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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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Table 1
The specifications of the front and rear tyres as included in the in-situ measurements of mean normal soil stress, and FRIDA calculated parameters of tyre-soil contact stress.

	Hypothesis	*Treatment*	*Name*	*Dimension*	F_{wheel} *Mg*	P_{tyre} *kPa*	*A* m^2	*MGP* *kPa*
Front	1: Construction	$Axio_{80}$*	AxioBib	600/70 R30, IF	2.9	80	0.44	64
		$Cerex_{80}$	CerexBib	620/70 R30, IF, CFO			–#	–#
		Evo_{80}	EvoBib	600/70 R30, VF			0.41	69
	2: Inflation pressure	Evo_{80}	EvoBib	600/70 R30, VF	2.9	80	0.41	69
		Evo_{60}*				60	0.47	61
		Evo_{40}				40	0.58	49
	3: Tractive potential	Evo_{60RL}	EvoBib	600/70 R30, VF	2.3	60	0.45	51
		$Axio_{80}$*	AxioBib	600/70 R30, IF	2.9	80	0.44	64
Rear	1: Construction	$Axio_{80}$*	AxioBib	710/70 R42, IF	4.3	80	0.54	78
		$Cerex_{80}$	CerexBib	710/70 R42, IF, CFO			–#	–#
		Evo_{80}	EvoBib	710/70 R42, VF			0.56	75
	2: Inflation pressure	Evo_{80}	EvoBib	710/70 R42, VF	4.3	80	0.56	75
		Evo_{60}*				60	0.64	66
		Evo_{40}				40	0.79	53
	3: Tractive potential	Evo_{60RL}	EvoBib	710/70 R42, VF	3.5	60	0.52	66
		$Axio_{80}$*	AxioBib	710/70 R42, IF	4.3	80	0.54	78

IF, increased flexion; CFO, Cyclical Field Operation; VF, Very High Flexion; F_{wheel}, wheel load; P_{tyre}, tyre inflation pressure; *A*, calculated tyre-soil contact area; *MGP*, calculated mean ground pressure.

* 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.

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 tractive 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 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 $Axio_{80}$ (Michelin, 2018) with a 20 % load reduction and 25 % inflation pressure reduction (Table 1).

Throughout this text and in the tables, the treatments are referred to by a part of the tyre name and the inflation pressure. For example, $Axio_{80}$ refers to *AxioBib* at an inflation pressure of 80 kPa. The *RL* in Evo_{60RL} stands for reduced load. When talking about the tyres regardless of their inflation pressure or load, their full name is used. The treatments $Axio_{80}$ and Evo_{60} were included in the work presented by Ten Damme et al. (2019), as *AxioBib* and *EvoBib* respectively.

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 $Axio_{80}$, and N = 9 for each probe position for $Cerex_{80}$ and Evo_{80}. Different letters behind the value indicate significant differences between the tyres at a given probe position at a significance level of 2.5 %.

Tyre		*Probe position (placement and depth)*					
		Centre			*+0.3 m*		
Axle	Treatment	*0.2 m*	*0.4 m*	*0.6 m*	*0.2 m*	*0.4 m*	*0.6 m*
Front	$Axio_{80}$*	82	46	16	40	37	10
	$Cerex_{80}$	98	50	17	35	36	11
	Evo_{80}	99	48	17	45	42	12
	p-value	0.668	0.779	0.981	0.138	0.668	0.666
Rear	$Axio_{80}$*	87	55	21	46 a	45	14
	$Cerex_{80}$	96	60	22	58 b	52	17
	Evo_{80}	92	58	21	55 b	49	15
	p-value	0.585	0.967	0.911	0.024	0.351	0.569

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

2.2. In-situ measurements of mean normal stress

The experimental field was divided into four blocks (replicates) where measurements of mean normal stress were made using fluid inclusion probes (Berli et al., 2006; Bolling, 1987). Six probes were installed per block to measure stress at six positions simultaneously: below the centreline and at 0.3 m lateral distance from the centreline (hereafter centre and +0.3 m) at 0.2, 0.4 and 0.6 m depth. For details on the installation of the probes and on the measurements, we refer to Ten Damme et al. (2019). We randomised two to three passes of the treatments in each block – the total number of measurements in the analysis is included with the Tables 2 and 3 and in Fig. 1. During the tests, no extra pulling force was added. The aimed driving speed during the measurements was 0.83 m s^{-1}.

2.3. Calculations of mean normal stress

The mean normal stress for each of the six probe positions was derived from the maximum measured inclusion pressure, $P_{i\text{-}max}$, and a proportionality coefficient, k_s, [Eq (1) — a method adapted from Berli et al. (2006) and Naderi-Boldaji et al. (2018)]. The proportionality coefficient is an empirical factor introduced by Bolling (1987) and primarily a function of Poisson's ratio, ν. The Poisson's ratio was derived from confined and unconfined compression tests of 100-cm^3 soil samples that were sampled from control areas (undisturbed) in each block of the experimental field. Details on the soil sampling and laboratory measurements are described in Ten Damme et al. (2019).

$$\sigma_m = P_{i-max} k_s \approx P_{i-max} \frac{1+\nu}{3(1-\nu)} \quad (1)$$

2.4. Statistics

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 of 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 $\lambda/2$, with $\lambda = 0.05$.

Table 3
Median of maximum measured mean normal stress (kPa) for the tyres used to test for the effect of the weight-pull ratio. N = 12 for each probe position for $Axio_{80}$ and N = 9 for each probe position for Evo_{60RL}. P-values provided tested for differences at a significance level of 2.5 %.

Tyre		*Probe position (placement and depth)*					
		Centre			*+0.3 m*		
Axle	Treatment	*0.2 m*	*0.4 m*	*0.6 m*	*0.2 m*	*0.4 m*	*0.6 m*
Front	$Axio_{80}$ *	82	46	16	40	37	10
	Evo_{60RL}	79	40	14	40	35	10
	p-value	0.564	0.248	0.149	0.387	1	1
Rear	$Axio_{80}$ *	87	55	21	46	45	14
	Evo_{60RL}	78	49	18	46	41	12
	p-value	0.191	0.149	0.248	0.564	0.885	1

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

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 $Axio_{80}$ (-16 % to -21 %, p-value 0.024). The differences between $Axio_{80}$ and $Cerex_{80}$ 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 $Axio_{80}$ and Evo_{80} 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 participated in the contact area (Ten Damme et al., 2019). Evo_{80} was thus wider than $Axio_{80}$ (mean width of wheel rut 0.77 m vs 0.71 m), which meant that the measurements at +0.3 m of Evo_{80} were influenced by a larger part of the contact area.

The different axle loads allowed for a discussion of the effect of wheel load on soil stress, but only for the measurements 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).

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 in the upper part of the soil profile (Fig. 1). At 0.2 m depth, mean normal stress was significantly highest for *EvoBib* with the highest inflation pressure (80 kPa, Evo_{80}). The reduction of the inflation pressure from 80 to 60 kPa (Evo_{60}) reduced mean normal stress with 22 % for the tyres at both the front and rear axle. Additionally, also at 0.2 m depth, a reduction of the inflation pressure from 60 to 40 kPa (Evo_{40}) resulted in a significant reduction of 11 % for the tyres at the rear axle.

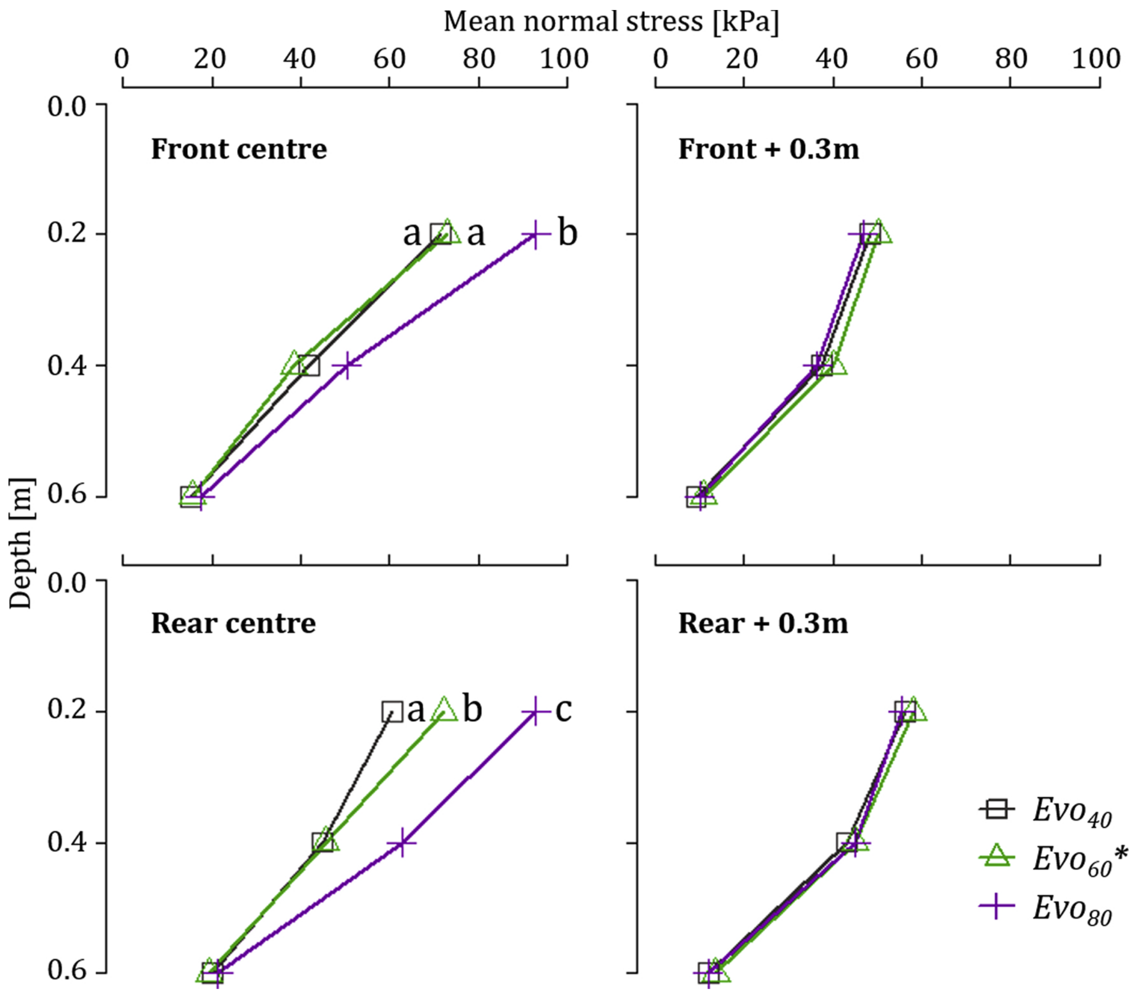

Fig. 1. Median of maximum measured mean normal stress (kPa) for EvoBib at an inflation pressure of 40, 60, and 80 kPa. N = 12 for each probe position for Evo_{60}, and N = 9 for each probe position for Evo_{40} and Evo_{80}. Different letters behind the symbol indicate differences between the tyres at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

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 Evo_{80} 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* (Evo_{60RL} and $Axio_{80}$, 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 Evo_{60RL} 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 Evo_{60RL}, implies that stresses from horizontal directions must have been higher in comparison to $Axio_{80}$ – 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 Evo_{60RL} than $Axio_{80}$ 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.

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 vs. radial tyres inflated to 240 kPa) either. In their analysis of the effect of tyre evolution, the biggest reduction of mean normal stress related to the introduction of wide, low-inflation pressure tyres.

The results presented in section 3.2 emphasize the importance of adjusting the tyre inflation pressure between traffic on the road and in the field for protection of the topsoil. For *EvoBib*, the recommended inflation pressure for transport on the road generally is 180 kPa above the recommended inflation pressure in the field. Yet, even at the low inflation pressures tested, we measured a significant reduction of mean normal stress when decreasing the inflation pressure by 20 kPa – from 80 to 60 and to 40 kPa. This indicates that managing the tyre inflation pressure could make the difference between sustaining and deforming the soil structure – although depending on soil strength.

Tyre construction might minimise damage done to soil structure by improvements of the weight-pull ratio, as the reduction in wheel load and associated tyre inflation pressure potentially reduces stress in both the top- and subsoil. Yet we did not find significant effects, as discussed in section 3.3.

All things considered, these results indicate that tyre dimension and inflation pressure are of primary importance to soil stress, rather than specific tyre construction. However, the construction defines a tyres' dimensions and may allow for different inflation pressures. The results imply that calculations of the contact stress distribution based on tyre dimension, inflation pressure, and wheel load (e.g. (Keller, 2005; Schjønning et al., 2008) might be valid for many types of pneumatic tyres. When aiming for a reduction of soil stress, the development and use of tyres with large diameters and very low inflation pressure seem most beneficial, if wheel loads are not reduced. Systems as CTIS can then be very beneficial, as it allows adapting the inflation pressure to the specific need, for example between field and road traffic, as the inflation pressure on the road should be higher to reduce rolling resistance and minimise tyre wear.

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 Evo_{80} 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 soil 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.

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