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Impacts of bulk density and water content on the tire-soil contact area of agricultural field vehicles

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ABSTRACT. We tested the hypothesis that the increase in soil stiffness, induced by variations in bulk density and water content at the tire-soil contact interface, causes a reduction in the contact area. For this, we examined the contact area from different tire-ground contact scenarios and compared the measurements and simulations using a contact area description model. Front and rear tractor tires were used for the measurement of the contact area under tilled soil, sugarcane field, unpaved road, and paved ground scenarios, which induced different bulk densities and water content levels. The results revealed that soil stiffness reduced the tire-soil contact area. The tire-soil contact area increased as the water content increased and the bulk density was reduced. For the front tractor tire, the theoretical contact area was similar to the values found for tilled soil, but there was a large difference between the measurements (2,200 cm^2, for the tilled soil) and the theoretical estimates (3,100 cm^2) for the rear tractor tire (likely induced by tire dimensions). Our results suggest that increases in soil stiffness reduce the tire-soil contact area. The higher the soil bulk density and the lower the soil moisture, the lower the contact area. The results also revealed that the tire tractor tread might reduce the contact at the hard surface, making the shape of the contact area more geometrically irregular and different from those predicted by models using regular geometry (e.g., cycles, ellipses, or rectangles). This study suggests that two-body (soil and tire) contact models for deformable surfaces should be used in future tire-soil contact models of agricultural field vehicles.

Keywords: soil strength; compaction; field traffic; soil stress.

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Introduction

The stress induced by agricultural machinery has its source over the area of the tire footprint. Researchers have used several geometric shapes and models to predict tire-soil contact (e.g., Hallonborg, 1996; Johnson & Burt, 1990; Keller, 2005; Schjønning, Lamandé, Tøgersen, Arvidsson, & Keller, 2008). It is important to consider the contact area tire-soil because it is the main parameter responsible for the distribution of soil stress (Ptak, Czarnecki, Brennensthul, Lejman, & Małecka, 2022) and because it can be used as input data for analyzing the distribution of stresses and strains along the soil profile (Keller, Defossez, Weisskopf, Arvidsson, & Richard, 2007).

There are models that describe the tire-soil contact area as circular (O'Sullivan, Henshall, & Dickson, 1999), rectangular (Johnson & Burt, 1990), or ellipsoidal (Keller, 2005). Circular and rectangular models facilitate the geometric estimation of the contact area as well as the calculation of stress over a contact area because the areas of these geometrics are easier to calculate. Among the various geometric shapes, ellipsoidal models have been reported to be more realistic and flexible to vary in response to tire configurations and dimensions (Hallonborg, 1996). The ellipse contact dimensions described by these models respond to tire properties such as wheel load, tire diameter and width, and tire inflation pressure (e.g., Keller, 2005; Schjønning et al., 2008). However, little attention has been paid to the impact of soil stiffness on tire-soil contact area variations.

Soil stiffness influencing the contact area size w reported by Diserens (2009), Hallonborg (1996), Söhne (1953), and Yong, Boonsinsuk, and Fattah (1980), used the scheme described by Söhne (1953) to illustrate how soil stiffness reduction (induced by an increase in soil moisture) could increase the tire-soil contact area.

Although Hallonborg (1996) recognized the impact of the soil water content on the size of the contact area, his modern and useful super-ellipse model was proposed for soft soils. Yong et al. (1980) and Diserens (2009) suggested that tire-soil contact area models should be based on the concept of two deformable bodies in contact. This means that both tire and soil in contact influence the size of the contact area and should therefore be taken into account when describing the models.

The two deformable bodies in the contact model proposed by Yong et al. (1980) took into account material properties such as Poisson's ratio and the Modulus of Elasticity, whereas Söhne (1953) and O'Sullivan et al. (1999) recognized the effect of soil stiffness quantitatively by considering simple basic physical properties such as soil bulk density and water content. Soil bulk density and water content govern the state of soil deformation and therefore influence soil stiffness (Horn & Fleige, 2003; Saffih-Hdadi et al., 2009). The higher the bulk density and the lower the water content, the higher the expected soil stiffness. However, soft soils are expected to have a higher water content and a lower bulk density. Based on Söhne (1953) and Hallonborg (1996), the higher the water content and the lower the bulk density at the tire-soil interface, the higher the expected contact area.

Considerable advances in the description of the contact area have been made, but many of the models are described considering only the impact of tire configuration on changes in the size of the contact area. In this study, we tested the hypothesis that the increase in soil stiffness, induced by variations in bulk density and water content at the tire-soil contact interface, causes a reduction in the contact area. For this, we examined the contact area in different tire-ground contact scenarios and compared the measurements and simulations using a modern contact area description model. The aim of this study was to describe the impacts of soil bulk density and water content on tire-soil contact area changes.

Material and methods

Experimental site and scenarios

The study was carried out at the Carpina Experimental Sugarcane Station (EECAC-UFRPE) in Carpina (7°51'9" S, 35°14'14" W – 178 m above sea level), Pernambuco State, northeastern Brazil. Carpina has an annual mean rainfall of approximately 1,400 mm and an annual mean temperature of 24°C. The soil was classified as a sandy-loam Ultisol (Soil Survey Staff, 2014), with 750, 100, and 150 g kg^{-1} sand, silt, and clay contents, respectively.

For this experiment, four different scenarios, based on ground stiffness, were chosen: paved ground, unpaved road, sugarcane field, and tilled soil. The physical description of the ground scenarios is given in Table 1. The paved ground scenario consisted of a concrete surface, and the unpaved road consisted of a farm road compacted by the constant flow of agricultural vehicles. The sugarcane soil scenario consisted of a nine-ratoon sugarcane field, i.e., a cultivated field with sugarcane under eight successive harvests without tillage intervention. The tillage procedure consisted of conventional tillage with a disk harrow at a depth of 0.20 m (Table 1).

Table 1. Soil physical characterization and experimental tyre-ground contact stiffness scenarios.

Contact stiffness scenarios	BD (kg m^{-3})	w (g g^{-1})	TP (m^3 m^{-3})	DS (%)
Tilled soil	1.54	0.24	0.42	57
Sugarcane field	1.64	0.09	0.38	24
Unpaved road	2.20	0.04	0.17	24
Paved ground	2.40	-	-	-

BD: bulk density; w: gravimentric water content; TP: total porosity; DS: degree of saturation.

Soil sampling and experimental procedure protocols

The experiment consisted of measuring the contact area induced by two agricultural tires with different dimensions (Table 2) under the soil stiffness scenarios. The contact area measurements were performed with three replicates for each soil scenario. Except for the paved ground scenario, disturbed and undisturbed soil samples were collected (three replicates) for soil physical characterization before contact stress induction (i.e., initial soil physical condition). Disturbed soil samples were used for particle size and particle density analyses, whereas undisturbed soil cores (0.05 m in diameter and 0.05 m in height) were used for the determination of the soil water content and the soil bulk density. The cores were previously weighed to determine the wet weight and then oven-dried at 105°C for 24h. Bulk density was calculated from the weight ratio of the oven-dried soil and the total volume of the soil cores. The gravimetric water content was calculated as the difference between the weight of the samples at each field water content and that at oven-dry conditions.

For the measurement of the contact area, front and rear tires of an agricultural tractor (Massey Ferguson - 265) were used in the experiment; the tire dimensions are given in Table 2. Figure 1A illustrates the types of tires used. Under the paved scenario (measurements performed at an agricultural garage), the tractor was lifted by a winch and the tire slowly driven into the ground contact. For the unpaved road, compacted soil, and tilled soil, the vehicle was driven to the field. In each scenario, the examined tire was suspended by a wooden platform (Figure 1B) and slowly induced into contact with the ground surface. Once the tire-ground contact was established, an agricultural limestone-based powder was used to delimit the contact area (Figure 1C). A rectangular shape mold was used to delimit the defined contact area so that images with known dimensions could be taken (Figure 1C) with a camera. The images were then processed, and the contact area dimension was defined using AutoCAD software procedures.

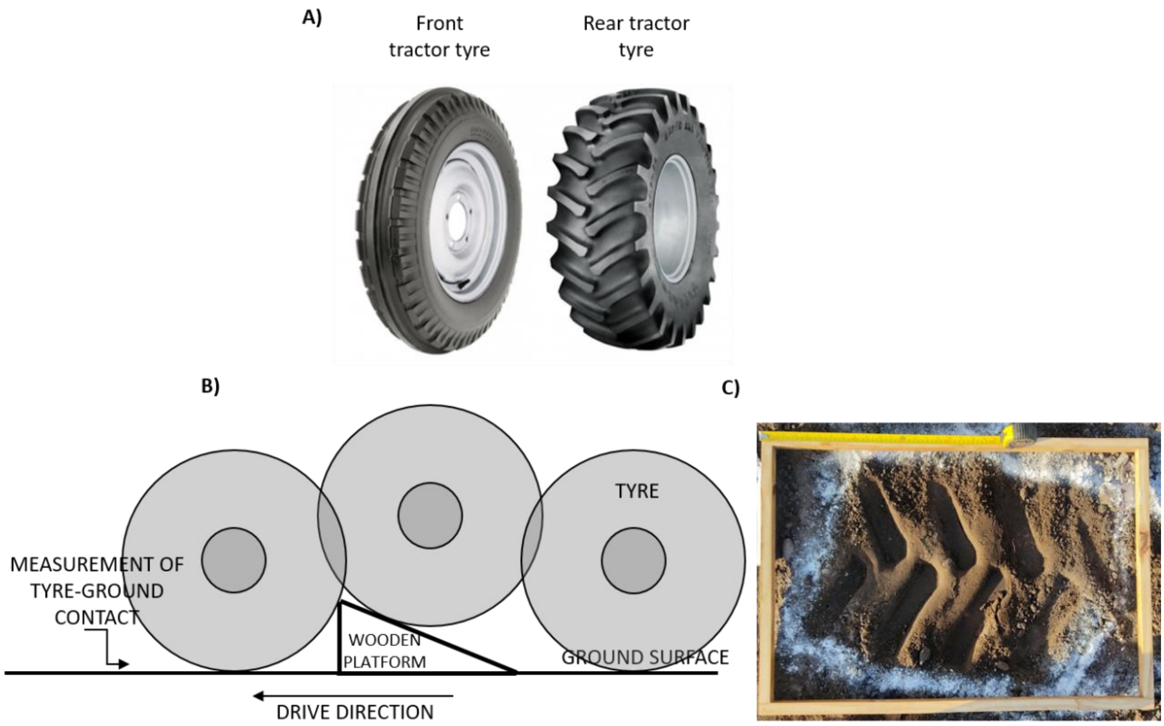

Figure 1. Experimental tyre types and protocol for establishing tyre-ground contact and measurements. A) Front and rear tractor tyres used in the experiment; B) Procedure for establishing tyre-soil contact at field scale using the wooden platform (no scaled); C) Rectangular shape mold used to delimit the defined contact area, so that images with known dimensions could be taken.

Theoretical estimate of the contact area

We used the *SoilFlex* compaction model (Keller et al., 2007) to simulate a theoretical contact area corresponding to the experimental tire configurations used for the measurements. The theoretical contact area was estimated using the model proposed by Keller (2005), optionally available in *SoilFlex*. The model by Keller (2005) is based on the super-ellipse model (Hallonborg, 1996), in which the contact area is changed in response to tire dimension inputs. The machinery parameters used to calculate the contact area are given in Table 2.

Table 2. Machinery and tyre configurations used for measurement of tyre contact area under the experimental ground surface scenarios.

Tractor	Tyre description	Wheel load (kg)	Tyre inflation pressure (kPa)	Tyre diameter (cm)	Tyre width (cm)
Front	7.50-18	435	206	84	20
Rear	16.9-30	720	117	160	43

Data analysis

The images of the contact area were processed using AutoCAD software procedures. With the images, the sizes of the contact areas were obtained and related to the conditions of the initial bulk density and water content, using simple regression relationships. In addition, the size of the contact area was examined by analysis of variance (ANOVA) and the Scott-Knott test applied for significant multiple comparisons of means ($p < 0.05$). The images were also processed and examined for the qualitative comparison of the results.

Results and discussion

Soil stiffness reduced the tire-soil contact area in all scenarios examined. The contact area was larger for tilled soil and was significantly reduced in the sugarcane field and further reduced on the unpaved road, which had similar values to those of the paved ground (Figure 2). The contact area for the front tractor was considerably smaller than that for the rear tractor tire due to the tire dimensions. For the front tractor tire, the theoretical contact area was similar to those found for tilled soil, but there was a large difference between the measurements (2,200 cm^2, for the tilled soil) and theoretical estimates (3,100 cm^2) for the rear tractor tire (Figure 2).

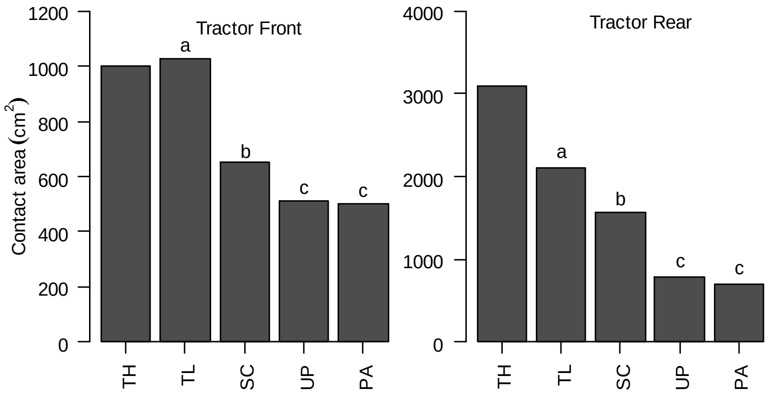

Figure 2. Theoretical and measured contact areas (cm^2) for front and rear tractor tyres under varied surface stiffness scenarios. TH: theoretical estimation using *SoilFlex* model; TL: tilled soil; SC: sugarcane field; UP: unpaved rural road; PA: paved ground. Means followed the same letter do not differ statistically by the Scott-Knott test. Since it has no replicates (no experimental data), the theoretical contact area was not included in the analysis of variance.

A high soil bulk density reduced the contact area (Figure 3), whereas a high soil water content increased the contact area (Figure 4). The effects of soil physical properties on the tire-soil contact area were clearer for the water content, where regressions showed a higher coefficient of determination (R^2). For bulk density, there was considerable data dispersion for the arable soil scenarios (tilled soil and sugarcane), whereas the water content seemed to more clearly govern the contact area linearly. Under tilled soil, particles are disaggregated, reducing soil stiffness and increasing the contact area. For the purposes of equation fitting, we assumed the gravimetric water content of the paved soil as zero. Note that, for the front tractor tire, the contact area was approximately 400 cm^2 for a water content equal to zero and reached 1,000–1,200 cm^2 for a gravimetric water content of 0.25 g g^{-1}. For the rear tractor tire, the contact area was ~600 cm^2 at the lower water content, reaching 2,200 cm^2 for the higher water content (Figure 4).

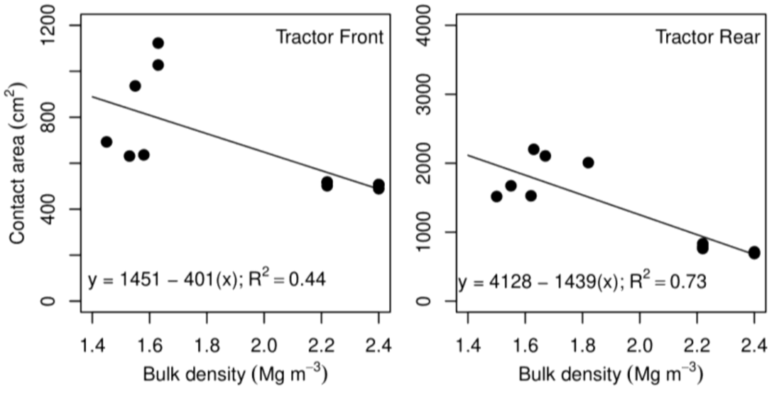

Figure 3. Measured contact areas (cm2) for front and rear tractor tyres as a function of soil bulk density under the varied surface stiffness scenarios.

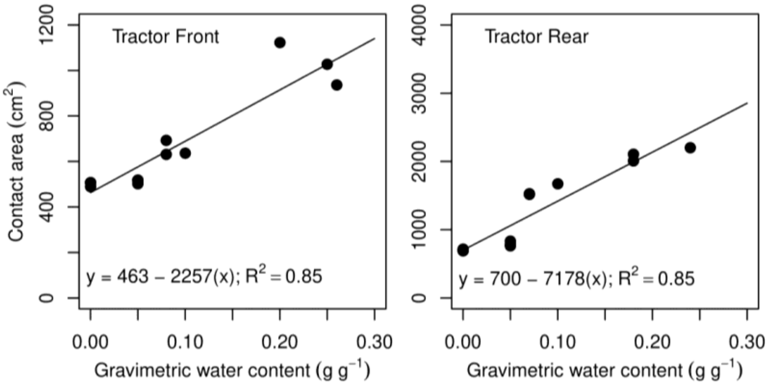

Figure 4. Measured contact areas (cm^2) for truck, front and rear tractor tyres as a function of soil water content under the varied surface stiffness scenarios.

Figure 5 shows the patterns of measured and theoretical contact areas for each scenario. For the front tractor tire, the shape of the contact area was moderately regular (geometric format) and geometrically similar to the super-ellipse assumed in theoretical models. For the rear tractor tire, the geometric shape of the contact area was geometrically irregular (without regular geometric shape), especially under arable soil scenarios (tilled soil and sugarcane field), which was considerably different from that of the contact area obtained under unpaved and paved grounds as well as from the theoretical estimate. According to Keller (2005), differences in the shape and geometry of the contact area are induced by tire dimensions and wheel load (see Table 2), which can change according to the agricultural vehicle.

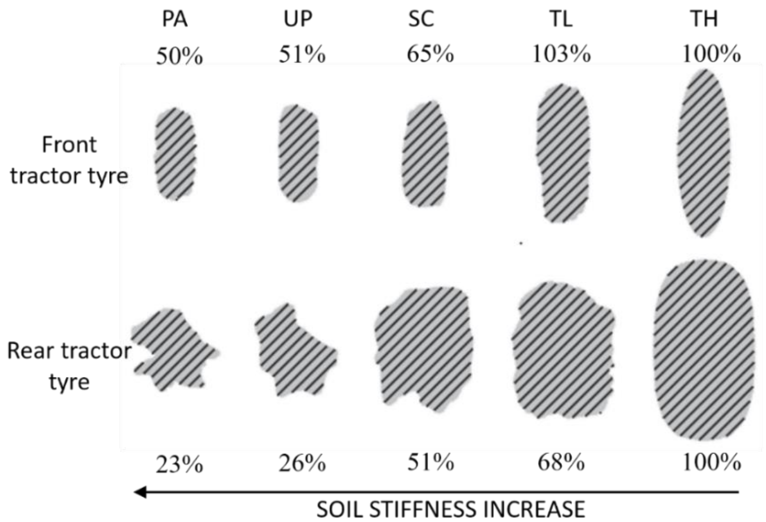

Figure 5. Qualitative images of the measured contact areas for the front and rear tractor tyres under the varied surface stiffness scenarios and the relative (%) contact areas in relation to the theoretical model. TH: theoretical estimation using *SoilFlex* model; TL: tilled soil; SC: sugarcane field; UP: unpaved rural road; PA: paved ground.

In this study, soil stiffness was applied by assuming different ground surface scenarios, identified by simple soil physical variables (water content and bulk density). The field-scale experimental results for these scenarios indicated that the tire-soil contact area decreases with soil stiffness (i.e., as the water content is reduced or the bulk density is increased), where the soil water content seems to be a dominant soil physical property in the process of changing the tire-soil contact area under constant tire dimension and inflation pressure. The effect of soil stiffness on the contact area caused a slight similarity with the theoretical models only for the scenarios with lower stiffness, which indicates that the model used for the estimation of the theoretical contact area should perform better for uncompacted or moist arable soils, slightly underestimating “hard” or "firm" soil scenarios.

In most models dedicated to modelling the size of the contact area (e.g., Keller, 2005; O’Sullivan et al., 1999), only tire components have been considered as factors changing the size of the contact area. In principle, when tire inflation is decreased, the contact area increases due to tire expansion; i.e., a reduction in tire stiffness occurs. Our data show that the same mechanical behavior must be applied to soil; i.e., as soil stiffness is reduced (due to soil physical properties), the tire contact area increases. In future tire-soil contact area modelling, tire-soil stiffness should be considered.

In agricultural soil compaction models, the contact area is an important component of the model, where the stress is distributed and propagated in the soil. The classical soil compaction models or contact area models proposed by Lima, Silva, and Silva (2021), Gupta and Larson (1982), Johnson and Burt (1990), Keller (2005), O'Sullivan et al. (1999), van den Akker (2004), Schjønning et al. (2008), and Stettler et al. (2014) take into account Fröhlich's concentration factor (Fröhlich, 1934) as a correction for the Boussinesq solution (Boussinesq, 1885) due to changes in soil stiffness, but only for the calculation of stress propagation. This means that little attention has been paid to the soil conditions affecting the tire-soil contact area since most models have focused on tire characteristics and dimensions.

According to Diserens (2009) and Yong et al. (1980), the contact area depends simultaneously on the elasticity and plasticity of the ground as well as the elasticity of the tire. A specific theoretical model for the contact area on a deformable surface was proposed by Yong et al. (1980). The prediction of the tire-soil contact area makes use of the solution for two cylindrical bodies in contact, as proposed by Poritsky (1950). Note that Yong et al. (1980) suggested that the size of the contact area should be modelled considering the contact between the two surfaces. The Poisson's ratio and Modulus of Elasticity were used as material properties, but both are not simple mechanical measures. Our results show that the water content could be properly applied in a future model or used in combination with tire inflation pressure as initial properties for the two deformable bodies (soil and tire) in contact.

Increases in soil moisture or decreases in soil bulk density induce greater soil deformation. This shows that simple physical properties can be used to compute a correction in the contact area due to changes in soil stiffness. This correction may not be different from that proposed by Söhne (1953), who suggested that Fröhlich's concentration factor is dependent on the soil water content, whereas O'Sullivan et al. (1999) suggested values of 3, 4, 5, and 6 for the concentration factor, which should be applied to "very hard", "hard", "firm", or "loose" soils, respectively, on a soil bulk density-dependent assignment.

Our results suggest that the size of the contact area is proportional to soil deformation, i.e., as soil surface deformation increases, the contact area increases (Farhadi, Golmohammadi, Sharifi, & Shahgholi, 2018). This anyway explains why at a softer soil surface, a higher contact area should be measured (Hallonborg, 1996). Silva et al. (2016) detected a significant impact of ground changes influencing the contact area. They verified that tire tread deepening increased the contact area, which corroborates our results, i.e., higher contact areas were observed at softer ground contact surfaces.

We used the model from Keller (2005) as a reference for estimating the theoretical contact area. This model uses the super-ellipse for modelling the contact area as a function of tire dimension, configuration, and wheel load. The model appears to have performed satisfactorily for the front tractor tire, whereas major differences were found for the rear tractor tire. Image analysis showed that the geometry of the contact area was greatly impacted by the tire type. The rear tractor tire tread appears to have reduced the contact area and made the geometry irregular, which was logically not captured by the model. The tire tractor tread therefore appears to be an important component for estimating the contact area.

These differences in the regularity of the contact area geometry may have been influenced by the contact surface. Under the paved and unpaved grounds, no geometrical regular pattern was found in relation to the theoretical contact area, whereas under the sugarcane and tilled soils, there was an approximation between measurements and simulations in relation to the geometry of the contact area. Anyway, it is possible to say that the increase in soil stiffness made the geometry more irregular and, therefore, more difficult to be predicted by a model that uses mathematical geometric shapes for prediction. In practice, in sugarcane soils, a larger contact area is expected after soil tillage for the implementation of the sugarcane fields (i.e., plant-cane). With advancing field traffic over cultivation years (harvest numbers), soil compaction increases, and the contact area could be reduced. Note that the results of this study have practical implications for compaction prediction simulations using theoretical models.

The contact patterns found for rear tractor tires in our study are similar to those found by Teimourlou and Taghavifar (2015), who observed an irregular geometry for a tread tire using image analyses. However, Teimourlou and Taghavifar (2015) found a better agreement between measurements and simulations using the super-ellipse model. It is important to point out that the super-ellipse model requires different inputs to determine the contact length and width, which can produce discrepant values. Teimourlou and Taghavifar (2015) concluded that the super-ellipse model is a promising tool in determining the contact area as it can describe the contact area with super-ellipse geometry, which differs from our observations only due to rear tractor tire tread.

In a more detailed investigation, Way, Kishimoto, Burt, and Bailey (2000) found that the pressures were concentrated more at the middle of a lug and at the edge of the tread than near the centerline of a tire. In this sense, more attention needs to be paid to the impacts of the tire tread on the contact area and stress distribution (Mohsenimanesh & Ward, 2007; Teimourlou & Taghavifar, 2015). Our study shows that the contact of the tire tread is influenced by surface stiffness, where a lower contact area should be expected for hard or firm surfaces.

Conclusion

Increases in soil stiffness reduce the tire-to-ground contact area. The higher the bulk density of the soil and the lower the soil moisture, the smaller the contact area. The results also revealed that the tractor tire tread can reduce contact on hard surfaces, making the contact area more geometrically irregular and different from that predicted by models that use regular geometries. Assuming the theoretical area to be 100%, the reductions in contact area with increasing soil stiffness reached 50% for the front tire and approximately 70% for the rear tire. For future studies, it is suggested to use two-body contact models (soil and tire) for deformable surfaces.

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