa already around 0.23 m depth for 2+2 H₁.

Significant differences were also found for 2+0 H₁ in comparison with the Reference at 0.09–0.10 and 0.22–0.25 m depth (Fig. 3 B). For 2+0 H₁, PR exceeded 2 MPa around 0.23 m depth. The PR for 2+0 L₁ followed much closer the PR of the Reference, although no significant differences between 2+0 L₁ and 2+0 H₁ were found (p-value > 0.1).
Regarding the effect of repeated wheeling of the passive trailer rear wheel with the high load (Fig. 3 C),

The PR was distinctly higher for $0+1 \ H_2$, $0+1 \ H_3$ and $0+1 \ H_6$ (two, three, and six repeated wheel passes) than the Reference down to 0.25 m depth. The mean PR at 0.10–0.20 m depth actually increased linearly from zero to six wheeling (Fig. 4, Table 3). As a consequence, the threshold of 2 MPa was exceeded nearer the surface as the number of wheeling increased. The threshold was exceeded at 0.28 m depth for the Reference, at 0.26 m depth for $0+1 \ H_2$ and $0+1 \ H_3$ and around 0.23 m depth for $0+1 \ H_6$. The PR was significantly higher for $0+1 \ H_6$ than for $0+1 \ H_1$ at 0.19–0.24 m depth. Additionally, the PR at 0.19 m depth was significantly higher for $0+1 \ H_6$ than for $0+1 \ H_2$. No other significant differences were found (Suppl. 1).

Figure 3. Geometric means of penetration resistance, PR (MPa), measured after experimental traffic (9–12 replicate measurements in each plot). The error bars indicate one standard deviation. The blue strips highlight the depth where soil samples were taken for measurements of soil structural properties. Statistical analysis was done for each cm increment, and the depths where significant differences in penetration resistance between configurations (p-value < 0.05) are highlighted by the grey strips marked *. p-values are given in Suppl. 1.

Figure 4. The effect of repeated wheeling with the passive trailer rear wheel (dynamic wheel load, $F_{\text{dynamic}}$, 5.6 Mg) on penetration resistance, PR (MPa, presented as the mean over 0.10–0.20 m depth and one standard deviation).

Table 3. Summary of the linear regressions of the soil response to repeated wheeling with the passive trailer rear wheel ($F_{\text{dynamic}}$, 5.6 Mg) presented in Fig. 4 and Suppl. 2.

3.2 Soil porosity and air permeability

The quantified soil structural properties for $2+2 \ H_1$ did not differ significantly from the Reference (Fig. 4 A–F), but we found some noteworthy trends. The $\varepsilon_{<30\mu m}$ was higher for $2+2 \ H_1$ (0.30 m$^3$ m$^{-3}$) than for the Reference (0.28 m$^3$ m$^{-3}$) with a p-value of 0.052, and $\varepsilon_{a\text{-blocked}}$ was twice as high for $2+2 \ H_1$ (0.005 m$^3$ m$^{-3}$) than for the Reference (0.002 m$^3$ m$^{-3}$) but with a p-value of 0.246.

We found no significant difference between the Reference and $2+0 \ L_1$ for any of the quantified soil structural properties. Comparing the Reference with $2+0 \ H_1$, almost significantly higher $\rho_b$ and $\varepsilon_{<30\mu m}$
values were found for the latter (Fig. 5 A, B), with p-values of 0.085 and 0.067, respectively: $\rho_b$ increased from 1.47 to 1.55 Mg m$^{-3}$, and $\varepsilon_{<30\mu m}$ from 0.28 to 0.30 m$^3$ m$^{-3}$. The $\varepsilon_{a\text{-blocked}}$ was significantly higher, by more than three times, for 2+0 H$_1$ (0.008 m$^3$ m$^{-3}$) than for the Reference (0.002 m$^3$ m$^{-3}$, Fig. 5 D), while $\varepsilon_{\text{eff}}$, $k_a\text{-Darcy}$ and PO were significantly lower for 2+0 H$_1$ ($\varepsilon_{\text{eff}}$ 0.10 m$^3$ m$^{-3}$, $k_a\text{-Darcy}$ 1.35 and PO 13.9 $\mu$m$^2$) than for the Reference ($\varepsilon_{\text{eff}}$ 0.16 m$^3$ m$^{-3}$, $k_a\text{-Darcy}$ 12.9 $\mu$m$^2$ and PO 83.5 $\mu$m$^2$, Fig. 5 D-F). Comparing 2+0 L$_1$ with 2+0 H$_1$, $\varepsilon_{<30\mu m}$, and $\varepsilon_{a\text{-blocked}}$ were significantly higher for 2+0 H$_1$ (Fig. 5 B,D, $\varepsilon_{<30\mu m}$ 0.27 and 0.30 m$^3$ m$^{-3}$, $\varepsilon_{a\text{-blocked}}$ 0.002 and 0.008 m$^3$ m$^{-3}$), and $k_a\text{-Darcy}$ was significantly lower for 2+0 H$_1$ (Fig. 5 E, 8.2 and 1.35 $\mu$m$^2$).

No significant differences in $\rho_b$ and PO were measured between 2+0 L$_1$ and 2+0 H$_1$.

We found no significant differences between the Reference and 0+1 H$_1$, 0+1 H$_2$ and 0+1 H$_3$, but the effect of repeated wheeling of a passive wheel on several of the soil structural properties was apparent for 0+1 H$_6$ (Fig. 5 A–F). The $\rho_b$ was significantly higher for 0+1 H$_6$ (1.57 Mg m$^{-3}$) than for the Reference, 0+1 H$_1$, 0+1 H$_2$ and 0+1 H$_3$ (both 0.002 m$^3$ m$^{-3}$), but was was not significantly different from 0+1 H$_3$ (p-value 0.088) nor from the Reference (p-value 0.105). The $k_a\text{-Darcy}$ was significantly lower for 0+1 H$_6$ (2.9 $\mu$m$^2$) than for 0+1 H$_1$ and 0+1 H$_3$ (27.7 and 17.3 $\mu$m$^2$) while no significant difference from 0+1 H$_2$ (11.0 $\mu$m$^2$) was found (p-value 0.128). The $k_a\text{-Darcy}$ was almost significantly lower for 0+1 H$_6$ (2.9 $\mu$m$^2$) than the Reference (13.1 $\mu$m$^2$) with p-value 0.076. Finally, PO was significantly lower for 0+1 H$_6$ (29.8 $\mu$m$^2$) than for 0+1 H$_1$ (170 $\mu$m$^2$), whereas no other significant differences were observed. We found no significant effect of repeated wheeling of a passive wheel on $\varepsilon_{<30\mu m}$. The soil structural response had a reasonably good linearly fit to the increased number of wheeling passes (0–6) for $\rho_b$ (Suppl. 2), whereas the linear fit of $k_a\text{-Darcy}$ and PO to the increased number of passes was poor (Suppl. 2).

Fig. 5. B–F, Soil structural properties around 0.16 m depth, at -100 hPa matric potential, A–C: mean and one standard deviation, D–F: geometric mean. Different letters within each figure indicate significant difference (p-value < 0.05) between the configurations.
4. Discussion

4.1 Soil response to traffic using the standard steering mode

Based on measurements of drawbar pull and soil stress for the tractor-trailer combinations (Ten Damme et al., accepted), we had anticipated a high risk of soil deformation for 2+2 H₁. The drawbar pull of 2+2 H₁ was similar to that of 2+0 H₁, for which we did measure soil structural properties differing significantly from the Reference (see sections 3.2 and 4.3). What is more, both vertical and longitudinal (horizontal in the driving direction) soil stresses were highest for the trailer (Ten Damme et al., accepted). The 2+2 H₁ was thus a combination of two active wheels of the tractor with the high traction followed by two passive trailer wheels with a high wheel load and high soil stress. Based on this information, severe soil deformation was anticipated.

Yet the soil structural properties around 0.16 m depth for 2+2 H₁ did not differ significantly from the Reference. There was, however, a strong trend of a larger volume of small pores ($\varepsilon_{<30\mu m}$) (p-value 0.052) and a weak trend of greater blocked air-filled porosity ($\varepsilon_{p\text{-}\text{blocked}}$) for 2+2 H₁ (p-value 0.246). These results indicate that macropores might have been partially disrupted while more small pores and blocked air-filled pore space developed, without a change in bulk density ($\rho_b$). This distortion rather than compression indicates that the effect of shearing from horizontal stresses may have been larger than the effect of compaction from normal vertical stress. Such effects on the soil structure were also reported by Berisso et al. (2013) at the lateral edge of the wheel track. On the other hand, the lack of difference of PO between the Reference and 2+2 H₁ (p-value > 0.5) indicates that the pore size distribution and continuity have largely remained, as the pore space contributes proportionally to air permeability (Groenevelt et al., 1984).

The lack of significant effect of the standard configuration, 2+2 H₁, on the soil structural properties around 0.16 m depth may be related to natural variability of the field. Soil structural deformation for 2+2 H₁ may, however, have been more prominent at depths where the soil cores were not extracted.
Penetration resistance (PR) was significantly higher for 2+2 H₁ compared to the Reference in the soil layer just below the sampling layer (0.19–0.25 m depth, Fig. 3). Differences in the soil structural properties between the two configurations might then have been more apparent at this depth, compared with the depth of soil core sampling. It was also at these depths that PR for 2+2 H₁ exceeded 2 MPa. These are values that can seriously hamper root growth, sufficient to reduce root elongation by half of its unhampered rate (Bengough et al., 2011; Dexter, 1987). Differences in PR at greater depths are likely reflecting a natural dense cemented layer, that is present in the area generally between 0.6–1.4 m depth (Schjønning, 1992).

4.2 Soil response to driven wheels
The soil response to 2+0 H₁, the tractor with the highest drawbar pull, was substantial. We found strong trends and significant differences from the Reference across the spectrum of assessed the soil structural properties for this configuration. The PR did not detect these on soil core-measured deformations, although PR was clearly highest for 2+0 H₁ at the depth of soil sampling.

At -100 hPa matric potential, effective porosity ($\varepsilon_{\text{eff}}$) was reduced from 0.16 to 0.10 m$^3$ m$^{-3}$ and $\varepsilon_{\text{a-blocked}}$ increased from 0.002 to 0.008 m$^3$ m$^{-3}$ (for the Reference and 2+0 H₁, respectively). The level of Darcian air permeability ($k_{\text{Darcy}}$) decreased from 12.9 to 1.4 µm$^2$, which is close to the limit of 1 µm$^2$ suggested by Ball et al. (1988) for impermeable soil and means that transport of water and air is greatly restricted. At the same time, the significant reduction in pore organisation (PO) from 83.5 µm$^2$ for the Reference to 13.9 µm$^2$ for 2+0 H₁, indicates that the soil pore characteristics other than $\varepsilon_{\text{eff}}$ govern the observed differences in $k_{\text{Darcy}}$ and that soil was densified and homogenised by 2+0 H₁ (Groenevelt et al., 1984; Pulido-Moncada et al., 2020; Schjønning and Thomsen, 2013). Both $\rho_b$ and the $\varepsilon_{<30\mu m}$ tended to be higher for 2+0 H₁ than for the Reference, and although the results were not significant, they indicate even more clearly than for 2+2 H₁ (as discussed in section 4.2) that shearing may have been the prominent process.
of soil deformation. As also concluded by Horn et al. (2003), measurements of \( \rho_b \) alone will not capture the sum of compression and shearing.

On the other hand, we found no significant differences between the Reference and 2+0 L\(_1\) or strong trends in the soil response. Significant differences between the two configurations with traffic, 2+0 L\(_1\) and 2+0 H\(_1\), were limited to \( \varepsilon_{<30\mu m}, \varepsilon_{\text{a-blocked}}, \) and \( k_a\text{-Darcy}. \) Considering that the set-up of the tractor was similar in these two configurations (same tyres, static wheel load, inflation pressure), these results indicate a gradual effect of traction on soil deformation, with the additional drawbar pull leading to the soil deformation for 2+0 H\(_1\). These results imply that traction influences the stress-state beneath a tyre, and strengthens the hypothesis that traction may be another key driver of soil structure deformation. In fact, an additional analysis with drawbar pull as an extra, continuous, variable revealed that traction explained the differences observed between the Reference and 2+0 H\(_1\) (p-value < 0.05, data not shown).

Ten Damme et al. (accepted) reported that an increase in drawbar pull caused a redistribution of the tractor’s load from the front to the rear axle. The effect of the increased wheel load on mean ground pressure and in the contact area was compensated by an increase in the tyre-soil contact area. Moreover, an increase in drawbar pull evened out the distribution of vertical contact stresses beneath the tractor rear wheel, which cancelled out the effect of the higher wheel load on maximum vertical stress in the contact area. Therefore, the smaller soil deformation at 0.16 m depth for 2+0 L\(_1\) as compared to 2+0 H\(_1\) (Fig. 5) could have resulted from lower horizontal stresses.

Yet, Ten Damme et al. (accepted) found no significant effect of traction on horizontal stresses (at 0.33 m depth). The different results between soil response at 0.16 m depth (effect of traction) and stress measurements at 0.33 m depth (no effect of traction) highlight that the propagation of horizontal stress through the soil profile still is poorly understood. Horizontal stress from wheels with traction might have quickly vanished with increasing depth (Koolen et al., 1992). A model evaluation by Kirby (1989) showed that shear damage may be found at depths of 1.5–2 times the tyre width in a profile of uniform strength,
but can be reduced or even eliminated by lowering the tyre pressure. In SOCOMO (Van den Akker, 2004),
one of the existing models that calculate the risk of soil compaction by comparing soil strength and
applied stress, a coefficient factor of 0.5 is used for estimating horizontal load at the soil surface from
vertical load at the soil surface, based on Tschebotarioff (1951). However, De Pue et al. (2020) highlight
how currently used models underestimate or neglect the effect of traction. We urgently recommend
more experimental studies to capture the stress distributions beneath wheels broadly, as it is of critical
importance for an understanding of how soil deforms in order to potentially mitigate the effects of traffic
on soil compaction.

4.3 Soil response to repeated wheeling of a towed tyre
Håkansson and Reeder (1994) and references therein reported a linear response of soil structural
properties to the logarithm of the number of wheel passes. The first of multiple passes then accounts for
the majority of soil structural deformation (in those studies, mainly in the form of increased $\rho_b$). In our
experiment, soil deformation increased, but did not consistently increase or reduce the soil structural
properties. In fact, the impact was very little within the first three passes ($0+1H_1$, $0+1H_2$ and $0+1H_3$),
and the only significant differences from the Reference after six passes ($0+1H_6$) were for $PR$ at 0.19–0.24
m depth (Fig. 3), and for $\rho_b$ and $\varepsilon_{\text{eff}}$ at 0.16 m depth (Fig. 5 A and C). The effect of repeated wheeling on
the different soil structural properties was however reasonably well described by a linear function (Suppl.
2, Table 3), although the fit was clearly better for $PR$ and $\rho_b$ compared to $k_a$-Darcy and $PO$.

The fact that no significant differences were measured between the Reference and $0+1H_6$ for $k_a$-Darcy or
$PO$ indicates that a change of $\rho_b$ does not always reflect soil structural changes caused by traffic. On the
other hand, the increase in $\rho_b$ may impact soil functions, as for example crop yield. The degree of
compaction was calculated based on Håkansson (1990), with the reference bulk density (1.67 Mg m$^{-3}$)
calculated from Eq. 12 in Keller and Håkansson (2010). For $0+1H_6$ the degree of compactness had
increased from 88 % for the Reference to 94 %, where a range of 84–87 % is considered optimal for many
The consequences of such an increase will vary between different crops. Håkansson (2005) documented that a degree of compaction of 94 % resulted in a yield reduction of > 5 % for autumn sown wheat or rye in ~75 % of trials, for spring sown barley in ~60 % of trials and for autumn sown rape in ~90% of the trials included in his study. The fact that the increases of $PR$ and $\rho_b$ were linear indicate that limiting the number of passes can protect the soil structure from compaction.

We tested the soil response for a logarithmic fit of the number of wheel passes, but this relation was poorer ($R^2 = 0.57$ for $PR$, $R^2 < 0.1$ for $\rho_b$ and $PO$, data not shown). The different fits, linear versus logarithmic, might relate to the soil conditions prior to the first wheeling: the logarithmic fit is generally reported in studies with traffic on loosened soil (Håkansson and Reeder, 1994, and references therein), whereas in our study, traffic took place on roughly 10-month-old stubble without further disturbance of the soil structure. A loose soil generally has a low strength, and this soil then compresses most during the first wheeling(s). Such results were supported by a laboratory-study by Peth and Horn (2006), who subjected homogenised soil samples to repeated loading with an oedometer, and also found that the resulting compression was well described by a logarithmic function. This gradual deformation is a process of cyclic creep and can be expected to go on until the soil is fully consolidated (Peth and Horn, 2006).

Another explanation for the different response of loosened and undisturbed soil to repeated wheeling was suggested by Fu et al. (2019). The authors found contrasting results at the different depths where a reduction in total soil porosity was measured over five consecutive passes (dragging a steel roller) over a soil tilled to ~0.15 m depth. In their study, the first of five passes contributed 59 % of the total reduction of total soil porosity, with the second and third passes accounting for 21 % and 20 % of the total reduction, respectively, at 0.03 m depth. At 0.13 m depth, however, the first pass accounted for only 33 % of the total reduction of total soil porosity, whereas the second and third passes accounted for 38 % and 34 %. The authors hypothesised that the effect of repeated wheeling on soil structural deformation
might be different in different soil layers, just like the risk of soil compaction is driven by different machinery characteristics, namely ground pressure and wheel load, respectively.

The fact that we see no significant negative effect of the first three repeated wheeling of the passive trailer rear wheel with the high wheel load, even though stress measurements for the tractor-trailer combinations used in our experiment showed that both vertical and horizontal stresses were largest for the trailer rear wheels \((215 \pm 22 \text{ kPa and } 17 \pm 2 \text{ kPa}, \text{Ten Damme et al., accepted})\) may be explained by the Coulomb law (1776). This law states that whether or not soil stress leads to failure depends on the ratio between normal and shear stresses. In this case, the soil might have been able to resist the horizontal stresses due to the (higher) level of vertical stress. Additionally, the stress measurements in Ten Damme et al. (accepted) were performed 0.2 m below the depth of soil coring, and the stresses are expected to be larger closer to the soil surface.

Surprisingly, we found significant differences between \(O+1 H_1\) and \(O+1 H_6\) for \(\varepsilon_{a-blocked}, k_{a-Darcy},\) and \(PO\) where we did not find differences between the Reference and \(O+1 H_6\) (Fig. 5 and Suppl. 2). These results may partly relate to variability of the field that we could not escape despite randomising the treatments. Although we expected a densification and strengthening of the topsoil, these results indicate that the first, single wheel pass of the passive trailer might have actually disrupted the soil structure. It is generally considered that the only force exerted by passive (towed) pneumatic tyres come from (dynamic) wheel load. The contact area below driven wheels, on the other hand, is also subjected to shear and vibration forces (Soane et al., 1981). However, vibration can also originate from shock effects due to an uneven surface (Soane et al., 1981), which might explain the deviating results for configuration \(O+1 H_5\), where the passive trailer rear wheel passed untrafficked, stubble soil.
4.4 Traction and repeated wheeling: perspectives

In sections 4.2 and 4.3 we discussed how soil deformation worsened both with increasing traction and with an increasing number of passes of a passive wheel. Between the extremes in both cases, i.e., $2+0 H_1$ and $0+1 H_6$, we found no significant differences in PR, nor in the soil structural properties around 0.16 m depth. The lack of differences between these extreme configurations indicates that it is important to both limit the level of traction and to limit the number of repeated wheeling, to reduce the risk of soil compaction. Yet, as described in section 3.2, we found no significant differences between $0+1 H_6$ and the Reference for $k_a$-Darcy and PO, whereas these soil structural characteristics were significantly lower for $2+0 H_1$ than for the Reference. This indicates a stronger reduction of $k_a$ and higher densification of the soil of the soil subjected to the two tractor wheels (front and rear) with a $F_{\text{dynamic}}$ of 5.3 Mg (front + rear), compared to six passes of the trailer wheel with a $F_{\text{dynamic}}$ of 5.5 Mg (total 33 Mg).

5. Conclusion

We investigated the effect of traction (two active tyres) and repeated wheeling (with a single passive tyre) on soil structural properties around 0.16 m depth and penetration resistance to 0.71 m depth independently. We found that soil structural deformation increased with higher drawbar pull, and increased with increasing number of wheel passes. Although the overall effect of repeated wheeling was reasonably well explained by linear fits, the deformation was not stepwise. First six repeated passes of the passive trailer wheel were needed to induce approximately similar levels of structural properties as the configuration with the high drawbar pull. These results highlight the substantial effect of traction on soil compaction, yet the underlying mechanisms remain speculative until the propagation of horizontal stress through the soil profile is better understood.
6. References


Naderi-boldaji, M., Keller, T., 2016. Degree of soil compactness is highly correlated with the soil physical quality index S. Soil Tillage Res. 159, 41–46. https://doi.org/10.1016/j.still.2016.01.010


ten Damme, L., Schjønning, P., Munkholm, L.J., Green, O., Nielsen, S.K., Lamandé, M., n.d. Traction and repeated wheeling – effects on contact area characteristics and stresses in the upper subsoil. Accepted, STILL-S-20-01565. Soil Tillage Res.


Fig. 1. Layout of the experimental field. The grey area in the centre of each block was used for measurements of soil stress (Ten Damme et al., accepted). The configurations other than the reference are built-up as \(x+y ZN\), where \(x\) = number of tractor wheels and \(y\) = number of trailer wheels passing in the wheel track where measurements are collected, \(Z\) = low (L) or high (H) load, and \(N\) = number of passes. Further specification of the different configuration are given in Table 2.
Fig. 2. Conceptual drawing of the tractor-trailer combination, explaining the two steering modes of the trailer: standard and offset on the top and bottom, respectively. The red points indicate where penetration resistance was measured and soil cores were sampled [for the configurations with experimental traffic]. Figure not to scale.
Figure 3. Geometric means of penetration resistance (MPa) measured after experimental traffic (9–12 replicate measurements in each plot). The error bars indicate one standard deviation. The blue strips highlight the depth where soil samples were taken for measurements of soil structural properties. Statistical analysis was done for each cm increment, and the depths where significant differences in penetration resistance between configurations (p-value < 0.05) are highlighted by the grey strips marked *. p-values are given in Suppl. 1.
Figure 4. The effect of repeated wheeling with the passive trailer wheel ($F_{dynamic} = 5.6$ Mg) on penetration resistance (presented as the mean over 0.10–0.20 m depth and one standard deviation).

\begin{align*}
y &= 1.16 + 0.0897 \times x \\
R^2 &= 0.80
\end{align*}
Fig. 5. B–F. Soil structural properties around 0.16 m depth, at -100 hPa matric potential. A–C: mean and one standard deviation, D–F: geometric mean. Different letters within each figure indicate significant difference (p-value < 0.05) between the configurations.
Table 1. Tyre specification, static and dynamic wheel loads (Mg) and tyre inflation pressure (kPa) (Table is adapted from Ten Damme et al., accepted).

| Specification | Tractor | | | | | Trailer | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 600/65R28 | 650/75R38 | 710/50 R26.5 | 170D TL | 710/50 R26.5 | 170D TL |
| øtyre | m | 1.490 | 1.935 | 1.380 | 1.380 |
| Wtyre | m | 0.595 | 0.695 | 0.726 | 0.726 |
| SLR | m | 0.670 | 0.890 | 0.594 | 0.594 |
| L, low load | | | | | | | | | | |
| Fstatic | Mg | 2.0 | 3.6 | 4.6 | 4.1 |
| Fdynamic | Mg | 1.4 | 3.5 | 4.2 | 3.8 |
| Ptyre | kPa | 60 | 60 | 90 | 90 |
| H, high load | | | | | | | | | | |
| Fstatic | Mg | 2.0 | 3.6 | 6.0 | 6.0 |
| Fdynamic | Mg | 1.2 | 4.1 | 5.2 | 5.5 |
| Ptyre | kPa | 60 | 60 | 140 | 140 |

øtyre = tyre diameter; Wtyre = nominal width section of the tyre; SLR = Static Loaded Radius; Fstatic = static wheel load. Fdynamic = dynamic wheel load. Ptyre = tyre inflation pressure.
Table 2. Specifications of the experimental traffic for each of the configurations.

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<tr>
<th>Configurations</th>
<th>Reference</th>
<th>2+2 H J</th>
<th>2+0 L J</th>
<th>2+0 H J</th>
<th>0+1 H J</th>
<th>0+1 H J</th>
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<th>0+1 H J</th>
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<td>1</td>
<td>2</td>
<td>3</td>
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<td>$F_{\text{dynamic}}$ [Mg]</td>
<td>Tractor</td>
<td>1.2+4.1</td>
<td>1.4+3.5</td>
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<td>Traction</td>
<td>Repeated passive wheeling</td>
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</table>

* The number of wheels passing in the wheel track where the measurements were collected; $F_{\text{dynamic}}$ = dynamic wheel load (Table 1) of the wheels that passed the wheel track where measurements were collected (as indicated by the red dots in Fig. 2). All configurations with the tractor-trailer are also included in Ten Damme et al., accepted.
Table 3. Summary of the linear regressions of the soil response to repeated wheeling with the passive trailer wheel ($F_{\text{dynamic}}, \text{5.6 Mg}$) presented in Fig. 4 and Suppl. 2.

<table>
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<tr>
<th>Response</th>
<th>Intercept</th>
<th>Slope</th>
<th>Determination coefficient, $R^2$</th>
<th>p-value</th>
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<tr>
<td>$PR$ [Mpa]</td>
<td>1.16</td>
<td>0.090</td>
<td>0.80</td>
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<td>$\rho_b$ [Mg m$^{-3}$]</td>
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<td>$k_{a-Darcy}$ [$\mu$m$^2$]</td>
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<td>$PO$ [$\mu$m$^2$]</td>
<td>125</td>
<td>-14.5</td>
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<td>0.026</td>
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</table>

$PR = \text{penetration resistance, mean 0.10–0.20 m depth; } \rho_b = \text{dry bulk density; } k_{a-Darcy} = \text{Darcian air permeability; } PO = \text{pore organisation. } \rho_b, k_{a-Darcy}$ and $PO$ around 0.16 m depth at -100 hPa matric potential.
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<th>2+0 H₁</th>
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**Suppl. 1** Results of the multiple comparison on penetration resistance, *PR*, per cm depth increment from 0.05–0.71 m depth. Different letters apply to a single depth, and indicate significant differences between the configurations at that depth (p-value < 0.05).
Suppl. 2 The effect of repeated wheeling with the passive trailer wheel ($F_{\text{dynamic}} = 5.6$ Mg) on (A) dry bulk density ($\rho_b$), (B) Darcian air permeability ($k_{\text{Darcy}}$) and (C) pore organisation (PO) around 0.16 m depth, at -100 hPa matric potential. Data is presented as mean and one standard deviation. Different letters indicate significant differences between the configurations (p-value < 0.05). The regression coefficients are also presented in Table 3 in the main text.