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Effects of Tractor Bias-ply Tyre Inflation Pressure on Stress Distribution in Silty Loam Soil

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Abstract

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The aim of this paper was to quantify vertical stress distribution in silty loam soil by applying three combinations of tyre inflation pressures of front and rear wheels of a four-wheel drive tractor weighing 3560 kg. The tyres on the tractor were bias-ply, front 11.2-24 and rear 16.9-30, and inflation pressures were 67, 100, and 150% of the recommended pressure. Soil stresses were measured at 10, 30, and 50 cm depths using a stress transducer consisting of ten sensors with a 10 cm distance between sensor centres. Decrease in tyre inflation pressure resulted in a decrease of maximum soil stress at all measured depths. Tyre inflation pressures greatly influenced soil stresses measured in the topsoil. Maximum soil stress in the topsoil depth below front wheel tyres was significantly higher than that below rear wheel tyres. There were no significant differences between tyre contact areas at recommended, high, and low tyre inflation pressures.

Keywords: ground pressure; soil stress; tyre-soil contact area; wheel tractor

The problem of soil compaction caused by machinery traffic in agriculture is well-recognized in many parts of the world as one of the most important factors responsible for soil physical degradation, which has serious consequences for crop production and environment (Soane & van Ouwerkerk 1994). Compaction damage can create problems anywhere in the soil system, but it is much more difficult and costly to be alleviated once it extends to the subsoil, so appropriate machinery and soil management practices must be adopted to ensure this does not occur (Spoor *et al*. 2003). This damage may be visible due to the above-ground deformation of the soil or it may be completely hidden below ground and invisible from the soil surface. Either way, the effect of machinery traffic can have a negative impact on crop production due to the compacted soil condition, which is unable to adequately support a plant production system (Raper 2005). As soil compaction is mainly a result of stresses acting upon the soil, one of the farmer's main options for reducing soil compaction is to reduce these stresses. Ground contact stress can be reduced by reducing the wheel load or by increasing the ground contact area, e.g. by using tracks instead of tyres, by using more tyres or by reducing tyre inflation pressure. Pressures applied to the soil surface by tractor drive tyres are an important factor affecting soil compaction and tractive performance (Way & Kishimoto 2004). Enlargement of the soil-tyre contact area reduces the negative effect of tractor movement over the field and restricts physical degradation of soil characteristics (Šmerda & Čupera 2010). The size of contact area is described, in general terms, by the contact area length and width, which in turn depend on tyre parameters (type and size), inflation pressure, tyre load, and soil parameters. Low inflation pressure, high tyre load, and soft soil give a larger contact area (Hallonborg 1996).

Inflation pressure of the tyres has a major influence on stresses and compaction in the topsoil (Raper *et al*. 1995), while the influence of inflation pressure is small at greater depths (Danfors 1994). Stresses in the contact area and the topsoil are closely connected

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to inflation pressure (Arvidsson & Ristic 1996) and the mean ground contact stress can be often approximated by the inflation pressure (Burt *et al.* 1992). The average ground contact pressure (wheel load divided by contact area between tyre and soil surface) estimates the average value of vertical stress in the contact area (Gysi *et al.* 2001).

Two types of tyres are generally used for agricultural tractors: bias-ply and radial. A great deal of research has been conducted for radial tyres, while although bias-ply tyres are still widely used in many countries, little research has been done to investigate the effects of inflation pressure on their performance (Lee & Kim 1997). The objective of this study was to investigate the effects of different bias-ply tyre inflation pressure on vertical stress distribution in the soil during wheeling of a four wheel drive tractor in the medium power range, commonly used by Croatian farmers.

MATERIAL AND METHODS

Study site. The experiment was carried out in October 2014 at the Tractor Testing Station, part of the Agricultural Engineering Department, Faculty of Agriculture, University of Zagreb, Croatia (latitude 45°3'N, longitude 16°02'E, altitude 152 m). The climate is semi humid with average annual precipitation of 852.2 mm and average annual temperature of 10.7°C. The soil of the site is classified as Mollic Fluvisol (Humic, Hypereutric, Siltic) according to the WRB classification (FAO 2014) and belongs to the silty loam textural class. In all layers, the soil water content was slightly lower than field capacity. Basic soil physical properties are shown in Table 1.

Tractor and tyre characteristics. This experiment was carried out with the four wheel drive tractor in the medium power range commonly used by Croatian farmers, with the engine power of 54.0 kW and weight 3560 kg (1580 kg on the front axle and 1980 kg on the rear axle, 2.41 m distance between axles). The tyres were bias-ply, front 11.2-24 and rear 16.9-30, with the inflation pressures recommended by the producer 140 kPa and 80 kPa, respectively. According to Arvidsson and Ristic (1996), low inflation pressure in the experiment was 67% and high inflation pressure was 150% of the recommended pressure.

Contact area measurements. Many theories have been developed for tyre-soil contact area measurement by different approaches (Sharma & Pandey 1996). Contact area can be measured directly by registration of the footprint or indirectly by measuring the tyre deflection (Hallonborg 1996). In this experiment, we used the direct method after Schwanghart (1991). Footprints were registered by powdering with white calcium carbonate around the edge of the tyre-soil contact area. After removing the tractor wheel, the remaining footprint in the field was copied onto transparent paper and the size of the contact area was later determined with a planimeter. The mean ground pressure exerted by the tyre on the supporting surface was represented by the wheel load-contact area ratio.

Soil stress measurements. The measurements were made using a stress transducer, which consists of ten sensors installed in a steel beam dimensioned 1100 × 150 × 125 mm with a distance of 10 cm between sensor centres. Stress transducer was inserted into soil at three depths (10, 30, and 50 cm) perpendicularly to the driving direction. Upper soil layer was excavated for each depth and the soil was backfilled after the transducer was installed. In this way, the original soil structure was destroyed. The tractor was driven at a forward velocity of about 3 km/h in such a way that the right wheels overdrove the centre of the stress transducer. Cables from the transducer were taken to the digital amplifier HBM DMC 9012 A (Hottinger Baldwin Messtechnik, Darmstadt, Germany) through a flexible PVC tube. Data from the digital amplifier were transferred to a personal computer. Three passes were made per each depth and tyre inflation pressure and mean stress values were calculated for further data analysis. Statistical data analysis was done with the SAS software, Version 9.1 (SAS Institute 2002)

Table 1. Basic soil physical properties

Soil properties	Depth (cm)		
	10	30	50
Particle size distribution (%)			
Clay (< 0.002 mm)	8.5	13.2	14.9
Silt (0.06–0.002 mm)	69.1	67.3	68.4
Sand (2.0–0.06 mm)	22.4	19.5	16.7
Texture	silty loam	silty loam	silty loam
Consistency limits (%)			
Liquid limit	26.9	29.5	29.9
Plastic limit	19.3	22.1	22.6
Plasticity index	7.6	7.7	7.1
Specific gravity (t/m^3)	2.58	2.69	2.72

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using the analysis of variance. The significance of differences was assessed by the LSD test at the level of probability $P < 0.05$.

RESULTS AND DISCUSSION

The measured tyre contact area and calculated mean ground pressure at different inflation pressures are presented in Table 2. The width of the contact area was found to be equal or slightly smaller than the tyre width while tyres expanded in length due to changes in tyre inflation pressure. As expected, the tyre contact area increased with a decrease in inflation pressure and *vice versa*, but the differences between contact areas at different inflation pressures were not significant. Increasing the front-wheel tyre pressure by 150% of that recommended (140 kPa) resulted in a 2.6% decrease of tyre contact area, while the decreasing of tyre inflation pressure by 67% of that recommended resulted in an increase of tyre contact area by 2.2%. At the rear wheel, increasing and decreasing of tyre inflation pressure by the same percentages as recommended (80 kPa) resulted in a decrease or increase of tyre contact area by 2.6 and 3.1%, respectively. This is similar to the results reported by Way *et al.* (2000) on a loose sandy loam soil, which showed that the estimated footprint area increased by only 3% when the inflation pressure was increased from 40 to 120 kPa and the dynamic load was increased from 17 to 31 kN. Tractor wheel loads were not changed in this experiment, but Lamandé and Schjønning (2008) found nearly identical tyre contact areas when comparing correctly inflated tractor tyres under different loads.

Mean ground pressures were lower than inflation pressures in all measurements but the differences between mean ground pressures at different inflation pressures were not significant for the same wheel. Mean ground contact pressure below the front wheel tyres was on average 1.8 times higher than below the rear wheel tyres. The reasons are higher tyre inflation pressures and lower contact area at the front wheel tyres. According to Sharma and Pandey (1996), the mean ground pressure decreased as the contact area of the tyre increased with the increase in tyre size for constant load and inflation pressure.

Differences between the mean ground contact pressure and tyre inflation pressure were more obvious as the tyre inflation pressure was increased. The differences in mean ground pressures were the greatest at high tyre inflation pressures below front and rear wheel tyres, while at the recommended tyre inflation pressures, the mean ground pressures were considerably lower than the tyre inflation pressures. Differences were smaller at low tyre inflation pressures under front and rear wheel tyres. According to Lamandé and Schjønning (2011), the mean ground pressure is often higher than the tyre inflation pressure. Koolen *et al.* (1992) assumed the mean normal stress in the contact surface to be 1.2–1.3 times the inflation pressure due to the stiffness of the tyre carcass. In contrast, Gysi *et al.* (1999) found that the measured average contact stress was lower than the inflation pressure, which is in accord with the results of our study.

The soil stress distribution below front and rear tractor wheels with different tyre inflation pressures is shown in Figure 1. Maximum soil stress was measured at 10 cm depth and it was found that the tyre inflation pressure changes affected the soil stress significantly (Table 3). Increasing of tyre inflation pressure over that recommended (140 kPa) by 150% at the front wheel resulted in an increase of maximum soil stress by 28.2%, while decreasing of tyre inflation pressure over that recommended by 67% resulted in a decrease of maximum soil stress by 14.8%. At the rear wheel, increasing and decreasing of tyre inflation pressure over that recommended (80 kPa) by the same percentages resulted in more obvious differences and the increase of maximum soil stress at high tyre inflation pressure was 31.4% and the decrease at low tyre inflation pressure was 19.0% compared to that recommended. Comparison of maximum soil stress at high and low tyre inflation

Table 2. Measured tyre contact area and calculated mean ground contact pressure at different inflation pressures

Tyre inflation pressure (kPa)	Tyre contact area (cm^2)	Mean ground contact pressure (kPa)
Front wheel		
High 210	943.5[a]	82.1[a]
Rec. 140	968.8[a]	80.0[a]
Low 95	990.3[a]	78.3[a]
Rear wheel		
High 120	2126.1[b]	45.7[b]
Rec. 80	2194.9[b]	44.2[b]
Low 55	2251.7[b]	43.1[b]

Rec. – recommended; values followed by the same letter are not significantly different ($P < 0.05$)

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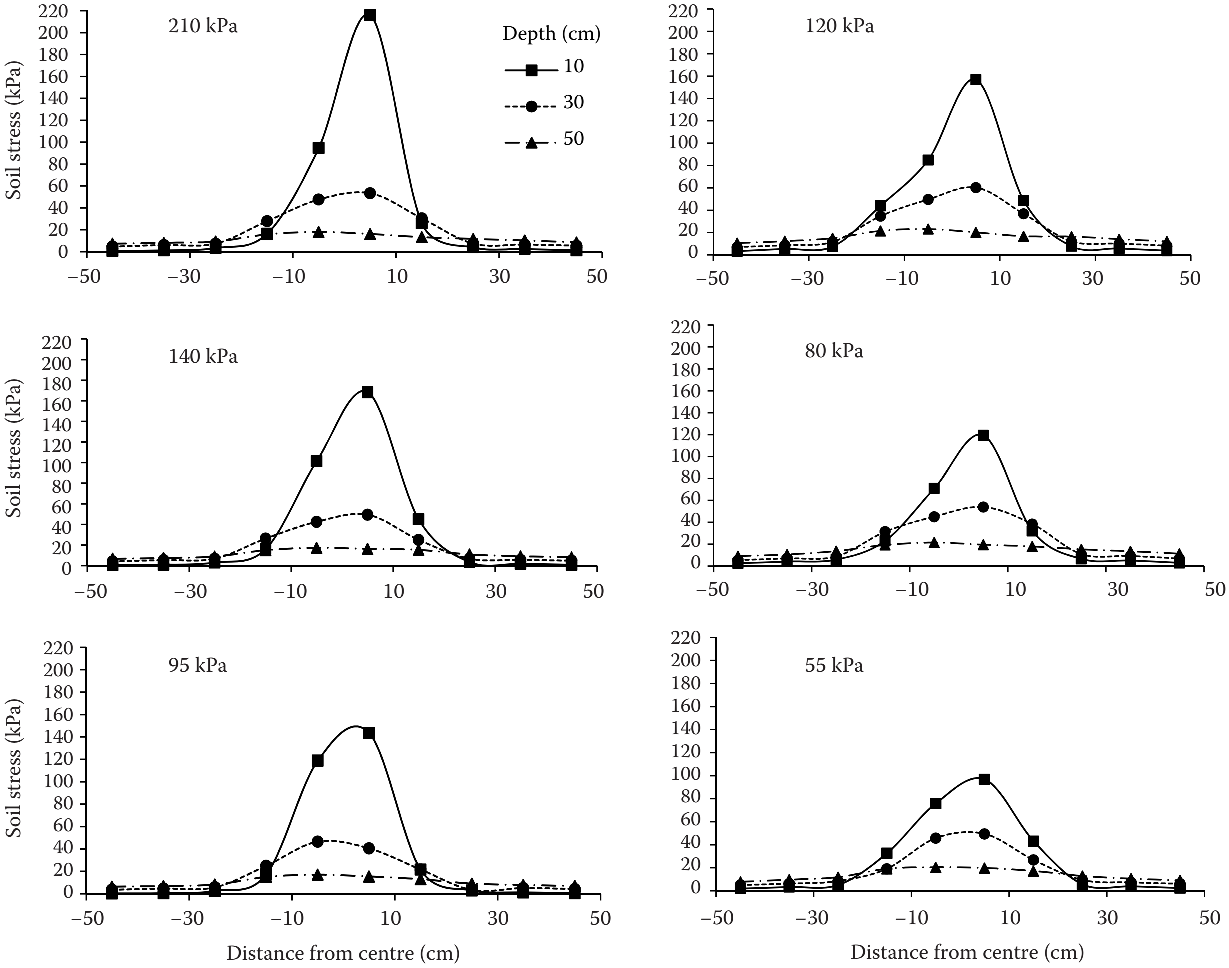

Figure 1. Measured vertical stress below front wheel with tyre inflation pressure

pressures revealed a significant reduction of stress by 33.5 and 38.4% below front and rear wheels, respectively. Reduced stress in the topsoil due to reduced tyre inflation pressure has been also reported by Raper *et al.* (1995) and Botta *et al.* (2002).

Maximum soil stress at a 10 cm depth was higher than the tyre inflation pressure in all measurements. The ratio of maximum vertical stress to tyre inflation pressure was higher for lower tyre inflation pressure and the highest ratio of the measured maximum soil stress to tyre inflation pressure was 1.5 and 1.8 below front and rear tyres, respectively. In that case, the effective differences were 48.5 and 41.7 kPa below front and rear tyres, respectively. Differences were smaller for higher tyre inflation pressures. These results are in accord with Schjønning *et al.* (2008), who pointed out that maximum stress in the contact area was by about 50 kPa higher than inflation pressures. Keller (2005) also measured peak stresses from 40 to 120 kPa in excess of the inflation pressure in a range of soil types.

Maximum stress could be predicted as a function of tyre inflation pressure, wheel load, and the ratio of tyre inflation pressure to recommended tyre inflation pressure at a given load. Stress distribution was generally found to be more homogeneous and consequently the ratio of maximum stress to average stress was lower the higher was the tyre inflation pressure (Bulinski & Majewski 2006). Maximum topsoil stress at the recommended inflation pressure maximum stress was 2.1 and 2.7 times higher than the mean ground contact pressure below front and rear wheel tyres, respectively. This is in agreement with Burt *et al.* (1992) and Gysi *et al.* (2001), who have concluded that maximum stresses can be considerably higher than the mean contact stress, sometimes by a factor of two or four. The highest vertical stress was in all cases measured in one of the two central sensors, which is in accord with Keller (2005), who has shown that the highest stress was below the central line between the front and rear

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edge of the tyre footprint, which was directly below the wheel axle.

Most investigations of soil stress were conducted with rear wheels, but in many cases soil stress was greater under front wheels like in this experiment. Maximum soil stress at a 10 cm depth below front wheel tyres was on average by 42.3% higher than below rear wheel tyres. The main reasons are higher tyre inflation pressures and lower contact area at front wheel tyres, but also the mass distribution of the tested tractor. Bulinski and Majewski (2006) found that front wheels of the smallest tractor and of the least weight transferred the highest pressures to the soil and explained it by the tractor mass distribution and tyre-soil contact area, resulting mainly from tyre size.

When comparing soil stress values in the topsoil and subsoil, the maximum soil stress at a 10 cm depth was significantly greater. Maximum soil stress at 30 cm was on average 36.9%, while at a 50 cm depth it was on average only 14.1% of the stress at a 10 cm depth. Stress distribution in the soil is a function of depth and it is logical and predictable that soil stress in the subsoil should be smaller than in the topsoil (Pytka 2005).

Tyre inflation pressure had a significant effect on soil stress measured in the subsoil only at 30 cm below rear wheels at high tyre inflation pressure. At a 50 cm depth, no significant difference in vertical stress was found between the different tyre inflation pressures. These results are in accord with Arvidsson *et al.* (2002), who reported significant differences in stress due to the varying tyre inflation pressure at a 0.3 m depth, but not in deeper subsoil.

Table 3. Measured maximum soil stress at different depths (in kPa)

Inflation pressure	Maximum soil stress at depth		
	10 cm	30 cm	50 cm
Front wheel			
High 210	215.9[a]	53.4[a]	18.1[a]
Rec. 140	168.4[b]	49.4[a]	17.4[a]
Low 95	143.5[c]	46.6[a]	17.0[a]
Rear wheel			
High 120	156.9[b,c]	60.3[a,b]	23.1[b]
Rec. 80	119.4[d]	54.0[a]	21.5[b]
Low 55	96.7[e]	49.4[a]	20.4[b]

Rec. – recommended; values followed by the same letter are not significantly different ($P < 0.05$)

Unlike stress in the topsoil, maximum soil stress in the subsoil was greater below rear wheel tyres, but the differences were smaller. Maximum stress at a 30 cm depth below rear wheel tyres was on average by 9.4% higher than below front wheel tyres, while it was by 23.7% higher at 50 cm, but effective values were much lower. Stress in the subsoil below rear tyres was more distributed over the width and stress measured at the end left and right sensors at a 50 cm depth was on average 41.2% of the maximum stress at that depth. For comparison, stress measured at a 10 cm depth below rear tyres at the end left and right sensors was on average only 2.1% of the maximum stress.

CONCLUSION

There were no significant differences between tyre contact areas at recommended, high and low tyre inflation pressures. Mean ground pressures were lower than the inflation pressures in all measurements and the differences between mean ground pressures at different inflation pressures were not significant for the same wheel but the mean ground contact pressure below front wheel tyres was on average by 1.8 times higher than below rear wheel tyres. Decreasing the tyre inflation pressure resulted in a decrease of maximum soil stress at all measured depths and tyre inflation pressure had a strong influence on soil stresses measured in the topsoil (at a 10 cm depth). Maximum soil stress in the topsoil depth below front wheel tyres was also higher than below rear wheel tyres, on average 42.3%. Maximum soil stress in the topsoil was higher than the tyre inflation pressure in all measurements and the ratio of maximum vertical stress to tyre inflation pressure was higher for lower tyre inflation pressure. Maximum soil stress in the topsoil was significantly greater than in the subsoil. The obtained results point to the conclusion that tyre inflation pressure, tractor weight distribution, and tyre size have a significant influence on soil stress.

References

Arvidsson J., Ristic S. (1996): Soil stress and compaction effects for four tractor tyres. Journal of Terramechanics, 33: 223–232.

Arvidsson J., Trautner A., Keller T. (2002): Influence of tyre inflation pressure on stress and displacement in the subsoil. In: Pagliai M., Jones R. (eds): Sustainable Land Management – Environmental Protection. Advances in GeoEcology 35. Reiskirchen, Catena Verlag: 331–338.

doi: 10.17221/124/2015-SWR

Botta G.F., Jorajuria D., Draghi L.M. (2002): Influence of the axle load, tyre size and configuration on the compaction of a freshly tilled clayey soil. Journal of Terramechanics, 39: 47–54.

Bulinski J., Majewski Z. (2006): Analysis of changes in soil compaction in the zone next to tracks of agricultural tractor passages. Tarim Makinalari Bilimi Dergisi (Journal of Agricultural Machinery Science), 2: 153–160.

Burt E.C., Wood R.K., Bailey A.C. (1992): Some comparisons of average to peak soil-tire contact pressures. Transactions of the ASAE, 35: 401–404.

Danfors B. (1994): Changes in subsoil porosity caused by heavy vehicles. Soil & Tillage Research, 29: 135–144.

FAO (2014): World Reference Base for Soil Resources. Rome, FAO.

Gysi M., Ott A., Flühler H. (1999): Influence of single passes with high wheel load on a structured, unploughed sandy loam soil. Soil & Tillage Research, 52: 141–151.

Gysi M., Maeder V., Weisskopf P. (2001): Pressure distribution underneath tires of agricultural vehicles. Transactions of the ASAE, 44: 1385–1389.

Hallonborg U. (1996): Super ellipse as tyre-ground contact area. Journal of Terramechanics, 33: 125–132.

Keller T. (2005): A model for the prediction of the contact area and the distribution of vertical stress below agricultural tyres from readily available tyre parameters. Biosystems Engineering, 92: 85–96.

Koolen A.J., Lerink P., Kurstjens D.A.G., van den Akker J.J.H., Arts W.B.M. (1992): Prediction of aspects of soil-wheel system. Soil & Tillage Research, 24: 381–396.

Lamandé M., Schjønning P. (2008): The ability of agricultural tyres to distribute the wheel load at the soil-tyre interface. Journal of Terramechanics, 45: 109–120.

Lamandé M., Schjønning P. (2011): Transmission of vertical stress in a real soil profile. Part II. Effect of tyre size, inflation pressure and wheel load. Soil & Tillage Research, 114: 71–77.

Lee D.R., Kim K.U. (1997): Effect of inflation pressure on tractive performance of bias-ply tires. Journal of Terramechanics, 34: 187–208.

Pytka J. (2005): Effects of repeated rolling of agricultural tractors on soil stress and deformation state in sand and loess. Soil & Tillage Research, 82: 77–88.

Raper R.L. (2005): Agricultural traffic impacts on soil. Journal of Terramechanics, 42: 259–280.

Raper R.L., Bailey A.C., Burt E.C., Way T.R., Liberati P. (1995): Inflation pressure and dynamic load effects on soil deformation and soil-tire interface stresses. Transactions of the ASAE, 38: 685–689.

Schjønning P., Lamandé M., Tøgersen F.A., Arvidsson J., Keller T. (2008): Modelling effects of tyre inflation pressure on the stress distribution near the soil-tyre interface. Biosystems Engineering, 99: 119–133.

Schwanghart H. (1991): Measurement of contact area, contact pressure and compaction under tyres in soft soil. Journal of Terramechanics, 28: 309–318.

Sharma A.K., Pandey K.P. (1996): A review on contact area measurement of pneumatic tyre on rigid and deformable surfaces. Journal of Terramechanics, 33: 253–264.

Soane B.D., van Ouwerkerk C. (1994): Soil compaction problems in world agriculture. In: Soane B.D., van Ouwerkerk C. (eds): Soil Compaction in Crop Production. Amsterdam, Elsevier: 1–26.

Spoor G., Tijink F.G.J., Weisskopf P. (2003): Subsoil compaction: risk, avoidance, identification and alleviation. Soil & Tillage Research, 73: 175–182.

Šmerda T., Čupera J. (2010): Tire inflation and its influence on drawbar characteristics and performance – Energetic indicators of a tractor set. Journal of Terramechanics, 47: 395–400.

Way T.R., Kishimoto T. (2004): Interface pressures of a tractor drive tyre on structured and loose soil. Biosystems Engineering, 87: 375–386.

Way T.R., Kishimoto T., Burt E.C., Bailey A.C. (2000): Soil-tire interface pressures of a low aspect ratio tractor tire. In: Horn R., van der Akker J.J.H., Arvidsson J. (eds): Subsoil Compaction: Distribution, Processes and Consequences. Advances in GeoEcology 32. Reiskirchen, Catena Verlag: 82–92.

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