Risk of farmland degradation induced by traffic of tracked and a tired vehicles: Soil stress measurements and model simulations

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Abstract: Vehicle traffic induced soil compaction has negative effects on soil functions and ecosystems which may cause the degradation of farmland. This study investigated the magnitude and distribution of soil stress under the tracked and tired vehicles to explore the penitential of using rubber track instead of tire to reduce the subsoil compaction. The field experiment in this study included three replicates and was conducted on a sandy loam soil. Vertical and horizontal soil stress were measured under the centerlines of the rubber track and tire at a depth of 0.35m by using embedded transducers. The SoilFlex model was applied to simulate vertical and horizontal stress in the soil profile. Unevenly distributed vertical and horizontal stress were observed under the tire and rubber track. The vertical stress was characterized by one peak under the tire and several peaks under each of track wheels and rollers. The horizontal stress exhibited peaks before and after the tire and each of track wheels and rollers. The measured maximum stress was significantly higher under the tire than under the rubber track: that is, vertical and horizontal stress were approximately 3.4 and 2.0 times higher, respectively. This finding indicated that using rubber track maybe an effective method to reduce soil stress when compared with the tire, and was more effective in reducing the vertical stress than horizontal stress. Improving the uniformity of stress distribution under the track is the key to improve the ability of tracked vehicle to mitigate soil compaction.

Key words: farmland degradation; rubber track; vehicle velocity; soil stress; stress distribution; model simulations

1. Introduction

Subsoil compaction is considered a serious problem mainly because of its negative effects on soil functions and ecosystems; these effects persist for a considerable amount of time and may cause the degradation of farmland (Schjønning et al., 2013; de Andrade Bonetti et al., 2017; Abdollahi et al., 2014). Relatively high ground pressure at the soil–tire interface suggests that relatively high mechanical stress is transferred to the subsoil layers (Vermeulen et al., 2013; Schjønning et al., 2015a). This increase raises the risk of stress exceeding the soil strength and thus causes subsoil compaction.

Mechanical soil stress under a vehicle is a combination of compressive and shear stresses, which are caused by vehicle weight and vibration, and vehicle traction and slip (Horn et al., 1995). Compressive stress may cause the densification of soil, and shear stress may lead to the distorsion of soil pores (McGarry, 2003). The combination of these two types of stress results in the compression and distortion of soil pores, which affect soil functions and ecological aspects (Kirby and Blunden, 1991; Berisso et al., 2013). Thus, soil stress in both the vertical and horizontal directions must be determined. Previous studies have observed one peak for vertical stress under a tire as the tire makes a pass over a sensor (e.g., Gysi et al., 2001; Way and Kishimoto, 2004; Keller, 2005; Lamandé and Schjønning, 2008; Lamandé et al., 2018). Furthermore, the vertical stress under a rubber track typically has multiple peaks, one under each track wheel and roller (Blunden et al., 1994; Keller et al., 2002; Arvidsson et al., 2011). However, few studies have discussed the distribution of horizontal stress in soil beneath tires and tracks.

At relatively shallow depths, the soil stress of a single wheeling event can be decreased by increasing the contact area between the tire and the soil. Using rubber tracks instead of tires is an effective method of increasing contact area (Alakukku et al., 2003). Studies have shown that tracks cause less vertical soil stress than do tires at similar axle loads (Blunden et al., 1994; Keller et al., 2002; Arvidsson et al., 2011; van den Akker., 2018; Lamandé et al., 2018) (Table 1). However, the ability of tracks to reduce horizontal stress compared with that from tires is unclear. Soil functions can be considered as an indicator of soil compaction. Studies have shown that soil bulk density resulting from the passage of rubber track was less than from the tire (Bashford et al., 1988; Blunden et al., 1994; Arvidsson et al. 2011) (Table 1), but higher penetration resistance (Blunden et al., 1994) and lower air permeability (Lamandé et al., 2018) after the passage of the rubber track relative to the tire was observed (Table 1). The authors hypothesized that higher penetration resistance and lower air permeability are a result of higher horizontal stress under the rubber track than under the tire. However, horizontal stresses were not measured in these studies.

Loading time, which is determined by the longitudinal dimension of the contact area and the vehicle velocity, is another factor that can influence the soil stress, then soil compression and distortion. Bolling (1987) studied the effects of the traffic velocity on vertical soil stress below a tire; the results revealed that the maximum vertical stress under the tire central plane at a depth of 0.3 m decreased as the traffic velocity increased from 2 to 10 km h^{-1}. Similar results were reported by Horn et al. (1989); an increase in the traffic velocity, from 0.7 to 8 km h^{-1}, reduced both vertical and horizontal stress at a depth of 0.35m. This effect likely results from an insufficient amount of time for soil to experience maximum stress due to the shorter loading time at a higher vehicle velocity (Horn et al., 1989; Pytka, 2013). However, Naderi-Boldaji et al. (2018) observed a contrasting result that vertical stress was higher at a higher vehicle velocity (1 m s^{-1}) than at a lower vehicle velocity (0.5 m s^{-1}). The stress applied to the soil surface is not immediately transferred throughout the soil profile. The process of stress transmission in soil is time-dependent because energy can be stored through soil elastic deformation or converted into heat through the breaking of bonds during soil plastic deformation (Horn et al. 1989). However, no study has investigated the effect of the vehicle velocity on the soil profile's stress transmission speed.

The objectives of this study were: (1) to investigate the distribution of vertical and horizontal (longitudinal) soil stress under rubber tracked and tired undercarriages along the driving direction based on field measurements and (2) to determine the effects of the two types of undercarriages and vehicle velocities on the magnitude of soil stress and on the soil stress transmission speed.

2. Materials and methods

2.1. Soil and sites

The experiment was conducted in June 2018 in Foulumgaard (56°30'N, 9°34'E), Denmark. The mean annual temperature and precipitation (1961–1990) were 7.3°C and 626 mm, respectively. The soil had a sandy loam texture with 9% clay. Soil water potential was close to

−100 hPa at the time of the experiment. Some characteristics of the soil are given in Table 2. The field was annually ploughed to a depth of 0.2 m and had been grown with a cereal dominated crop rotation.

2.2. Vehicle used for traffic

The experiment was conducted using a Claas Lexion 770 combine harvester (Claas GmbH & Co. KGaA, Harsewinkel, Germany) equipped with rubber tracks on the front axle and tires on the rear axle (Fig. 1). The rubber track system comprised a front wheel and a rear wheel with two support rollers in between. The tires at the rear axle were 710/60R30 Continental SVT tires (Continental AG, Hanover, Germany) with 180 kPa inflation pressure. During the experiment, the harvester was unloaded and without its header. The static loads on one rubber track and one tire were 6.5 and 5.1 Mg, respectively.

2.3. Soil stress measurements

The soil stress measurements were conducted using three replicates in one field at four velocities (3, 5, 10, and 15 km·h^{-1}). As depicted in Fig. 2, vertical and horizontal (longitudinal) soil stress under the rubber track and tire were measured below the centerlines of the track and tire paths by using transducers buried at a depth of approximately 0.35 m. The precise depth from the soil surface to the piston of each transducer was measured during extraction from the soil. Each transducer had a cylindrical steel housing with a wedging system. Solid contact between the soil and the piston of each transducer was created by the wedging action of the cylindrical housing. For a detailed description, see Lamandé et al. (2007). In total, four transducers were installed at each plot: two transducers for vertical stress, and two transducers for horizontal stress (piston facing the vehicle's driving direction). A laser sensor fixed on the ground was employed to track the positions of the rubber track and tire and, in turn, the front and rear axles in relation to the transducers during wheeling. Data from the transducers were automatically recorded using a computer for subsequent processing.

2.4. Estimation of vertical stress transmission speed in the soil profile

Studies reporting vertical stress measurements at the soil–tire interface have recorded the maximum vertical stress under the axle during a tire pass (e.g., Gysi et al., 2001; Way and Kishimoto, 2004; Lamandé and Schjønning, 2008). We assumed that the maximum vertical stress under the wheels and the rollers of the rubber tracks at the soil surface would occur below each axle of the wheels and the rollers. Subsequently, the vertical stress transmission speed, V_s [m s^{-1}], was estimated using the following equation:

$$V_s = \frac{\sqrt{d^2 + S^2}}{t_{max} - t_{axle}} = \frac{\sqrt{d^2 + \left[V\left(t_{max} - t_{axle}\right)\right]^2}}{t_{max} - t_{axle}} \quad (1)$$

where S [m] is the horizontal distance from the maximum vertical stress point to the laser-recorded axle location (i.e., A and B to the nearest axle in Fig. 2), d [m] is the depth of each transducer (i.e., the vertical distance from the soil surface to the piston of each transducer in Fig. 2), V [m s^{-1}] is the vehicle velocity, t_{axle} [s] is the time at which the axle passed over the transducer, and t_{max} [s] is the time at which the maximum vertical stress was recorded.

2.5. Statistics

The effects of the traffic velocity and undercarriage (rubber track vs. tire) on the measured maximum soil vertical stress σ_v (kPa), maximum soil horizontal stress σ_h (kPa), and soil profile stress transmission speed V_s (m s^{-1}), and the differences in maximum vertical stress and maximum horizontal stress under the wheels and the rollers of the rubber tracks at a specified vehicle velocity were tested using one-way analysis of variance on ranks (Kruskal–Wallis test). We used Origin 8.0 data analysis software (OriginLab Corp., Northampton, Mass., USA) for all calculations.

2.6. Model simulations

In the simulation, we assume that the dynamic load was equal to the static load. The vertical stress at the soil–tire interface was calculated using the FRIDA model (Schjønning et al., 2008), with parameters estimated from tire dimensions and loading (Schjønning et al., 2015b). The vertical stress at the soil–track interface was estimated using the model established by Keller and Arvidsson (2016). The relevant parameters used in the simulations are presented in Table 3. The vertical and horizontal stress in the soil profile were calculated using the SoilFlex model (Keller et al., 2007), which implements the analytical equations for vertical and horizontal stress propagation (Boussinesq, 1885; Fröhlich, 1934). Soil vertical and horizontal stress at any depth from a distributed stress of soil–tire and soil–track interfaces can be calculated using the summation procedure proposed by Söhne (1953). The contact area A is divided into i small elements A_i, and a normal load P_i is applied to each element, which is treated as a point load. Then the radial normal stress $\sigma_{r,i}$ at depth z can be given as

$$\sigma_{r,i} = \frac{\xi P_i}{2\pi r_i^2} \cos^{\xi-2}\theta_i \qquad (2)$$

Where ξ is the concentration factor (Fröhlich, 1934), r is the distance from the point load to the desired point, θ is the angle between the normal load vector and the position vector from the point load to the desired point, and δ is the angle between the shear load vector and the vertical plane that contains the position vector to the desired point. The soil vertical stress σ_z, and the horizontal stresses σ_x and σ_y, can then be given as

$$\sigma_z = \sum_{i=0}^{i=n} \sigma_{r,i} \cos^2\theta_i \quad (3)$$

$$\sigma_x = \sum_{i=0}^{i=n} \sigma_{r,i} \sin^2\theta_i \cos^2\delta_i \quad (4)$$

$$\sigma_y = \sum_{i=0}^{i=n} \sigma_{r,i} \sin^2\theta_i \sin^2\delta_i \quad (5)$$

3. Results

3.1. Stress measurements

3.1.1. Soil stress in the vertical and horizontal (longitudinal) directions

Vertical stress under the tire exhibited one peak during the tire pass (Fig. 2) On the other hand, vertical stress exhibited several peaks under the rubber track (one peak under each of the front and rear wheels; one peak total for the two rollers). Thus, the rubber track could be considered a number of consecutive passes by the wheels and rollers along the track.

Horizontal stress under the tire exhibited two peaks, one forward of and one to the rear of the axle (Fig. 2). The transducers were installed with their pistons facing the driving direction so we considered the measured horizontal stress levels after the axle had passed over the transducers to be unreliable. The lower peak to the rear of the axle may have been due to the soil stress applied to the transducer housing opposite the piston that transmits soil stress to the load cell. Similarly, horizontal stress under the rubber track exhibited peaks one forward of the front wheel and one rearward of the rear wheel, with a relative plateau under the rollers. (Fig. 2).

The maximum vertical and horizontal stress measurements under the wheels and the rollers of the rubber tracks at specified vehicle velocities are presented in Fig. 3. Stress was unevenly distributed along the length of the rubber track. Vertical stress tended to be higher at the rear of the rubber track than at the front (Fig. 3a, $p = 0.310$). However, the highest horizontal stress was recorded rearward of the second roller and forward of the rear wheel (Fig. 3b, $p = 0.035$).

3.1.2. Effect of vehicle velocity on the magnitude of soil vertical and horizontal stresses, and vertical stress transmission speed

The effects of undercarriage (rubber track vs. tire) and the vehicle velocity were investigated to obtain the maximum soil vertical and horizontal stresses levels σ_v and σ_h and the soil profile's vertical stress transmission speed V_s. Although the maximum vertical and horizontal stress levels were not influenced significantly by the vehicle velocity for either type of undercarriage, both types of stress tended to decrease as the vehicle velocity increased (Table 4). Moreover, no significant influence from either type of undercarriage or the vehicle velocity on the stress transmission speed was observed (Table 4). The mean values of maximum vertical and maximum horizontal stress were significantly higher for the tire than for the rubber track (Table 4), although the load of the rubber track was approximately 1.4 Mg higher than that of the tire. Nevertheless, the effect of the undercarriage type was more pronounced for vertical stress than for horizontal stress. The mean maximum vertical stress was approximately 3.4 times higher under the tire than under the rubber track, whereas the mean maximum horizontal stress was approximately 2.0 times higher under the tire than under the rubber track. The mean value of vertical stress transmission speed in the soil profile was approximate 1 m s^{-1} (Table 4).

3.2. Model simulations

3.2.1. Simulated distribution of soil stress

The simulated distributions of vertical and horizontal soil stress under the rubber track and tire at a depth of 0.35 m are depicted in Fig. 4. The simulated vertical stress under the tire exhibited one peak, with the maximum stress occurring below the axle. Vertical stress under the rubber track exhibited one peak under each of the front and rear wheels and a higher peak between the two rollers (Fig. 4a). The shape of the simulated vertical stress was similar with to that of the measured stress (Fig. 2).

The simulated horizontal stress under the tire exhibited two similar peaks, one forward of and one rearward of the axle, with the local minimum stress found directly below the axle. The simulated horizontal stress under the rubber track exhibited peaks forward of and rearward of the front and rear wheels, with a local minimum stress occurring directly below each axle of the wheels, and a local minimum stress between two rollers (Fig. 4b). The shape of simulated horizontal stress was quite similar to that of the measured stress. The slight difference was that a plateau was observed under the track rollers in the measurement (Fig. 2).

3.2.2. Simulated stress in the soil profile

Fig. 5 illustrates the attenuation of the simulated maximum vertical and maximum horizontal stress at a specified depth under the rubber track and tire, and the maximum measured vertical stress and maximum measured horizontal stress, with error bars. The measured vertical stress was lower than the simulated stress for the rubber track, but was higher than the simulated stress for the tire (Fig. 5a). Furthermore, the measured horizontal stresses were markedly lower than their corresponding simulated values for both the rubber track and tire (Fig. 5b). The simulation predicted higher vertical and horizontal stress for the tire than for the track at a depth of 0.35m (Fig. 5a and b). The difference between tire and track was greater for vertical stress than for horizontal stress. These findings are in agreement with the vertical and horizontal stress measurements (Table 4).

4. Discussion

The distribution of soil stress is highly dependent on the stress distributed at the soil–track and soil–tire interfaces. We observed one peak for vertical stress for the tire; this finding is in accordance with results reported in previous studies, including those by Gysi et al. (2001), Lamandé and Schjønning (2008), and Lamandé et al. (2018). In previous studies, vertical stress at the soil–track interface exhibited one peak below each of the wheels and rollers (Blunden et al., 1994; Lamandé et al., 2018); in our measurements, a similar pattern was also noted at a depth of 0.35 m. However, only one peak was observed between the two rollers (Fig. 2), and this observation may be due to the interaction between stress fields below the rollers and an insufficient horizontal distance between the two rollers for distinguishing the rollers' individual peaks.

The measured horizontal stress at a depth of 0.35 m under the tire presented one peak forward of and one peak to the rear of the axle. Similarly, the measured horizontal stress under the track presented peaks one forward of the front wheel and one rearward of the rear wheel, but a relative plateau under the rollers (Fig. 2); the interaction between stress fields below the rollers and the insufficient horizontal distance between the two rollers may contribute to this finding. Another reason may be the influence of horizontal stress from the soil surface. Therefore, horizontal stress at the soil surface markedly influenced the distribution of horizontal stress in the soil; this observation warrants further investigation of the distribution of horizontal stress at the soil–track and soil–tire interfaces.

Our measurements revealed that vertical stress tended to be the highest below the rear end of the rubber track (Fig. 2a). Another study observed the same for a tractor equipped with long tracks pulling an implement (Keller et al., 2002). For the combine harvester in the present study, the rubber track on the front axle may contribute to most of the traction, as one such track did in the study by Keller et al (2002). However, the measured maximum horizontal stress under the rubber track occurred rearward of the second roller and forward of the rear wheel, possibly because the traction force and the rolling resistance of the wheels and rollers interfered with each other, and the higher vertical stress below the rear end than the front of rubber track.

The shapes of the simulated vertical and horizontal stress distributions were similar to those of the measured stress distributions (Fig. 2 and 4). However, the maximum simulated vertical stress and minimum simulated horizontal stress occurred precisely at the axle (Fig. 4); this finding differed from the measured findings, which revealed that the maximum and minimum points always occurred to the rear of the axle (Fig. 2). This indicates that the stress required time to be transferred from the soil surface to the transducer, which is not accounted for in the model. Moreover, the measured shape of the horizontal stress distribution exhibited a relative plateau under the track rollers (Fig. 2), but a local minimum point was found between the rollers in the simulation (Fig. 4); this may have been due to unconsidered horizontal stress (i.e., the traction force and rolling resistance of the wheels and rollers) at the soil surface in the simulation.

A rubber track undercarriage has been shown efficient for reduction of vertical soil stress compared to a tire, resulting from a larger contact area (Brown et al., 1992; Kinney et al., 1992). In our measurements, the mean ground pressure of the rubber track was approximately 57% lower than that of the tire. At a depth of 0.35 m, the track showed a 71% decrease in vertical stress but only a 49% decrease in horizontal stress (Table 3). Similarly, the model simulations to compare the tire and track revealed a more marked decrease in vertical stress than in horizontal stress, although relatively large difference between measured and simulated values for both vertical and horizontal stresses (Fig. 5a and b); this finding indicated that the rubber track may be more efficient for reducing vertical stress than horizontal stress.

Below the tire, the measured vertical stress was higher than its corresponding simulated value (Fig. 5); similar findings have been observed in other studies (e.g., Lamandé and Schjønning, 2011; Arvidsson et al., 2011). One study attributed this finding to inaccurate soil stress readings or uncertainty regarding upper model boundary conditions (Keller and Lamandé, 2010). However, in the present study, the measured horizontal stress was lower than its corresponding simulated value (Fig. 5), possibly because of unconsidered horizontal stress at soil–tire interface in the simulation. Under the rubber track, both the measured vertical stress and the measured horizontal stress were considerably lower than their corresponding simulated values. Again, the effect of horizontal stress at soil–track interface was not included in the model. This exclusion may partially explain the difference between the simulated and measured values; another reason could be uncertainty regarding distributed vertical stress at the soil–track interface. Interactions between rubber track and deformable soil are complex. The length of the track contact patch is related to the mechanical properties of soil; the length may be shorter on firm soil and longer on soft soil (Keller and Arvidsson, 2016). Besides, the uncertainty selection of concentration factor ξ in the model simulation may also responsible for the difference between the simulated and measured values. At present, there is no uniform standard for the selection of concentration factor ξ, which is generally selected by experience, and its value range from 2.0 to 14.3 (Horn, 2003; He et al., 2017). The concentration factor of 5 was used in our simulation according to the recommendation by Lamandé et al. (2007). However, the fixed value can not describe the efficiency of stress transfer in each soil layer at the same time, due to the difference of physical properties at different soil depth. Thus, the accurate prediction of the distribution of stress on tire/track surface and the reasonable selection of concentration factor are the key to model simulations.

Although no significant effect of the vehicle velocity on the magnitude of soil stress was observed, the mean stress value tended to decrease as the vehicle velocity increased (Table 4). This pattern is in agreement with the findings of Horn et al. (1989) and Bolling (1987), both of whom have observed that vertical stress decreases as the vehicle velocity increases (from 0.7 to 8 km h^{-1} and from 2 to 10 km h^{-1}, respectively), but the pattern is different from the result of Naderi-Boldaji et al. (2018), who observed higher vertical stress at a higher vehicle velocity (1 m s^{-1}) than at a lower velocity (0.5 m s^{-1}). The causes of these differing results regarding the relationship between soil stress and vehicle velocity in our study and these previous studies may be (i) the different types of soil used in the tests, (ii) inaccurate soil stress readings, or (iii) low numbers of measurement repetitions (Horn et al., 1989; Naderi-Boldaji et al., 2018). In addition, no significant effect of the vehicle velocity on the soil profile's stress transmission speed was observed; therefore, soil stress may have a constant transmission speed under specific soil conditions (i.e., soil stress transmission speed is a soil-specific characteristic). In the present study, the stress transmission speed in the soil was approx. 1 m s^{-1}, which is much lower than of transmission speed of seismic waves and acoustic waves in the soil (in the range of 150–1700 m s^{-1} and 1400–3900 m s^{-1}, respectively, depending on the types of waves) (Yang and Wu , 1997; Li et al., 2015). Further research on soil stress transmission speeds in different types of soil with different moisture levels is needed.

5. Conclusions

This study investigated the distribution of vertical and horizontal stress under a rubber track and tire of a combine harvester at a depth of 0.35 m and the effects of undercarriage type and the vehicle velocity on the magnitude of soil stress and stress transmission speeds. The maximum vertical and maximum horizontal stress levels were significantly higher under the tire than under the rubber track. Vertical stress was distributed with one peak under the tire and multiple peaks under the rollers and wheels of the rubber track. Under the tire, horizontal stress was distributed with peaks forward of and to the rear of the tire axle. Under the rubber track, horizontal stress was distributed with peaks one forward of the front wheel and one rearward of the rear wheel, and a relative plateau under the track rollers. Stress was unevenly distributed under the rubber track, with the highest vertical stress level occurring at the rear end and the highest horizontal stress level occurring rearward of the second roller and forward of the rear wheel.

The shapes of vertical and horizontal stress distributions were similar for the measured and simulated stress. However, the measured vertical stress was lower and higher than its corresponding simulated values for the rubber track and the tire, respectively. By contrast, the measured horizontal stress was considerably lower than its corresponding simulated values for both the rubber track and the tire.

Although no significant influence of the vehicle velocity on the magnitude of soil stress was observed, both horizontal and vertical stress tended to decrease as the vehicle velocity increased. The speed of stress transmission seemed soil condition specific and not influenced by the conditions of load application (undercarriage or driving speed).

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Conflict of interest

We declare that we do not have any commercial or associative interest that represents a conflict of interest in connection with the work submitted

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Table 1 Soil stresses and functions resulting from the compaction of tire and track

Authors	Soil conditions	Characteristics of the tire and track used	Comparison of soil stresses under the tire and track	Comparison of soil functions under the tire and track
Lamandé et al. 2018	Loamy sand soil with 24.6 % water content	1050/50R32 tire with 150 kPa inflation pressure and 5.25 Mg static load; 0.92 m × 1.325 m rubber track with 6.0 Mg static load.	Vertical stress at 0.1 m depth was 1.2 times higher under the tire than the rubber track; vertical stress at 0.35 m depth was 1.6 times higher under the tire than the rubber track	lower air permeability was detected under the rubber track than under the tire at 0.15 and 0.35 m depths; No significant different in dry bulk density was found at both depths.
van den Akker. 2018	Silty clay soil with high water content	900/60R38 tire with 170 kPa inflation pressure and 14.15 Mg static load; 0.9 m × 1.95 m rubber track with 16.76 Mg static load.	The maximum soil pressures under the rubber track are about $2/3^{th}$ of the soil pressures under the tire at 0.2 m depth.	
Arvidsson et al. 2011	Clay soil with 24 % and 31 % water content	600/65R34 tire with 60 kPa inflation pressure and 57 kN static load; 2×520/70R38 dual tire with 40 kPa inflation pressure and 62.5 kN static load; 0.6 m ×1.8 m rubber track with 57 kN static load.	Vertical stress under the single wheel considerably higher than under the tracks or dual wheels; vertical stresses were practically the same for the tracks and the dual wheels at 0.3 and 0.5 m depths.	Single wheel created greater compaction in terms of increased penetration resistance and bulk density, and reduced saturated hydraulic conductivity
Keller et al. 2002	Sandy loam soil with 17 % water content	520/70R38 tire with 120 kPa inflation pressure and 57 kN static load; 3.1 m × 0.7 m rubber track with 92 kN static load.	Vertical stresses were measured lowest under the track despite the total load of the track being approximately twice that of the tire	
Blunden et al. 1994	Earthy sand with 4 % water content	Dual tires (28 × 43) with 74-81 kPa contact pressure; rubber track with 58 kPa contact pressure.	Rubber track exerted less norma1 stress on the soil than the tire at 0.4 and 0.5 m depths; no significant differences were measured in normal stress at 0.15 and 0.3 m depth.	Soil have a higher penetration resistance after the passage of the rubber track relative to the tire; the only significant differences in the dry bulk density data among the traffic treatments were found at 0.2 m depth.
Bashford et al. 1988	Silty clay loam soil at dry, medium and wet soil water content conditions	Dual tire (20.8 × 38) with 98 kPa inflation pressure and 3.25 Mg static load; 0.635 m × 2.74 m rubber track with 3.5 Mg static load.		Soil bulk density resulting from the rubber track was numerically less than from the tire at three soil water content conditions.

Table 2 Selected properties of soil in the plough layer (0.13–0.17 m).

Soil parameter	Value
Organic carbon （$g\ 100g^{-1}$）	1.6
Clay (<2mm) （$g\ 100g^{-1}$）	9.0
Fine silt (2–20mm)（$g\ 100g^{-1}$）	11.1
Coarse silt (20–63mm)（$g\ 100g^{-1}$）	12.4
Fine sand (63–200mm)（$g\ 100g^{-1}$）	27.9
Coarse sand (200–2000mm)（$g\ 100g^{-1}$）	36.9
Particle density ($g\ cm^{-3}$)	2.61
Bulk density in the reference soil ($g\ cm^{-3}$)	1.4
Soil water content (0.32–0.37m) (%)	27.3

Table 3 Vehicle parameters used in the model simulations

	Parameters	Notation	unit	Value
	Rubber track load	G_{front}	Mg	6.5
	Tire load	G_{rear}	Mg	5.1
Tire	Tire width	W	m	0.71
	Tire overall diameter	D	m	1.646
	Static loaded radius	SLR	m	0.442
	Recommended inflation pressure	P_{rec}	kPa	140
	Actual inflation pressure	P_{tire}	kPa	180
Rubber Track	Nominal track width	W_n	m	0.95
	Nominal ground contact length	L_n	m	1.8
	Roller diameter	D_{roller}	m	0.2
	Number of support rollers	N	-	2
	Front wheel diameter	$D_{wheel,front}$	m	0.5
	Rear wheel diameter	$D_{wheel,rear}$	m	0.5

Note: Recommended inflation pressure P_{rec} as recommended by the manufacturer for the wheel load and speed of 0–15 km h^{-1}.

Table 4 Mean values of measured maximum vertical soil stress σ_v and maximum horizontal (longitudinal) soil stress σ_h, mean calculated vertical stress transmission speed V_s in the soil profile obtained using equation (1) and mean ground pressure P_{mean}. The letters and p values lower than 0.05 indicate significant differences in the measured parameters between the rubber track and tire undercarriages and significant differences in the traffic velocity.

	V	P_{mean}	V_s	σ_v	σ_h
	km h^{-1}	kPa	m s^{-1}	kPa	kPa
Rubber track	3		0.98	46.8	6.9
	5		1.24	44.7	6.8
	10		0.91	42.5	6.2
	15		1.11	36.4	3.4
			P=0.13	P=0.611	P=0.210
Tire	3		0.93	182.3	15.3
	5		1.04	146.9	13.5
	10		0.87	148.9	10.9
	15		1.16	108.3	6.0
			P=0.09	P=0.297	P=0.113
Rubber track	Mean	44.2a	1.06a	42.6a	5.8a
Tire	Mean	103.4b	1.0a	146.6b	11.4b
			P=0.350	P=0.0005	P=0.041

Note: According to the results shown in Fig. 3, regarding the rubber track, the maximum vertical soil stress σ_v occurred below the rear wheel of the track, whereas the maximum horizontal soil stress σ_h occurred rearward of the second roller and forward of the rear wheel. The mean ground pressure P_{mean} of tire and rubber track was calculated using SoilFlex model.

Figure Captions

Fig. 1. Combine harvester equipped with rubber tracks on the front axle and tires on the rear axle.

Fig. 2. Example of soil stress measurement at a depth of 0.35 m in the vertical (black curve) and horizontal (longitudinal) (gray curve) directions as a function of longitudinal distance, one pass of the track and tire with a forward velocity of 3 km h^{-1}. Dashed line: Axle locations determined by the laser; A: maximum vertical stress under the tire; B: maximum vertical stress under the front wheel of the rubber track. Black portion denoted as “Piston” on each sensor indicates direction of stress measurement, so left sensor measures vertical stress and right sensor measures horizontal stress.

Fig. 3. Mean values of maximum measured vertical stress (a) and maximum horizontal (longitudinal) stress (b) under the wheels and the rollers of the rubber tracks at specified velocities. Each half bar is one standard error. Letters indicate significant differences in stress between the wheels and rollers ($p = 0.05$).

Fig. 4. Simulated distribution of static soil vertical stress (a) and horizontal (longitudinal) stress (b) under the rubber track (front axle) and tire (rear axle) at a depth of 0.35 m. A concentration factor of 5 (Equation. 2) was used in the simulation. In both (a) and (b), the peaks at the left are from the rubber track and those at the right are from the tire. Vertical dashed lines denote the longitudinal locations of the axles of the front wheel, the rollers, and the rear wheel of the rubber track, and the axle of the rear tire.

Fig. 5. Measured maximum stress (symbols) and simulated stress (curves) under the rubber track and tire at depth of 0.1–1.0 m for vertical stress (a) and horizontal (longitudinal) stress (b). The error bars indicate the standard error of the mean.