Soil Displacement and Soil Bulk Density Changes as Affected by Tire Size

D. L. Antille, D. Ansorge, M. L. Dresser, R. J. Godwin

Abstract. *The selection of the appropriate tire size and inflation pressure for a particular load and soil condition is a critical consideration to ensure that the effects of vehicle traffic on soil compaction are minimized and that agricultural soils are managed in a sustainable manner. This study investigated the changes in soil bulk density from soil displacement data produced by a range of combine harvester tires (680/85R32, 800/65R32, and 900/60R32) with vertical load of 10.5 t and inflation pressures in the range of 0.19 to 0.25 MPa to provide a valuable indicator for tire selection. The study was conducted in a soil bin facility using a sandy loam soil (Cottenham series) maintained at 10% (w w^{-1}) moisture content. Results showed that the initial density (γ) was the main factor influencing soil displacement and soil bulk density changes beneath the tires. Increased tire size and low inflation pressure reduced soil displacement and the resultant increase in soil bulk density. After a single pass of the tires over the soil, these increases were approximately 26% for a low (γ = 1.20 g cm^{-3}), 17% for a medium (γ = 1.40 g cm^{-3}), and 4% for a high (γ = 1.60 g cm^{-3}) initial bulk density soil, respectively. The advantages of increasing tire size and lowering inflation pressure were also reflected in the results obtained from the cone penetrometer resistance data. The tire with the highest inflation pressure (0.25 MPa) produced a significantly ($p < 0.05$) higher increase in soil cone index (0 to 700 mm depth range) compared with the tires with lower inflation pressures (0.19 and 0.22 MPa, respectively), particularly at the centerline of the wheeling. Linear relationships ($R^2 \geq 0.98$) between drop cone penetration and rut depth were established; these data were subsequently related to the calculated increase in soil bulk density determined from soil displacement data. The increase in soil bulk density resulting from a single pass of a tire over the soil can be determined for a range of tire configurations and initial soil conditions with the data produced by this study.*

Keywords. *Drop cone penetrometer, Soil compaction, Soil deformation, Soil penetration resistance, Tire inflation pressure.*

Efficient mechanization in agriculture is an important factor underlying high productivity (Tullberg et al., 2007); larger machinery is often related with timeliness, higher work rates, and lower labor requirements. It is envisaged that the trend observed in the past few decades toward the use and development of larger and more powerful agricultural machinery will continue (Chamen et al., 1992; Kutzbach, 2000; Dain-Owens et al., 2012). One of the drawbacks, however, is that larger machinery usually means increased machinery weight, which increases the risk of soil damage due to compaction (Raper, 2005). This issue has brought about increased questioning on the maximum acceptable mechanical compressibility of arable soils (Mosaddeghi et al., 2007).

Traffic-Induced Soil Compaction

The use of heavy farm equipment leads to increased potential for subsoil compaction whose effects are often persistent and difficult to remove (Håkansson and Petelkau, 1994; Alakukku, 1999). Lamandé and Schjønning (2011a) emphasized that the relative importance of axle load and tire configuration (size and inflation pressure) have been extensively debated in soil compaction research (e.g., Soane et al., 1981a, 1981b; Tijink et al., 1995; Bédard et al., 1997). Similarly, the relative benefits of tires and tracks, and their effects on soil compaction, have received considerable attention (e.g., Culshaw, 1986; Erbach, 1994; Alakukku et al., 2003; Pagliai et al., 2003; Ansorge and Godwin, 2007, 2008). This debate merits consideration given the trend toward the use of larger machinery indicated above (Lamandé and Schjønning, 2011a), which has, to a large extent, offset the advances made by the industry in developing improved running gear such as tire and track designs to reduce contact pressures (Dresser et al., 2006; Chamen, 2011).

Soil compaction affects the physical, chemical, and biological properties of soils, and it is regarded as one of the main causes of degradation of agricultural soils (Håkansson

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and Voorhees, 1998). Its alleviation is expensive, and it requires regular, energy-intensive, relatively deep loosening operations to sustain crop yields (Spoor and Godwin, 1978, 1981; Chamen et al., 1990; Chamen et al., 2003). Generally, an increase in tire size is accompanied by a decrease in tire inflation pressure to support a given axle load (Ageikin, 1987). This also provides improved tractive performance and reduced soil deformation, since the average soil contact pressure under the tire is approximately equal to the inflation pressure plus the pressure caused by tire carcass stiffness (Plackett, 1984; Misiewicz et al., 2008). Optimal tire inflation pressures in relation to dynamic load and tractive efficiency may be achieved by equipping the vehicle with a central tire inflation system. Early studies showed that these systems offered enhanced vehicle mobility and that they can be fitted to be slip-controlled, controlled through the optimization of tractive efficiency or by tire deflection (Czako, 1974; Koolen and Kuipers, 1989; Lyne and Burt, 1989).

In agricultural soils, compaction occurs including compression of the soil in the lateral direction (Koolen and Kuipers, 1983). Alakukku (1999) indicated that some of the factors affecting the compaction capability of wheel traffic are the soil condition during traffic, the type and intensity of the applied forces, the number of loading events, and their duration. The strength of the soil is highly dependent on a number of parameters, including soil texture and structure, soil organic matter content, and, in particular, soil moisture content (Koolen and Kuipers, 1983; Dawidowski and Lerink, 1990; Horn and Lebert, 1994). In unsaturated soils, soil strength decreases progressively with increasing soil moisture content; this influences how traffic stresses are transmitted beneath the soil surface (Lamandé and Schjønning, 2011b) and therefore the extent of soil deformation at depth (Arvidsson et al., 2001). For a given stress, the effect on subsoil compaction will therefore be greater when the soil is moist than when it is dry (Salire et al., 1994; Alakukku, 1999). Soil compression behavior is also related to the initial soil bulk density, which is one of the most used measures of soil compaction (Håkansson and Lipiec, 2000). Low bulk density soils have naturally low strength to support load; hence, they can suffer from greater deformation and compaction compared with high bulk density soils.

Controlled-Traffic Farming

The need to minimize the effects of soil compaction and, in recent years, the availability of reliable global navigation satellite systems, in addition to efforts being spent on vehicle design, have contributed to the development of more efficient field-traffic management strategies, namely, controlled traffic farming (CTF) systems (Chamen, 2011). The aim of these systems is to confine vehicle wheeling to the least possible area of permanent traffic lanes (Tullberg, 1997), particularly for heavy equipment (Håkansson, 2005). Chamen (2011) showed that CTF was found to be practical and that it has fundamental advantages in maintaining all aspects of good soil structure with lower inputs of energy and time compared with conventional field traffic systems. Despite this, and the potential economic and environmental benefits arising from its adoption (Kingwell and Fuchsbichler, 2011; Gasso et al., 2013), the rate of uptake of this technology in Europe and other parts of the world has been relatively slow (Tullberg et al., 2007; Chamen, 2011). Although there have been numerous studies on the effects of tire characteristics on soil deformation and soil compaction, there is still a pressing need for robust quantitative data that describe these processes. Whilst acknowledging the need to quantify the effects of these processes for undisturbed soil conditions, the information reported in this article will add to the growing dataset through the use of a realistic soil bin facility with a simple yet highly effective methodology for determining soil displacement to quantify specific soil movements that occur during such events.

Objective

The objective of this study was to determine the changes in soil bulk density from soil displacement data for a selected range of combine harvester tires (680/85R32, 800/65R32, and 900/60R32), with inflation pressures in the range of 0.19 to 0.25 MPa and at a fixed vertical load of 10.5 t, by extending the graphical representation of the data reported in earlier investigations (Stranks, 2006; Ansorge and Godwin, 2007, 2008). The data presented herein will provide a valuable indicator for tire selection.

Materials and Methods

Description of the Tests

The work was conducted at the Soil Dynamics Laboratory at Cranfield University (Silsoe, U.K.) in a soil bin facility using uniform soil conditions. The soil bin, described in detail by Earl and Alexandrou (2001), was 22 m long, 1.7 m wide, and 1 m deep. The soil used in the study was a Cottenham series sandy loam (King, 1969) with 66% sand, 17% silt, and 17% clay, which commonly occurs in Bedfordshire and Cambridgeshire (Hodge et al., 1984). The soil was maintained at approximately 10% (w w^{-1}) moisture content throughout the tests, which is equivalent to about 40% of field capacity determined at 0.05 bar (Antille et al., 2013). Two different soil bulk densities (γ) were used: low (γ = 1.20 g cm^{-3}, standard deviation = 0.053) and high (γ = 1.60 g cm^{-3}, standard deviation = 0.072). These values were selected to provide a range of approximately ±15% compared with the value of soil bulk density (γ = 1.40 g cm^{-3}, standard deviation = 0.019) reported in earlier studies (Stranks, 2006; Ansorge and Godwin, 2007, 2008), which is representative of this soil series (Hodge et al., 1984).

The tests were conducted using three different combine harvester tires manufactured by Continental AG (Hanover, Germany) (table 1). The tires were operated at a speed of 0.8 m s^{-1} and a slip of 14% suitable for qualitative determination of soil displacement (Ansorge and Godwin, 2007, 2008) in a single, self-propelled, wheel test rig apparatus (Godwin et al., 2006). The operating speed of the tires was considered safe, given the length of the soil bin, despite that it was about 50% lower than that typically used in most combine harvesters. The previous studies by Ansorge and

Table 1. Characteristics of the combine harvester tires used in the soil bin studies.

Tire Specification	Section Width (mm)	Overall Diameter (mm)	Lug Height (mm)	Tire Construction	Load (t)	Inflation Pressure (MPa)	Notation
680/85R32[a]	680	1939	42	Radial	10.5	0.22	680/10.5/0.22
800/65R32[b]	800	1820	58	Radial	10.5	0.25	800/10.5/0.25
900/60R32[c]	900	1898	55	Radial	10.5	0.19	900/10.5/0.19

[a] Load index = 178, speed symbol = A8. For the manufacturer's designation of cyclic loading operations, a maximum speed of 10 km h^{-1}, and hillside operation up to a maximum of 11° (20%) slope, the correct inflation pressure would be 0.24 MPa for the 10.5 t load. Therefore, this tire was underinflated by 0.02 MPa (Continental AG, 2012).

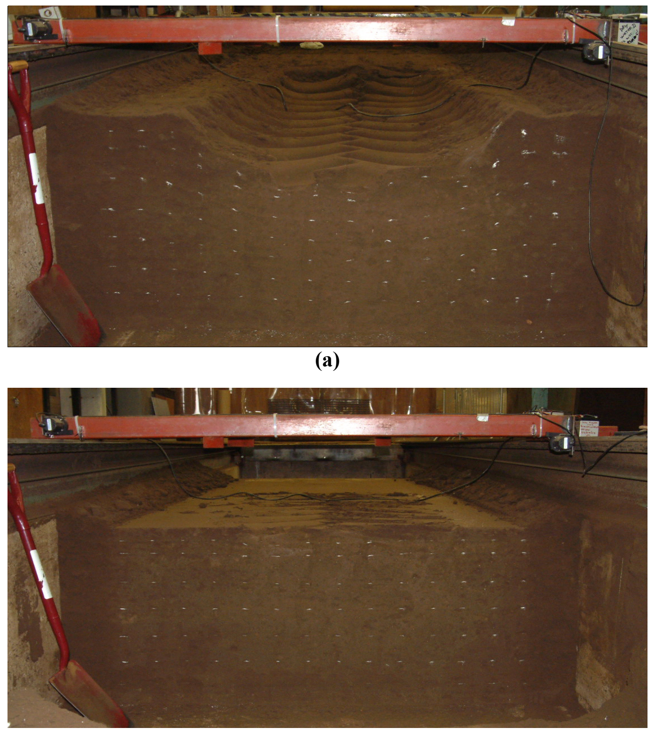
[b] Load index = 172, speed symbol = A8. For the manufacturer's designation of cyclic loading operations, maximum speed of 10 km h^{-1}, and hillside operation up to a maximum of 11° (20%) slope, the correct inflation pressure would be 0.25 MPa for the 10.5 t load. Therefore, this tire was correctly inflated (Continental AG, 2012).

[c] Load index = 176, speed symbol = A8. For the manufacturer's designation of cycling loading operations, a maximum speed of 10 km h^{-1}, and hillside operation up to a maximum of 11° (20%) slope, the correct inflation pressure would be 0.19 MPa for the 10.5 t load. Therefore, this tire was correctly inflated (Continental AG, 2012).

Godwin (2007, 2008) on the medium density soil used the same speed for all tires, which made it possible to compare the data. The tires were inflated to inflation pressures ranging from 0.19 to 0.25 MPa based on the specifications of the manufacturer for a fixed vertical load of 10.5 t. The tires are referred to in the text in the form of tire section width (mm) / vertical load (t) / inflation pressure (MPa). Data for a medium soil condition (γ = 1.40 g cm^{-3}) are quoted from Ansorge and Godwin (2007), which made it possible to show the effects of the tires for a wider range of soil conditions considered to be typical of arable (mineral) soils in the U.K.

Soil displacement (strain) and effective soil bulk density changes were determined employing the technique proposed by Ansorge and Godwin (2007), which is based on the principles outlined by Trein (1995). The technique used talcum powder stripes placed in the soil to a depth of 700 mm during the preparation of the soil bin. These talcum powder stripes were placed between two consecutive layers of soil of 50 mm each, except for the first and second sets, which were placed at 50 and 100 mm deep, respectively. Subsequently, the talcum powder stripes were placed at depth increments of 100 mm, i.e., at every second layer of soil. Each soil layer was rolled with the soil processor to achieve the required bulk density. The talcum powder stripes were placed after rolling and wetting the soil to enable them to stick to the soil on top of the corresponding layer. There were, therefore, a total of 14 layers of 50 mm each throughout the soil profile but only seven sets of talcum powder stripes. Each set had 14 stripes, each 200 mm long and 6 mm wide, across the width of the soil bin so that they were spaced vertically and horizontally at 100 mm on center, except for the first set, which was vertically spaced at 50 mm. For each running, the talcum powder marks were placed in three positions along the soil bin. Position 1 was on one end of the bin, and it represented the control (non-wheeled soil). Positions 2 and 3 (wheeled soil) were located in the middle of the bin and at 1.5 m toward the opposite end from the control, respectively. The control position was used as a reference for comparison with positions 2 and 3.

The position of the talcum powder stripes, which appeared as dots in a vertical cut in the soil profile (fig. 1), were obtained from the digitized output of two drawstring transducers following the procedure described by Ansorge and Godwin (2007). This provided the coordinates of the talcum powder dots with an accuracy of ±2 mm. For each of the three positions described above, the soil was cut vertically three times in order to obtain three different measurements (replications) of the dots' coordinates for the non-wheeled soil (control) and six measurements for the wheeled soil (positions 2 and 3). The vertical displacement in each layer was calculated by subtracting the mean vertical coordinate, taken from the four central dots of the control set, from the final position of the corresponding dots after the tire was driven over the soil. These four central points represent the central 300 mm of the rut, where soil displacement is predominantly vertical. The mean soil vertical displacement was plotted against the corresponding depth of the layer in the soil profile, and linear functions were fitted to the data. When these linear functions are differentiated with respect to depth, the displacement, i.e., the



(a)

(b)

Figure 1. Vertical cuts through the soil profile showing the talcum powder dots, the frame with drawstring transducers, and the ruts produced after a single pass of the 900/10.5/0.19 tire over (a) low (γ = 1.20 g cm^{-3}) and (b) high (γ = 1.60 g cm^{-3}) initial bulk density soils.

mean increase in soil bulk density, can be derived (Ansorge and Godwin, 2007). This technique provides a direct, accurate measure of the relative increase in soil bulk density ($\Delta\gamma$) that results from vertical soil displacement. The maximum error in measuring the depth of a soil layer was estimated to be ±0.5 mm, which translates into a maximum error of $\Delta\gamma$ of less than 1% when repeated measurements are conducted (Ansorge and Godwin, 2007).

The data obtained were used to compare the effects of the different tire configurations reported in this study. Based on the study conducted by Stranks (2006), who worked with a range of rear combine harvester tires (4.5 t vertical load, 500 to 800 mm section widths, and 0.09 to 0.29 MPa inflation pressures), the calculated increase in soil bulk density was plotted as a function of the initial soil bulk density, i.e., prior to the pass of the tires over the soil, for each of the tire configurations used in this study. From this, the graphical relationships reported by Stranks (2006) could be extended to a greater range of soil conditions and tire configurations.

Soil Penetration Resistance and Rut Depth

Cone penetrometer resistance (CP) was measured both before and after the tires were driven over the soil by pushing a cone (125 mm^2 base area, 30° apex) into the soil to a depth of 700 mm and digitally recording the force at 10 mm depth increments. Measurements were taken three times in ten positions across the soil bin, i.e., 120 mm spacing, for both the wheeled and non-wheeled soil (control). The data presented correspond to the average of the central four readings, which was subsequently plotted with respect to the depth. Drop cone penetration (DCP) was determined before the pass of the tires over the soil by releasing a 2 kg, 30° apex cone from a height of 1 m and measuring its penetration in the soil 20 times for each of the three initial bulk density soils, i.e., low (γ = 1.20 g cm^{-3}), medium (γ = 1.40 g cm^{-3}), and high (γ = 1.60 g cm^{-3}). A full description of the device and instructions for its use is given by Godwin et al. (1991). The drop cone penetrometer provided a rapid assessment of soil strength and its suitability to support load. The data obtained from the DCP tests were related, by means of linear functions, to measurements of rut depth determined at the centerline of the wheeling. Rut depth was determined from the vertical displacement of soil at the surface. This vertical soil displacement was calculated by subtracting the mean vertical coordinate, taken from the two central points of the control set at the surface, from the final position of the corresponding points after the tire was driven over the soil. These two central points represent the centerline of the rut. Rut depth was subsequently related to the calculated increase in soil bulk density as determined from soil displacement data. Based on the study by Godwin et al. (1991), the proposed approach involving the use of the drop cone penetrometer is presented to provide a quick indication of the potential soil compaction as a result of machinery traffic.

Statistical Analyses

Statistical analyses were conducted using GenStat Release 10.1 (GenStat, 2007); these involved general analysis of variance (ANOVA) and least significant differences (LSD) to compare the means using a 5% probability level ($p < 0.05$). The linear functions fitted to the data were obtained by conducting simple linear regression analyses using the same statistical package.

Results and Discussion

Soil Displacement

Figure 2 shows the vertical soil displacement with respect to the depth that resulted from a single pass of the tires over the three initial soil conditions. The data corresponding to the medium density soil (γ = 1.40 g cm^{-3}) are quoted from Ansorge and Godwin (2007) for the same tire configurations. For all tires, vertical soil displacement was found to decrease progressively from the soil surface to a

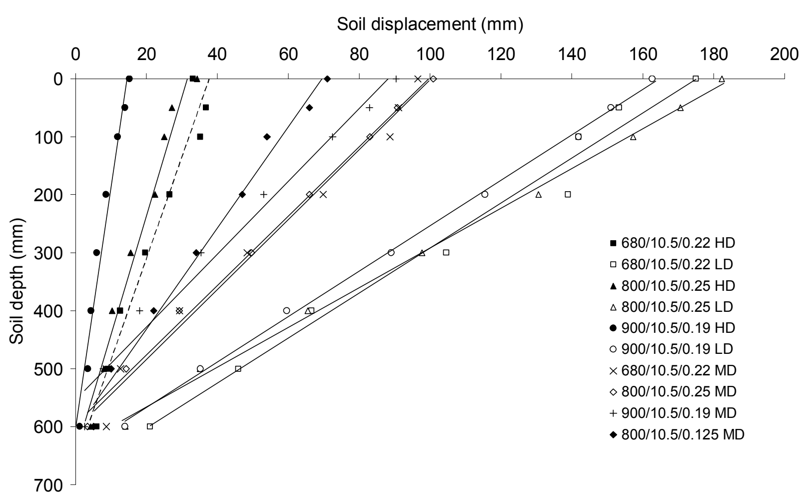


Figure 2. Vertical soil displacement versus soil depth for the various tire configurations and initial soil conditions used in the soil bin studies using a sandy loam soil, 10% (w w^{-1}) moisture content, and uniform soil conditions. LD, MD, and HD are low (γ = 1.20 g cm^{-3}), medium (γ = 1.40 g cm^{-3}), and high (γ = 1.60 g cm^{-3}) initial bulk density soils respectively. For γ = 1.20 and 1.60 g cm^{-3}, n = 6, LSD (5% level) = 7.05 mm, and $p < 0.001$. For γ = 1.40 g cm^{-3} (data from Ansorge and Godwin, 2007), n = 6, LSD (5% level) = 0.1 mm, and $p < 0.001$.

depth of approximately 600 mm. The data showed acceptable fits ($R^2 \geq 0.94$) to the linear models (table 2). The decrease in vertical soil displacement with depth was found to be significant for all soil conditions ($p < 0.001$). The values of bulk density for the three soil conditions used in this study were significantly different ($p < 0.001$), which explains the differences in soil strength and the capacity of the soil to support vehicle traffic.

Overall, in the low and the high bulk density soil conditions, there were significant differences in vertical soil displacement with respect to the tires ($p < 0.05$). However, the interaction tires × soil condition was found to be not significant ($p = 0.39$), which indicated that, on both soils, all tires produced a significant soil displacement compared with the control (non-wheeled soil). The differences observed between the tires were mainly due to the 900/10.5/0.19 tire, which produced consistently lower vertical soil displacement than the 680/10.5/0.22 and 800/10.5/0.25 tires. This was more evident on the firmer soil condition, where the soil displacement produced by the 900/10.5/0.19 tire was approximately 50% of that produced by the 800/10.5/0.25 and 680/10.5/0.22 tires. On the softer soil condition, the use of the 900/10.5/0.19 tire reduced vertical soil displacement by about 20% compared with the other two tires. Overall, vertical soil displacement produced by the 680/10.5/0.22 and 800/10.5/0.25 tires was of similar magnitude, which can be seen from the slope of the regression lines fitted to the data. The reduced effect on soil displacement of the 900/10.5/0.19 tire is attributable to the greater contact patch area resulting from its larger section width and lower inflation pressure compared with the 680/10.5/0.22 and 800/10.5/0.25 tires. There was also a beneficial effect of the overall tire diameter in reducing soil displacement, especially when comparing the 800/10.5/0.25 and 900/10.5/0.19 tires.

The interaction tire × soil layer was found to be significant ($p < 0.001$), which indicated that the effect of depth on soil displacement differed depending on the tire. Again, these differences were mainly due to the 900/10.5/0.19 tire except at a depth of 600 mm, where soil displacement for all tires was not significantly different for an LSD (5% level) value of 4.98 mm. Despite this, soil displacement at 600 mm was greater than zero for all tires, which suggested that soil compaction still occurred at a depth greater than the maximum depth at which measurements were made. In the top 100 mm, the effects of the 680/10.5/0.22 and 800/10.5/0.25 tires

Table 2. Linear relationships between vertical soil displacement and soil depth for the three tire configurations used in the soil bin studies (data for $\gamma = 1.40$ g cm^{-3} from Ansorge and Godwin, 2007).

Tire Configuration	Initial γ (g cm^{-3})	Regression Equation	P Value	R^2
680/10.5/0.22	1.60	$y = 659 - 17.5x$	<0.001	0.94
680/10.5/0.22	1.40	$y = 604.9 - 6.1x$	<0.001	0.98
680/10.5/0.22	1.20	$y = 679.8 - 3.9x$	<0.001	0.97
800/10.5/0.25	1.60	$y = 645.2 - 20.5x$	<0.001	0.96
800/10.5/0.25	1.40	$y = 595.6 - 6x$	<0.001	0.99
800/10.5/0.125	1.40	$y = 605.5 - 8.7x$	<0.001	0.98
800/10.5/0.25	1.20	$y = 634.3 - 3.4x$	<0.001	0.99
900/10.5/0.19	1.60	$y = 602.2 - 41.4x$	<0.001	0.96
900/10.5/0.19	1.40	$y = 552.9 - 6.3x$	<0.001	0.97
900/10.5/0.19	1.20	$y = 628 - 4.1x$	<0.001	0.99

on soil displacement were very similar, although the 800/10.5/0.25 tire produced slightly higher compaction than the 680/10.5/0.22 tire. Conversely, between 200 and 300 mm depth, the 680/10.5/0.22 tire caused slightly more soil displacement than the 800/10.5/0.25 tire, but the effects were overall very similar, as can be seen from the linear functions fitted to the data, which showed that both tires produced comparable effects at depths greater than 300 mm.

Similarly, for the medium density soil ($\gamma = 1.40$ g cm^{-3}), Ansorge and Godwin (2007) demonstrated that the 680/10.5/0.22 and 800/10.5/0.25 tires caused almost identical soil displacement, despite the differences in their section widths. This effect, observed in all soil conditions, is attributed to the larger overall diameter and lower inflation pressure (table 1) of the 680/10.5/0.22 compared with the 800/10.5/0.25, which resulted in approximately 10% greater contact patch area and consequently lower contact pressure. Vertical soil displacement was significantly ($p < 0.05$) reduced when the 800 mm section tire was inflated to half of the recommended inflation pressure (0.125 MPa) for the working load (Ansorge and Godwin, 2007; Continental AG, 2012). However, at 500 mm depth, soil displacement approached that of the tire at the recommended inflation pressure (0.25 MPa). This result agrees with Söhne (1953) in that inflation pressure determines soil compaction and soil movement at the surface, whereas axle load determines the effect at depth.

Vector diagrams (fig. 3) help to understand the response of the soil when it is subjected to stress. The length of the arrows indicates the magnitude of soil displacement, and the directions of the arrows indicate the directions of the displacements. Notice that there are eight rows of arrows in figure 3, one for each of the seven sets of talcum powder dots plus one row that corresponds to the measurements conducted on the soil surface. Ageikin (1987) suggested that soil deformation by a wheel may be subdivided into three types: vertical displacement, lateral displacement, and displacement in the direction of motion. The method used in this study allowed for measurements in only two dimensions. Ansorge and Godwin (2008) showed that the lateral movement of soil beneath self-propelled combine harvester tires on a medium soil condition ($\gamma = 1.40$ g cm^{-3}) was limited to approximately the first 150 mm below the surface. This behavior appears to be similar for the firmer soil ($\gamma = 1.60$ g cm^{-3}) used in this study; however, on the softer soil ($\gamma = 1.20$ g cm^{-3}), lateral displacement occurred at much greater depth. It is possible that the lateral displacement of soil recorded at depths greater than 600 mm on the soft soil occurred as a result of the depth of the soil bin, which could have impeded further vertical displacement of soil near the floor of the bin. This may require further investigation, and the facility to use a deeper (1.5 m) and wider (7 m) soil bin is now available at Cranfield University (Godwin et al., 2006).

Ansorge and Godwin (2008) developed a technique that was used to determine the effects of tires and rubber tracks on longitudinal soil movement. It was demonstrated that rubber tracks caused a significant backward movement of the soil at or near the surface. Conversely, the tires tended

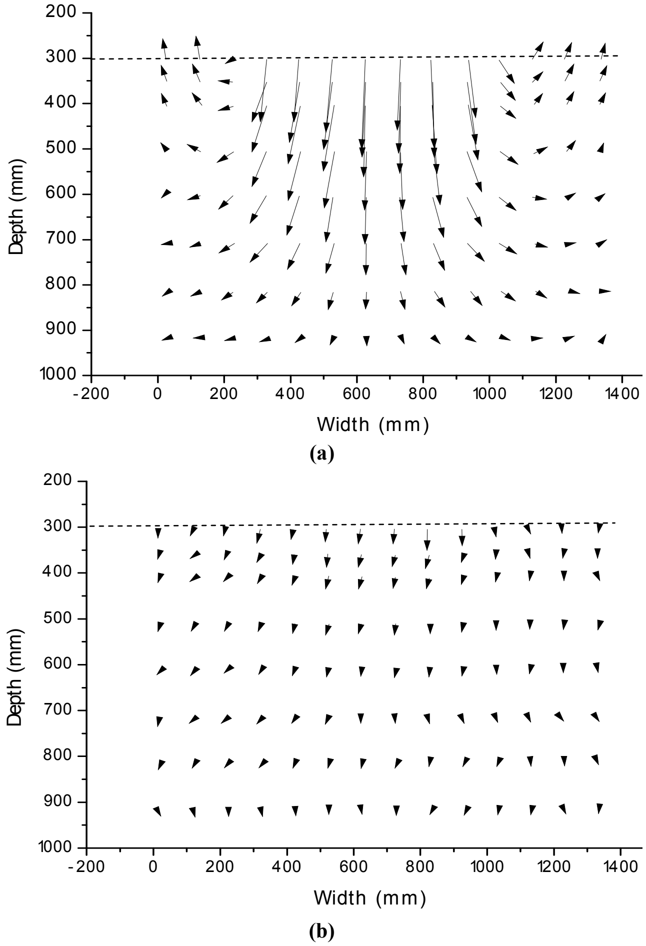


Figure 3. Vector diagrams showing the displacement of soil observed beneath the 900/10.5/0.19 tire for (a) low (γ = 1.20 g cm^{-3}) and (b) high (γ = 1.60 g cm^{-3}) initial bulk density soils. The *x*-axes indicate the width across the soil bin with the centerline of the tire at approximately 700 mm. The *y*-axes indicate the depth in the soil bin. The dotted lines show the soil surface level prior to the tests.

to provoke a forward movement of the soil in the same depth range, but this was not significantly different from zero. This behavior of the soil under the tracks resulted in relatively higher penetrometer resistance near the surface than that of the tires, and it was caused by the application of shear for a longer period of time for the tracks compared to the tires, leading to increased shear displacement beneath the tracks. As a result, the additional effect of a rear tire on soil compaction is negligible if that tire follows a rubber track, but it can be significant if it follows a leading tire (Ansorge and Godwin, 2008).

Increase in Soil Bulk Density

The graphical relationships reported by Stranks (2006) between initial soil bulk density and its percentage increase that resulted from a single pass of a range of tires over the soil were extended to a larger number of tire configurations (fig. 4). The study by Stranks (2006) was conducted with rear combine harvester tires loaded to 4.5 t having section widths from 500 to 710 mm, and inflation pressures from 0.09 to 0.29 MPa. In the present study, regardless of the tire configuration, the increase in soil bulk density decreased progressively as the initial soil bulk density increased, which is in close agreement with the results obtained by Stranks (2006). The regression analyses reflected the linearity of the relationship between the increase in soil bulk density and the initial soil bulk density for all tire configurations, with the data showing acceptable fits to the linear models ($R^2 \geq 0.98$). It may be argued that the analyses included only a set of three points from which these relationships were derived and that other relationships could therefore occur with a more complete dataset. However, the maximum error of $\Delta\gamma$ is estimated to be $\leq$1% when repeated measurements are conducted (Ansorge and Godwin, 2007), which supports the relationships obtained.

The 900/10.5/0.19 tire produced relatively less soil compaction than the 680/10.5/0.22 and 800/10.5/0.25 tires over the range of initial soil bulk densities investigated, and this is a result of its larger size (section width) and lower inflation pressure (table 1). Although the 680/10.5/0.22 tire is narrower than the 800/10.5/0.25 tire, given the larger overall diameter and lower inflation pressure of the 680/10.5/0.22, the contact patch area was, on average, approximately 10% larger over the range of soil conditions investigated. Hence, the contact pressure for this tire was also lower compared with the 800 mm section tire. Overall, the 680/10.5/0.22 tire resulted in reduced soil bulk density increases on the medium and low bulk density soil conditions compared with the 800/10.5/0.25 tire (approximately

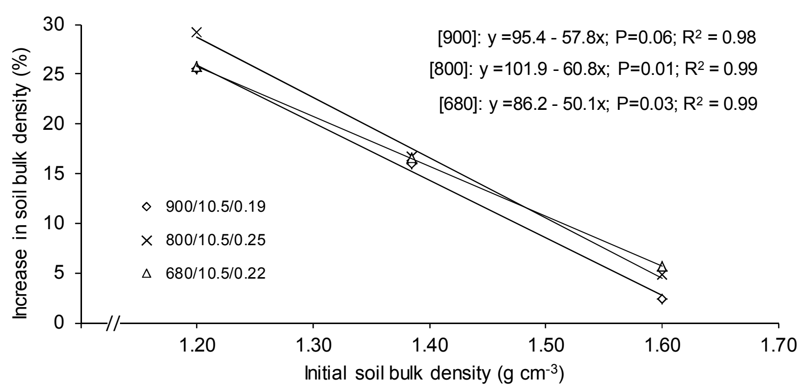


Figure 4. Percentage increase in soil bulk density as a function of initial soil bulk density for the range tire configurations used in the soil bin studies using a sandy loam soil, 10% (w w^{-1}) moisture content, and uniform soil conditions (corresponding increase in soil bulk density for γ = 1.40 g cm^{-3} from Ansorge and Godwin, 2007).

16% vs. 17% and 25% vs. 29%, respectively). This result confirms that of Håkansson et al. (1988), who suggested that narrower tires can reduce soil compaction if the contact area is maintained or increased by increasing the tire diameter, which appears to be more important as the soil becomes weaker. On the firmer soil, the differences observed between these two tires were relatively small (about 0.8%); consequently, the changes in soil bulk density appeared to be governed to a greater extent by the initial soil strength than by the tire inflation pressure.

For smaller tires (500/60-22.5 at 0.16 MPa and 700/50-26.4 at 0.09 MPa) with a vertical load of 4.5 t, Stranks (2006) showed that the changes in soil bulk density (%$\Delta\gamma$) were of similar magnitude (range of 25% to 30%) to that of the larger tires used in this study when they were operated on a relatively low bulk density soil (γ = 1.25 g cm^{-3}). The tires used by Stranks (2006) exhibited an exponential increase in $\Delta\gamma$ (%) as the initial soil bulk density decreased below a value of approximately 1.40 g cm^{-3}. Again, these relationships were derived from a dataset comprising three initial soil conditions (bulk densities in the range of 1.25 to 1.57 g cm^{-3}). However, the differences in the response of the soil to the pass of the tires observed in this study (linear vs. exponential) confirmed that the extent of soil compaction is largely dependent on the strength of the soil, closely linked to the initial density, and the way the load is spread over the soil.

Overall, the mean increases in soil bulk density for the three sets of tires, as estimated from soil displacement data, were 26.4% (range of 24.4% to 29.4%) and 4.3% (range of 2.4% to 5.7%) for the low and high bulk density soil conditions, respectively. For the medium soil, Ansorge and Godwin (2007) reported a mean increase in soil bulk density of 17% using the same tire configurations. The calculated increase in soil bulk density for the 800/10.5/0.125 tire (half the recommended inflation pressure) operated on the medium soil was approximately 12%, which is significantly lower ($p < 0.05$) than that of the other tires on the same soil condition.

Drop Cone Penetration

The data presented in figures 2 and 4 showed that the extent of soil displacement and the resultant increase in soil compaction depend on a combination of factors including vertical load, tire size and inflation pressure, and, notably, soil strength. Therefore, the assessment of soil strength becomes important prior to undertaking field operations. It enables the prediction of potential soil damage due to compaction, the selection of the adequate running gear, and it aids the decision-making process as to whether field operations should be conducted under the prevailing conditions. An advantage of the drop cone penetrometer over the shear vane is that the drop cone allows for a more accurate determination of the soil condition with fewer replicates (Godwin et al., 1991). This is explained by the larger volume of soil that is disturbed and the deeper penetration of the drop cone compared with the shear vane, which also has some difficulties in ensuring similar rates of shear for every test (Godwin et al., 1991).

Based on the approach proposed by Godwin et al. (1991), a relationship was established between drop cone penetration and rut depth at the center of the wheeling (fig. 5a). Since the increases in soil bulk density produced by the different tire configurations on the three soil conditions are known, they can now be related to rut depth (fig. 5b). These increases in soil bulk density correspond to the central part of the wheeling, as they were estimated from the displacement of the four central points of each soil layer. For uniform soil conditions of density and moisture content, the above relationships appeared to be linear.

The relationships between drop cone penetration and rut depth (fig. 5a) agree closely with those encountered by Godwin et al. (1991) in field conditions for a range of wheel systems and soil types. Given that a reasonably good agreement ($R^2 \geq 0.98$) of drop cone penetration and rut depth was found for the range of initial soil bulk densities investigated, this can prove to be a promising and simple way to derive the rut depth and the associated increase in soil bulk density without the need to take machinery into the field. Subsequently, wheel rut depth may be related directly to crop yield penalty, as shown by Godwin et al. (1991) and Vero et al. (2012). These studies showed that on medium-textured soils, dry matter yield of grass crops decreased approximately linearly with increased depth of wheel rut. Hence, the ability to predict accurately, and in a simple manner, the soil damage resulting from machinery traffic and potential loss of crop yield by employing this technique is an important practical consideration. While the relationships presented in figure 5 were possible under controlled conditions in the soil bin, these findings would benefit from further evidence obtained in field investigations.

Soil Penetration Resistance

Figure 6 shows the results of soil penetration resistance obtained before (control) and after one pass of the tires over the soil. The initial soil bulk density significantly affected ($p < 0.001$) the magnitude of the changes in soil cone index (0 to 700 mm depth range), which, after a single pass of the tires over the soil, increased approximately three times and 5% on the low and high initial bulk density soils, respectively. As expected, significant differences ($p < 0.001$) in soil cone index were obtained between the wheeled and non-wheeled soils. The interaction tire × before vs. after the pass of the tires over the soil was not significant ($p = 0.09$), which suggests that all tires induced increases in soil cone index to a similar extent compared to the non-wheeled soil. However, the 800/10.5/0.25 tire increased soil cone index by approximately 40% relative to the non-wheeled soil, whereas for the 680/10.5/0.22 and 900/10.5/0.19 tires the increases were 28% and 32%, respectively. This result reflects the effect of increased tire inflation pressure on the resultant increase in penetration resistance (Ansorge and Godwin, 2007, 2008; Way et al., 2009).

The higher aspect ratio of the 680/10.5/0.22 tire compared with the 900/10.5/0.19 tire appears to have a beneficial effect, since the overall soil cone index on the high and low initial bulk density soils was slightly lower despite the relatively higher inflation pressure of the 680/10.5/0.22 tire,

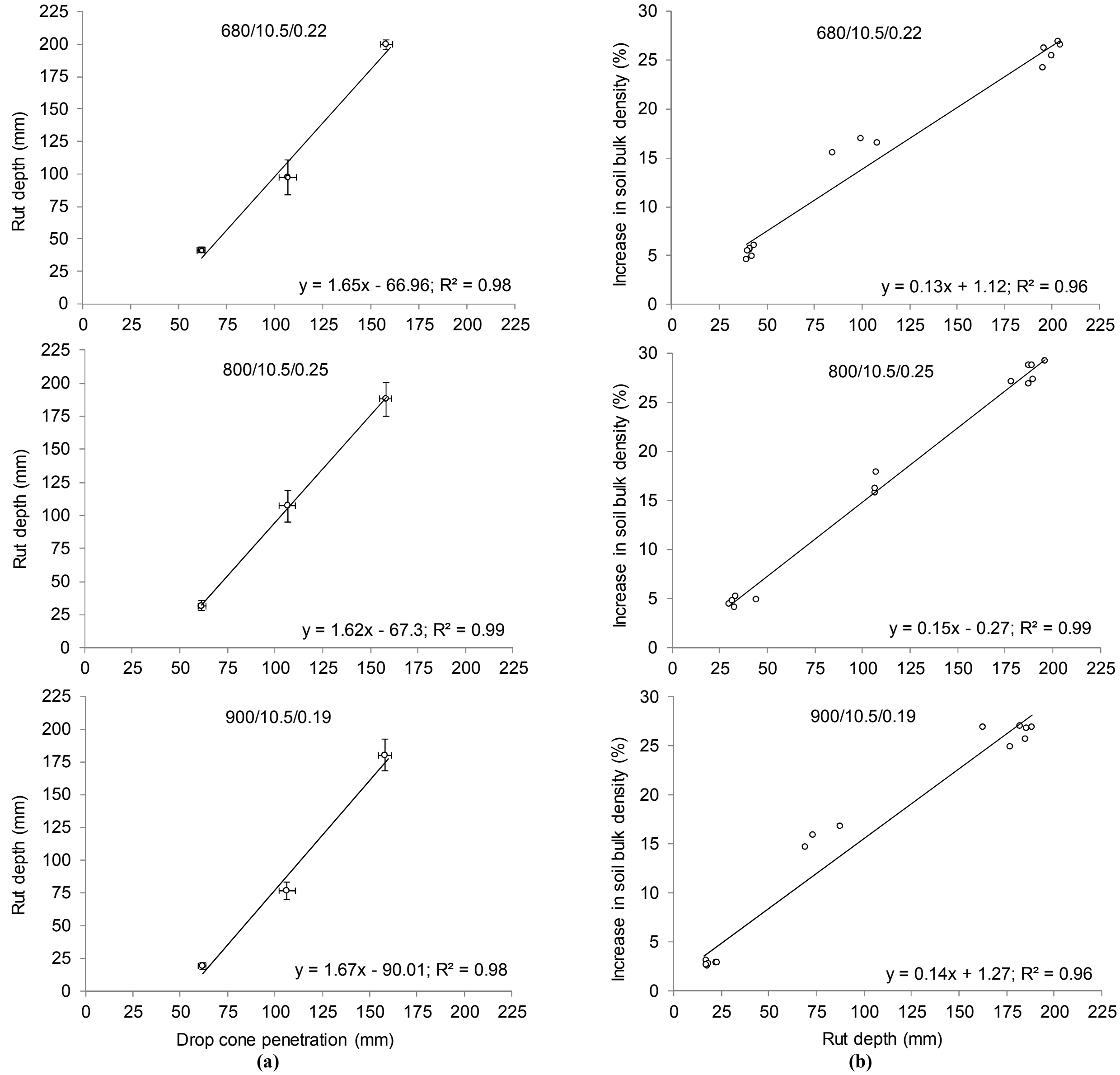


Figure 5. (a) Relationships between drop cone penetration before the pass of the tires over the soil and rut depth at the centerline of wheeling (error bars indicate standard deviations) and (b) relationships between rut depth at the centerline of wheeling and increase in soil bulk density. Sandy loam soil, 10% (w w^{-1}) moisture content, uniform soil conditions, and 1.20 to 1.60 g cm^{-3} initial soil bulk densities.

and this in agreement with Way et al. (2009). For similar aspect ratios but higher inflation pressure, the 800/10.5/0.25 tire increased soil cone index to a larger extent than the 900/10.5/0.19 tire. The increase in soil cone index across the width of the soil bin was significantly ($p = 0.02$) related to the tire inflation pressure and to some extent to the section width of the tire, and it increased significantly ($p < 0.001$) toward the centerline of the rut. The two wider tires increased soil cone index over a larger cross-sectional area than the 680/10.5/0.22 tire; therefore, the overall (mean) results were higher when all ten measurements across the width of the soil bin were averaged. This occurred despite the lower inflation pressure of the 900/10.5/0.19 tire and the similar contact patch areas of the 680/10.5/0.22 and 800/10.5/0.25 tires. For all tires, the maximum values of soil cone index occurred at the centerline of the wheeling. The relatively higher inflation pressure of the 800/10.5/0.25 tire increased soil cone index ($p < 0.05$) in the four central measurements of the rut by about 20% on the softer soil and by 5% on the firmer soil compared with the other two tires. This observation was in agreement with previous studies (Way et al., 1997, 2009), which suggested that higher tire inflation pressure tended to concentrate soil-tire contact stress at the centerline of the tire. For a given load, reduced inflation pressure increases the deformation of the tire, which tends to increase contact stress toward the outer edge of the tire. This reduces stress near the centerline and results in more even stress distribution beneath the tire. On average for all tests, there was an increase of less than 10% ($p < 0.001$) in soil cone index outside the wheeling, which was mainly due to the lateral displacement of soil, as recorded in the vector diagrams (fig. 3).

The interaction penetration resistance at depth × tire

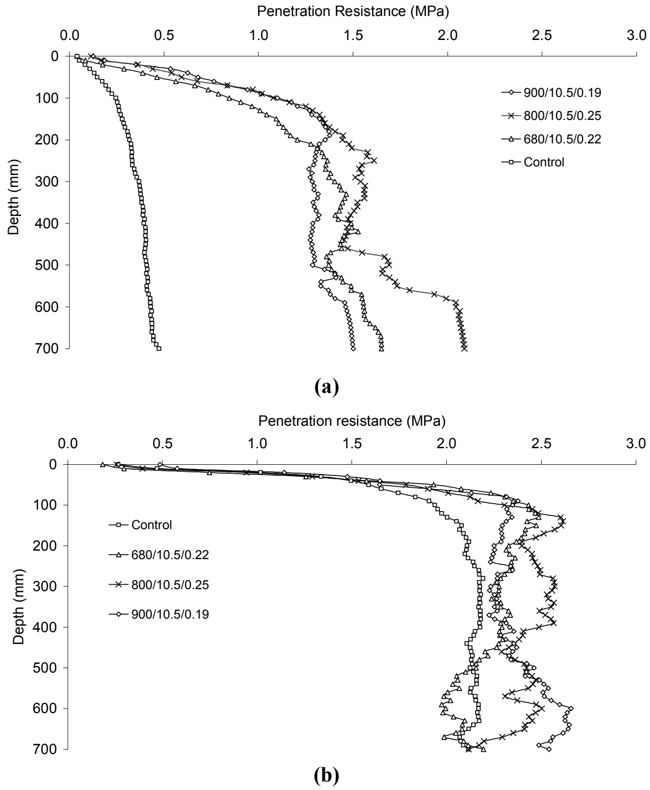


Figure 6. Soil penetration resistance with respect to depth corresponding to wheeled and non-wheeled soils for the four central measurements on (a) low ($\gamma = 1.20$ g cm^{-3}) and (b) high ($\gamma = 1.60$ g cm^{-3}) initial bulk density soils. LSD (5% level) = 0.17 MPa, $n = 30$, and p = 0.1.

showed a significant effect ($p < 0.001$). This effect was related to the tire inflation pressure, which agrees with Ansorge and Godwin (2007) and, to a lesser extent, to the width of the tire, as indicated earlier. The 800/10.5/0.25 tire consistently developed higher values of soil cone index over the measured depth range than the other two tires. These increases in soil cone index were in the range of 17% to 40% compared with the non-wheeled soil, whereas these increases were 10% to 33% for the 680/10.5/0.22 tire and 16% to 35% for the 900/10.5/0.19 tire. When considering all ten measurements across the width of the soil bin, the relatively higher values recorded for the 900/10.5/0.19 tire compared with the 680/10.5/0.22 tire can be attributed to the increase in soil cone index over a larger cross-sectional area, given the relatively greater section width of the 900/10.5/0.19 tire. However, the changes in soil cone index for these two tires at depths greater than 200 mm with respect to the non-wheeled soil were very similar, differing by less than 2% when all ten measurements across the soil bin were averaged. It is therefore emphasized that smaller section width tires can reduce soil compaction provided that the contact patch area is maintained (or increased) by means of a larger tire diameter (Bekker, 1956; Håkansson et al., 1988). This result was also indicated by Ansorge and Godwin (2007) in comparative studies of tires and tracks at high vertical loads (9 to 24 t).

Summary

The main conclusions derived from this research are summarized in the following paragraphs:

The initial soil bulk density was the main factor influencing the extent of vertical soil displacement, increase in soil bulk density, rut depth, and increase in soil penetration resistance under the prevailing experimental conditions. The overall increases in soil bulk density calculated from soil displacement data for all the tire configurations were approximately 26% for the low ($\gamma = 1.20$ g cm^{-3}), 17.5% for the medium ($\gamma = 1.40$ g cm^{-3}), and 4% for the high ($\gamma = 1.60$ g cm^{-3}) initial bulk density soil conditions.

The 900/10.5/0.19 tire produced the least soil displacement, and hence the lowest increase in soil bulk density, compared with the 680/10.5/0.22 and 800/10.5/0.25 tires in the three soil conditions investigated. This was attributable to the relatively larger contact patch area and lower inflation pressure of the 900/10.5/0.19 compared with the other two tires.

The 680/10.5/0.22 and 900/10.5/0.19 tires produced, overall, relatively lower increases in soil penetration resistance (range of 10% to 35%) than the 800/10.5/0.25 tire (range of 17% to 40%), particularly at the centerline of the wheeling. This effect was due to increased deformation of the tires with lower inflation pressure, which resulted in more even stress distribution beneath the tires. The increase in penetration resistance at locations laterally outboard of the wheeling was relatively small (<10%) and was attributed to lateral soil displacement following the pass of the tires over the soil, especially on the low bulk density soil, as recorded in the vector diagrams.

Linear relationships were established between the initial soil bulk density, prior to wheel traffic, and the resultant increase in soil bulk density calculated from the vertical soil displacement data. Linear relationships were also established between drop cone penetration and rut depth at the centerline of the wheeling, which enabled the estimation of the increase in soil bulk density following a single pass of a range of different tire configurations.

Given that a reasonably good agreement ($R^2 \geq 0.96$) was found in the above relationships for a range of initial soil conditions, this appears to be a promising and practical way to derive these parameters and predict potential damage to the soil before harvesting operations are conducted.

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