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Investigating the effect of farmyard manure on clay soil compactibility

Efecto de la aplicación de estiércol de granja en la compactibilidad de un suelo arcilloso
Efeito da aplicação de estrume de currais na compactação de um solo argiloso

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ABSTRACT

One of the important factors that can control and decrease soil compaction is incorporation farmyard manure to the soil. It increases soil elasticity and soil tolerance to the imported load. To evaluate the farmyard manure effect on the soil compaction, it was incorporated in the clay soil at different rates of 0, 45, 60, and 90 Mg ha^{-1}. Tests were conducted at different tire passes of 1, 6, 11 and 16 on the same track at three soil moisture contents of 8%, 11% and 14% (dry base); soil bulk density was measured at depths of 10, 20, and 30 cm. To evaluate soil compaction, cylindrical cores were employed to measure the soil bulk density. To assess soil behavior during the soil compaction process, three displacement transducers were placed in the soil in three coordinate directions of x, y and z. The soil volumetric change was measured using the transducers and soil sinkage was also measured. A single-wheel tester was used in a soil bin with a Barez 8.25-16 (8) P.R HLF agricultural tractor tire operated at a forward velocity of 0.8 m s^{-1} under a vertical load of 4 kN and an inflation pressure of 300 kPa. Incorporating the farmyard manure noticeably decreased the final vertical and longitudinal displacement below the tire track, while the lateral displacement increased. Bulk density decrements of 14.7%, 9.7% and 6.3% were occurred via farmyard manure application rates of 90, 60 and 45 Mg ha^{-1}, respectively. Maximum soil sinkage occurred at 14% moisture, 16 passes of tire and with no manure condition.

RESUMEN

La incorporación de estiércol de granja al suelo es un factor muy importante a la hora de controlar y disminuir la compactación del suelo. Asimismo, puede incrementar la elasticidad del suelo y su tolerancia a la carga. Para evaluar el efecto del estiércol de granja en la compactación del suelo, se añadieron cantidades de 0, 45, 60, y 90 Mg ha^{-1} a un suelo arcilloso. Se llevaron a cabo ensayos con 1, 6, 11 y 16 pasos de neumáticos sobre el mismo carril bajo contenidos de humedad del suelo de 8%, 11% y 14% (base seca). La densidad aparente del suelo se midió con cores cilíndricos a 10, 20 y 30 cm de profundidad. Para evaluar el comportamiento del suelo durante el proceso de compactación, se colocaron tres transductores de desplazamiento en las tres direcciones de los ejes de coordenadas x, y, z. El cambio volumétrico del suelo se midió utilizando los transductores y también se determinó el grado de hundimiento del suelo. Las pasadas se realizaron sobre un contenedor relleno de suelo utilizando un tractor agrícola de un solo neumático (Barez 8.25-16 (8) P.R HLF) operando con una velocidad de 0,8 m s^{-1}, bajo una carga vertical de 4 kN y una presión de inflado de 300 kPa. La incorporación del estiércol de granja disminuyó notablemente el desplazamiento final vertical y longitudinal bajo el neumático, mientras que el desplazamiento lateral aumentó. La aplicación del estiércol en dosis de 90, 60 y 45 Mg ha^{-1} produjeron una disminución de la densidad aparente de 14,7%, 9,7% y 6,3%, respectivamente. El máximo hundimiento del suelo se obtuvo con un 14% de humedad, 16 pases de neumático y sin adición de estiércol.

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RESUMO

A incorporação no solo de estrume proveniente de currais é um fator muito importante para o controlo e diminuição da compactação do solo. Este tipo de estrume pode aumentar a elasticidade do solo e a sua tolerância à carga. Para avaliar o efeito do estrume na compactação do solo, adicionaram-se a um solo argiloso as seguintes quantidades de estrume: 0, 45, 60 e 90 Mg ha^{-1}. Realizaram-se ensaios com 1, 6, 11 e 16 passagens de pneu na mesma pista com teores de humidade do solo de 8, 11 e 14% (base seca). A densidade aparente foi avaliada usando cilindros à profundidade de 10, 20 e 30 cm. Para avaliar o comportamento do solo durante o processo de compactação foram colocados três sensores (transdutores) de deslocamento nas três direções dos eixos de coordenadas x, y z. A alteração volumétrica do solo foi medida usando os sensores e também se determinou o grau de afundimento do solo. Um teste de roda única foi realizado num contentor cheio de solo utilizando um trator agrícola e um só pneu (Barez 8.25-16 (8) P.R HLF) operando a uma velocidade de 0,8 m s^{-1}, com uma carga vertical de 4 kN e uma pressão de inflação de 300 kPa. A incorporação de estrume de curral diminuiu visivelmente o deslocamento final vertical e longitudinal abaixo do rasto do pneu, enquanto o deslocamento lateral aumentou. A aplicação de estrume às taxas de 90, 60 e 45 Mg ha^{-1} levaram à diminuição da densidade aparente de 14,7%, 9,7% e 6,3%, respetivamente. O afundimento máximo do solo ocorreu com 14% de humidade, 16 passagens do pneu e sem adição de estrume.

KEY WORDS
Manure; soil compaction; strain transducers; tire passes.

PALABRAS CLAVE
Estiércol, compactación del suelo, transductores de deformación, pasadas de neumático.

PALAVRAS-CHAVE
Estrume, compactação do solo, sensores (transdutores) de pressão, passagens de pneu.

1. Introduction

Severe soil compaction problems mostly occur in areas where highly mechanized agriculture is carried out on land which is subjected to high rainfall. Excessive compaction reduces plant emergence in the seedbed and impedes plant rooting (Défossez et al. 2003). The extent of compacted soil is estimated about 68 million hectares over worldwide from vehicular traffic alone. Soil compaction is estimated to be responsible for the degradation of an area of 33 million ha in Europe and about 30% (about 4 million ha) of the wheat belt in Western Australia (Hamza and Anderson 2002).

Soil compactibility depends on soil type, soil moisture content, organic matter quantity, particle size distribution, plastic behavior of the clay, clay mineralogy and the number of tire passes and contact pressures under the tire. Managing soil compaction can be achieved through appropriate techniques such as the application of organic matter and controlled traffic (Hamza and Anderson 2005). In order to decrease soil compaction machine traffic on the field should be decreased and the amount of the soil organic matter content of soil should be increased using farmyard manure, compost, green manure, etc. (Cochrane and Aylmore 1994; Thomas et al. 1996; Aksakal et al. 2016). Green or brown manuring as a source of organic matter may not be an economically viable option in a high yielding environment (Fettell 2000) but it is a beneficial practice in improving soil physical properties in compacted soils. Increasing the soil organic matter content improves the soil physical characteristics, such as soil water retention and movement, soil structure and porosity, and favors the establishment of carbon cycling (Gill et al. 2008).

Soil moisture content is the most important factor in the compaction process and soil compactibility (Soane and Van Ouwerkerk 1994). Usually, farmers are not able to easily control soil moisture during trafficking by farm machinery (Mosaddeghi et al. 2000).

Addition of organic matter to topsoil through incorporation of plant residues or manure application has been widely studied by many researchers (Soane 1990; Ohu et al. 1989; Hamza and Anderson 2002). The elasticity of manure prevents the transmission of the stresses toward the subsoil layers (Soane 1990) thus acting as a buffer to decrease the impact of farm machinery on subsoil. Organic matter retains soil water thus helping soil to rebound against compaction. Maintaining an adequate amount of organic matter in the soil stabilizes the structure of soil and makes it more resistant to degradation (Cochrane and Aylmore 1994; Thomas et al. 1996), and decreases bulk density and soil strength (Sparovek et al. 1999; Carter 2002).

Mosaddeghi et al. (2000) reported that the application of manure 50 and 100 ton ha^{-1} to the soil counteracted soil compaction by decreasing its compactibility. They further demonstrated that the manure added up to the depth of 20 cm, increased soil trafficability and reduced subsoil compaction.

A 3-year annual application of manure at 0, 40 and 80 Mg ha^{-1} rates showed that traffic with a contact pressure of 250 kPa significantly reduced the cone index in comparison to no manure conditions (Soane 1990).

A displacement transducer system (DTS) developed by Kühner (1997) was utilized by Wiermann et al. (1999) to measure soil displacement beneath a 18.4R38 tractor drive tire in a firm sandy loam soil. The total vertical strain, calculated as the engineering strain in the vertical direction, was determined using the rut depth and vertical displacement of the sensor in the soil, following the first and second tire passes. The information concerning soil strain in the three mutually orthogonal directions beneath a moving tractor drive tire is expected to be useful in the development of systems that minimize undesirable soil deformation and in the development of computer models that predict traffic-induced soil strain. Shahgholi and Abuali (2015) and Way et al. (2005) investigated soil behavior under tractor tires using a strain transducer with a subsequent measurement of the effect of moisture content, tractor velocity and depth change on the soil compaction. Way et al. (2005) found that cylindrical cores and displacement transducers were recognizably distinct in terms of the obtained bulk density data. Therefore, Shahgholi and Abuali (2015) used standard cores whose length was equal to that of the displacement transducers, as a result of that similar data were obtained by two the methods.

The objectives of the present research were to determine the effect of farmyard manure on soil compaction and soil sinkage at manure application rates of 0, 45, 60, and 90 Mg ha^{-1} in clay soil at different moisture contents and different soil depths under four different number of tire passes. Soil compactibility and its behavior were further investigated through the use of strain transducers.

2. Materials and Methods

2.1. Experimental design

A soil bin featuring 23 m long by 2 m wide by 1 m deep was utilized in this study (Mardani et al. 2010). A rail road was used to facilitate the movement of the carriage and attached single wheel-tester at two sides of the soil bin. An electromotor was used to pull a carriage using chain system and also an inverter was used to control the electromotor rotation speed (**Figure 1**). A single-wheel tester with a lugged agricultural tractor tire of Barez 8.25-16 (8) P.R HLF was used. Tire inflation pressure was maintained at a constant value of 300 kPa under a vertical load of 4 kN, a recommended pressure corresponding to the applied load. Maximum recommended load for this tire was less than 890 kg. It was operated at a forward velocity of 0.8 m s^{-1} during all tests.

Experiments were conducted in three replications in a clay soil containing 43.5% clay, 22.2% silt and 34.3% sand, according to the USDA textural classification of soils, a common soil type in Urumia province, Iran. Some properties of tested soil are presented in (**Table 1**). The critical moisture content in which the maximum soil density can occur was determined

Figure 1. Schematic diagram of the soil bin and single-wheel tester.

Table 1. The physical and mechanical characteristics of the experimental soil

Item	Value
Clay (%)	43.5
Silt (%)	22.2
Sand (%)	34.3
Bulk density (kg m^{-3})	1454
Cohesion (kPa)	4.8
Frictional angle (°)	32
Cone Index (kPa)	700
Dilatational Angle (°)	36
Young Modulus (kPa)	200
Poisson ratio	0.49

by conducting the standard Proctor test (Davis 2008) which value was 18.7% (dry basis).

The experiments were conducted to investigate the effect of farmyard manure, tire passes, soil moisture content, and depth on soil compaction. Table 2 presents a summary of dependent and independent variables of the experiments. Farmyard manure (with a dry bulk density of 300 kg m^{-3}) was provided by the research farm of the University of Urmia. Physical and chemical properties of the tested manure are presented in Table 3. Manure was incorporated in the soil at rates of 0 (control without amendment), 45, 60 and 90 Mg ha^{-1} that are typical rates used by farmers in the research region. Moreover, the required water was sprayed during the mixing operation and it was left over a period of 6 months (September-March) as it was covered with plastic layer to prevent evaporation. During this period, the soil-manure mixture was settled, allowing the farmyard manure to be partially

Table 2. Independent and dependent parameters of experiments

Independent Parameters				
Farm yard manure, Mg ha^{-1}	**Number of passes**	**Moisture Content, % (d.b)**	**Depth, cm**	**Dependent Parameters**
0	1	8	10	Soil Bulk Density, kg m^{-3}
45	6	11	20	Soil sinkage, cm
60	11	14	30	
90	16			

Table 3. Physical and chemical properties of farmyard manure applied to soil

Dry density (Mg ha^{-1})	Organic matter (g kg^{-1})	Organic capon (%)	pH	EC (ds m^{-1})	C/N ratio	N (%)	P (%)	K (%)
0.3	42	25.3	8.7	18.21	17	1.97	0.64	2.04

decomposed. Before tests three soil moisture content of 8%, 11% and 14% (dry basis) were prepared by adding required water to the soil.
In order to analyze the particle movement in vertical and horizontal directions during wheeling, the displacement transducer system was installed (DTS) in the way described by Way et al. (2005). Three displacement transducers were placed in x, y and z directions and 36 cylindrical cores with a diameter and height of 5 cm were used to take soil samples from tire track at an area with a length, depth and width of 6, 0.4 and 0.4 m, respectively.

Cylinders were inserted in the trafficked soil along the displacement transducers after the tire pass, to minimize the likelihood of any difference in the soil bulk density between the transducer and core cylinder measurement locations. The cylinders were inserted in groups of three at different depths and the distance between each group of cylinders along the direction of travel was 40 cm (**Figure 2**). Three samples were taken at depths of 10, 20 and 30 cm to evaluate soil density change. Their average was considered as the average density of each test (**Figure 2**). Furthermore, for each pass, soil density was measured through the use of strain transducers at 20 cm depth, also to investigate soil behavior. In each phase of the tests, the cylindrical cores from each treatment were placed in plastic bags, loosely covered with plastic lids and weighed by a digital balance (Kern and Sohn GmbH, Germany) with 0.01 precision. The soil samples were placed in an oven heated at 105 C° for 24 hours and once again weighed and the soil

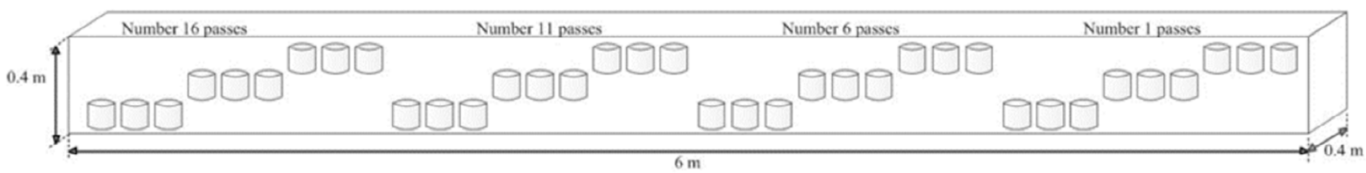

Figure 2. The arrangement of cylindrical cores inserted in the trafficked soil.

moisture content (dry base) and bulk density was determined (Barik et al. 2014).

The displacement transducers including three linear variable differential transformers (LVDT) of model DHL-A-50 with a maximum displacement measurement capacity of 50 cm were used. The strain transducers were mutually orthogonal and were buried directly beneath the centerline of the single-wheel tester path during the tire movement. Two plates were installed at the end points of the transducer to transfer

Figure 3. The arrangement of displacement transducers in three coordinate directions inside soil profile.

soil compression or tension pressure to the transducer and to ultimately measure the soil displacement accurately (**Figure 3**).

All data were logged to a laptop computer via a data logger model DT800 (DataTaker, Australia). The output voltages recorded in each transducer were converted to transducer lengths by use of the respective calibration factors.

The bulk density of the loose soil-manure mixtures was initially 1454, 1430, 1360, and 1290 kg m^{-3} at manure application rates of 0 (control without amendment) 45, 60 and 90 Mg ha^{-1}, respectively as measured using the cylindrical cores at depth range of 15-20 cm. To determine the changes in soil density using the displacement transducers, density was calculated using **Equation 1** and considering the mass of the soil located inside an imaginary hexahedron with dimensions consistent with the three transducers.

$$\rho_2 = \frac{\rho_1 \, l_x \, l_y \, l_z}{(l_x + \Delta_x)\,(l_y + \Delta_y)\,(l_z + \Delta_z)} \quad (1)$$

Where:

ρ_1 = initial soil density, kg m^{-3}

$l_x \times l_y \times l_z$ = initial length of lateral, longitudinal and vertical transducer, mm

$\Delta_x \times \Delta_y \times \Delta_z$ = The change in transducer length of lateral, longitudinal and vertical transducer, mm

ρ_2 = final soil density, kg m^{-3}

For the specification of soil sinkage, a Plexiglas plate was perforated in 2 cm intervals. A digital-vernier-caliper with 0.01 mm precision was applied by putting inside punctures of Plexiglas plate to yield the depth of soil sinkage after wheel pass considering the depression shape of the soil as shown in **Figure 4**. Soil sinkage was determined by measuring the depth of tire ruts. Elevations were measured relative to a reference level before and after the tire pass. A Plexiglas plate was placed at the initial soil surface and the height of the tire ruts was determined from the rut center relative to the initial soil surface.

2.2. Statistical analysis

The ANOVA (analysis of variance) procedure was used to evaluate the significance of each parameter and the influence of their interactions on soil bulk density. To predict and express the effect of the above parameters on soil bulk density and soil sinkage, empirical multiple regression analysis based model was developed using the step-wise selection technique of the SAS software (SAS Institute Inc 1996).

Figure 4. Measuring soil sinkage by means of a digital caliper and a Plexiglas plate.

3. Results and Discussion

3.1. Effect of farmyard manure on soil behavior during soil compaction

Due to the large number of graphs, only the graphs were presented in which the soil behavior was specified for four application rate of farmyard manures of 0, 45, 60 and 90 Mg ha^{-1} with a soil moisture content of 11% and strain transducers were at depth of 20 cm. **Figure 5** shows the soil behavior in the three coordinate directions during soil compaction process for the first pass. Displacement began when the tire was in an approximate 0.75 m distance from the transducers and maximum displacements occurred as the tire center was at the top of the transducers. By increasing the rate of manure application from 0 to 90 Mg ha^{-1}, the final vertical and longitudinal displacement below the tire track significantly decreased while the lateral displacement increased. The highest vertical displacement of 25 mm related to the no-manure treatment while the minimum displacement of 14 mm pertained to a manure application rate of 90 Mg ha^{-1}. The elasticity of manure preventing or lessening the transmission of the stresses toward the subsoil in the lower depths that reduced soil stress and also soil volume strain thus acting as a buffer to decrease the impact of farm machinery on soil compaction (Soane 1990). The vertical displacements in the manure-added treatments were close to one another; however, there was 10 mm difference between the displacements in no-manure and 45 Mg ha^{-1} treatments. Soil expansion in the lateral direction increased from 5 mm at no-manure to 8 mm at a manure application rate of 90 Mg ha^{-1}. The findings indicated that the bulk density decreased with the increment in the farmyard manure; similarly, Kinney et al. (1992) found that there was a direct relationship between soil bulk density and soil strain variations.

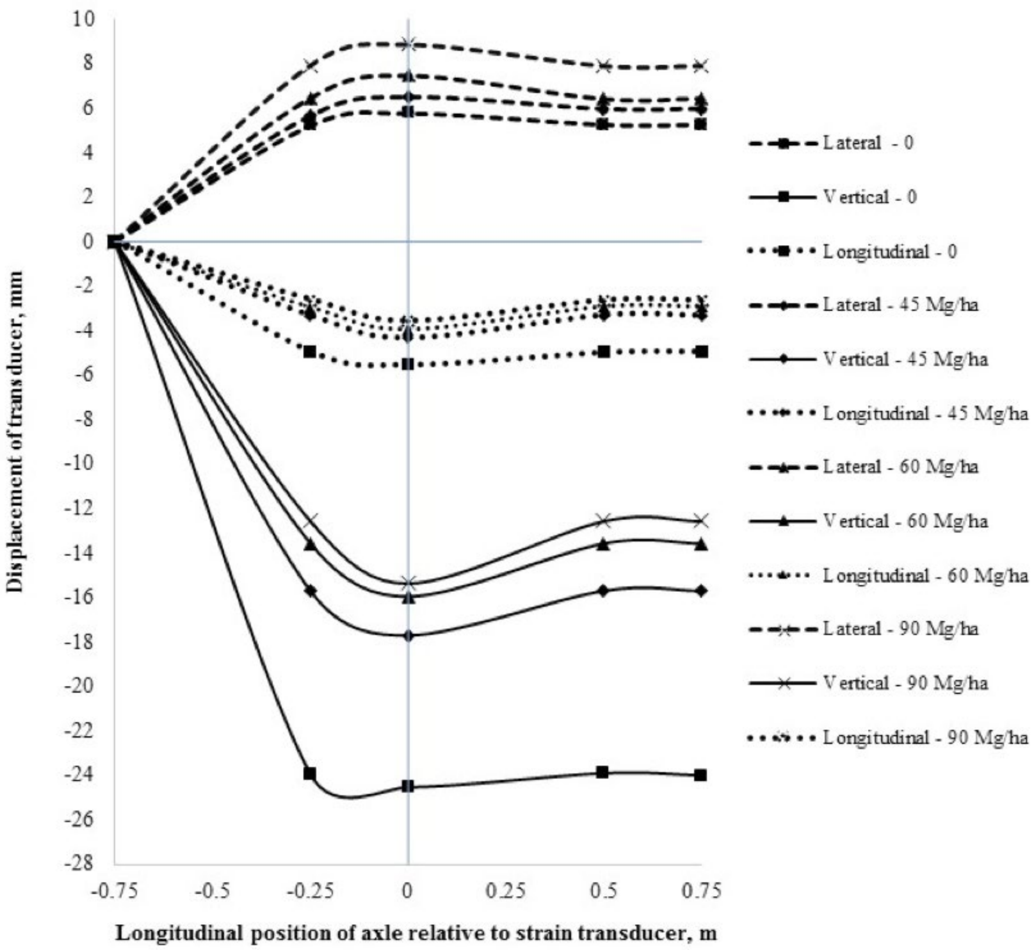

Figure 5. Representative in the three coordinate directions during soil compaction process of the transducer, induced by four manure application rates during the first tire pass.

3.2. Effect of number of tire passes on soil behavior during soil compaction

Figure 6 shows the effect of the number of tire passes on soil behavior at a manure application rate of 90 Mg ha^{-1} and soil moisture content of 8% as the strain transducers located at a depth of 20 cm. Displacement in the three coordinate directions during soil compaction process increased with increasing the tire passes. The number of tire passes that entailed the maximum displacement in all directions was sixteen. Vertical displacements of 8.4, 16.6, 20.4 and 22.6 mm occurred at pass numbers of 1, 6, 11 and 16, respectively. By augmenting the number of passes from 1 to 6, vertical displacement almost doubled, while an increment of 10% occurred as the pass numbers increased from 11 to 16. Considering vertical displacements, the outcome of the present study shows that augmentation of soil compaction gradually decreases with multiple passes. Moreover, an increase in the number of tire passes led to an increase in the lateral soil expansion and longitudinal compression below the tire. In the first pass, the soil compressed in a longitudinal direction with the approaching tire until the tire center was on the top of the transducer and after passing tire center it expanded and then compressed again and then remained constant. For the next passes of the tire, the soil was compressed by longitudinal displacement and no significant variation was observed in soil behavior. For vertical displacements, it was found that augmentation of soil compaction gradually decreases by multiple passes.

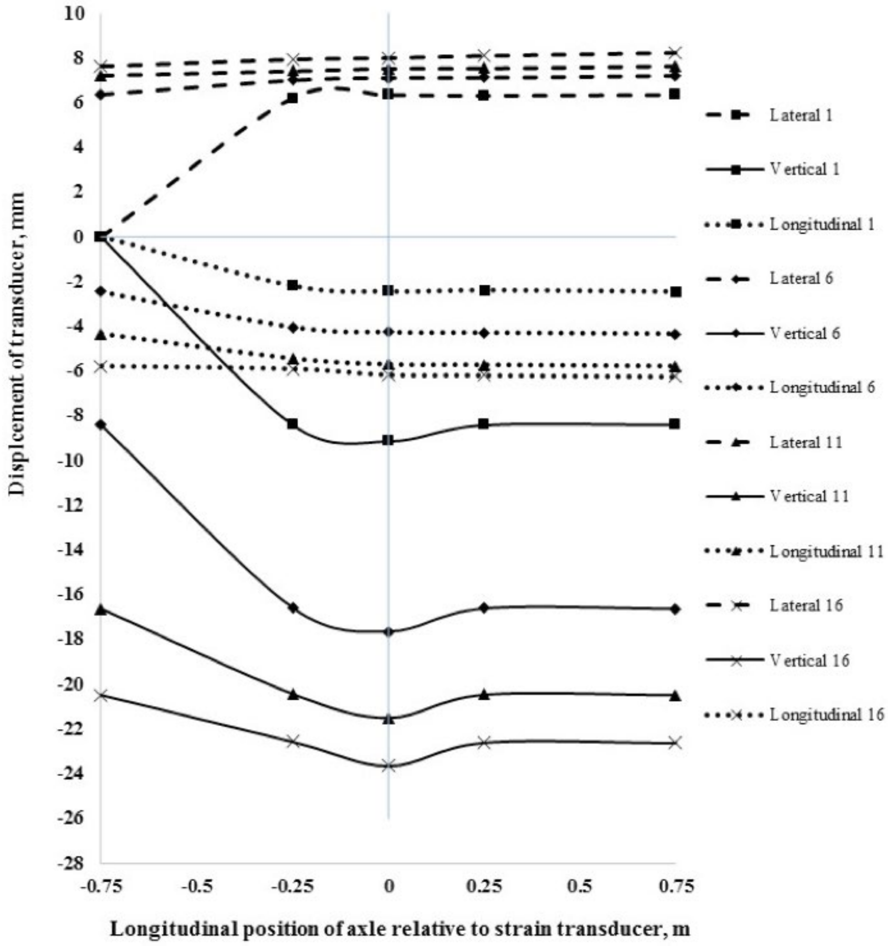

Figure 6. Representative in the three coordinate directions during soil compaction process of the transducer, induced by number of passes at manure application rate of 90 Mg ha^{-1}.

3.3. Effect of soil moisture content on soil behavior during compaction

Figure 7 shows the moisture content effect on soil behavior with a manure application rate of 90 Mg ha^{-1} and strain transducers located at a depth of 20 cm during the first tire pass. By augmenting the moisture content, a noticeable increase was observed in soil compaction at the three coordinate directions. Maximum displacement was related to the moisture content of 14% which was close to the critical moisture of the soil specified by the standard Proctor test. Maximum vertical displacements of 18, 23 and 29 mm occurred at moisture contents of 8%, 11% and 14%, respectively (**Figure 7**). This is typical soil compaction behavior where the soil is increasingly deformed with increasing moisture content and number of tire passes (Patel and Mani 2011). In agreement with the observations of Stone and Ekwue (1993) the greater the soil moisture content, the more the deformation and susceptibility of the soil to compaction will be (Stone and Ekwue 1993). Increasing the soil moisture under critical values resulted in a high soil compaction because the water in the soil acts as a lubricant (Canillas and Salokhe 2002).

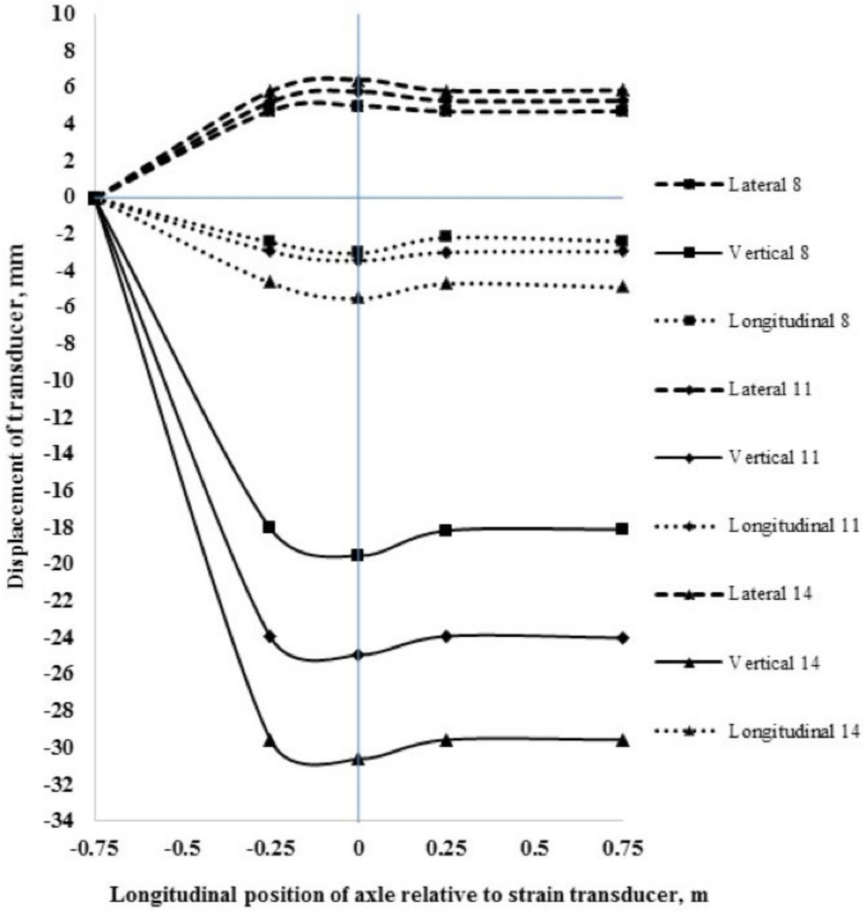

Figure 7. Representative in the three coordinate directions during soil compaction process of the transducer, induced by soil moisture during the first tire pass.

3.4. ANOVA for bulk density

Table 4 shows the analysis of variance of the effect of manure rate, soil moisture content, number of tire pass and depth significantly affected the soil bulk density at the 1% significance level. Mutual binary of manure with depth at the 5% significance level and the triplet interaction number of passes with depth and moisture were also significant at the 1% significance level. However, Mosaddeghi et al. (2000) found that the mutual binary of manure with moisture, manure with the number of passes and moisture with depth was not significant.

Table 5 shows the bulk density means of the main factors. Tukey's studentized range test at 1% significance level was used to determine the significance of each factor. Soil bulk density decreased with the increment manure application rate. The maximum density of 1815 kg m^{-3} occurred in condition without the manure. The highest application rate of 90 Mg ha^{-1} resulted in a significantly lower bulk density of 1546.7 kg m^{-3} compared to the other rates. The bulk density decrement rates were 14.7%, 9.7% and 6.3% at manure application rates 90, 60 and 45 Mg ha^{-1}, respectively. Similar results regarding the effect of manure on bulk density variation were reported by other researchers such as Mosaddeghi et al. (2000) and Soane (1990).

The Maximum density of 1728.44 kg m^{-3} occurred at 16 passes of tire, hence the more the tire passes, the more the density will be. Bulk

Table 4. Analysis of variance (ANOVA) table for the effect of manure, moisture, number of passes and depth on soil density

Factor	DOF	Sum of squares	Mean Square	F Value
Treatment	143	11417442	79842.2	14.2**
Manure	3	4112763.8	1370921.2	244.7**
Number of passes	3	794384.8	264794.9	47.2**
Moisture	2	2818025.6	1409012.8	251.5**
Depth	2	2489568	1244784	222.2**
Manure × Depth	6	93744.8	15624.1	2.7*
Manure × Moisture	6	63184.5	10530.7	1.8^{ns}
Manure × Number of passes	9	85543.3	9504.8	1.7^{ns}
Moisture × Depth	4	15357.6	3839.4	0.6^{ns}
Number of passes × Depth	6	113192.4	18865.4	3.3**
Number of passes × Moisture	6	172119.3	28686.5	5.1**
Manure × Number of passes × Moisture	18	168666.5	9370.3	1.67*
Moisture× Number of passes × Depth	12	103187.1	8598.9	1.54^{ns}
Manure × Number of passes × Depth	18	49467.5	2748.1	0.49^{ns}
Manure × Moisture × Depth	12	103954.7	8662.8	1.55^{ns}
Manure × Moisture × Number of passes × Depth	36	234281.3	6507.8	1.16^{ns}
Error	288	1613295.94	5601.72	
Total	431	13030737.94		

Note: ** = statistically significant (P < 0.01); * = statistically significant (P < 0.05); $^{n.s}$ = not significant.

Table 5. Anova statistics for the effect of manure, moisture, number of passes and depth on soil density

Manure application rate, Mg ha^{-1}	BD, kg m^{-3}	Number of passes	BD, kg m^{-3}	Moisture (db), %	BD, kg m^{-3}	Depth, cm	BD, kg m^{-3}
0	1815 a	1	1612.19 d	8	1578.81 c	10	1780.30 a
45	1700 b	6	1663.32 c	11	1669.34 b	20	1639.59 b
60	1637.5 c	11	1695.45 b	14	1776.41 a	30	1604.67 c
90	1546.7 d	16	1728.44 a				

Note: Different letters show there is statistically significant difference.

density increments of 51.13, 32.13 and 33 kg m^{-3} occurred as the tire passes increased from 1 to 6, 6 to 11 and 11 to 16, respectively; the bulk density increase was 3.17%, 5.16% and 7.21%, accordingly. Patel and Mani (2011) reported that 16 passes of the tire tractor induced the highest soil compaction.

The increment in the moisture content resulted in an increase in the soil bulk density. Average bulk densities of 1578.81, 1669.34 and 1776.41 were obtained at moisture contents of 8%, 11% and 14%, respectively. The bulk density increased by 5.73% and 7.92% following the increase in moisture content from 8% to 11% and 14%, respectively. Soil compaction was reduced as the soil depth increased due to the decrease in the stress of sub-soil layers. Maximum bulk density of 1780.3 kg m^{-3} occurred at the depth of 10 cm, declined to 1639.59 and 1604.67 kg m^{-3} at depths of 20 and 30 cm, respectively. Decrement rates of 7.90% and 9.86% happened as soil depth increased from 10 to 20 cm and 30 cm, respectively. These results are similar to those reported by Barik et al. (2014). They found that the increment rate in bulk density after the tractor traffic was 14.5, 5.3 and 6.7% at the depth ranges of 0-10 cm, 10-20 and 20-30 cm, respectively.

The impacts of manure rate, moisture, and number of tire passes were more noticeable on soil compaction, respectively. Soane and Van Ouwerkerk (1994) indicated that soil moisture content is the most important factor affecting soil compactibility; the results showed that manure application showed the same effect on decrement soil compaction as moisture content.

Table 6 illustrates the mutual binary effect of manure, number of tire passes, moisture and depth on soil compaction. Tukey's studentized range test at 5% significance level was used to determine the significance of the difference. Maximum density of 1927.4 kg m^{-3} occurred at the depth of 10 cm and in the absence of manure, while it was 1653.5 kg m^{-3} at the manure rate of 90 Mg ha^{-1}. Increasing the depth from 10 to 30 cm led to the decrement of bulk density in average of 10% at all application rates. The increase in soil moisture augmented soil compaction and the highest compaction was obtained at the soil moisture content of 14%, and a maximum density of 1853.5 kg m^{-3} occurred at 16 tire passes. The statistical analyses showed that the effect of tire passes and depth on soil compaction was significant only at a depth of 10 cm. In terms of their effect on soil compaction, manure rate, moisture content, number of tire passes and depth were the more important factors. However, the arrangement was changed to moisture content, number of passes and manure rate as far as the effect on soil sinkage is concerned.

Table 6. Statistical analyses effects of manure, number of passes, moisture and depth on soil compaction

Soil bulk density, kg m^{-3}			
Manure application rate, Mg ha^{-1}	**Depth of 10 cm**	**Depth of 20 cm**	**Depth of 30 cm**
0	1927.4 a	1803.7 b	1713.8 ed
45	1796 cb	1659.5 feg	1644.6 hfg
60	1744.2 dc	1583.2 ji	1585.2 i
90	1653.5 g	1511. 8k	1474.9 lk
Number of passes	**Depth of 10 cm**	**Depth of 20 cm**	**Depth of 30 cm**
1	1683.9 ed	1586 kg	1566.5 lijk
6	1766.2 cb	1626.8 hefg	1596.9 jfg
11	1813.3 ba	1653.5 fd	1619.5 ifg
16	1857.6 a	1692 d	1635.7 gd
Number of passes	**Moisture of 8% (db)**	**Moisture of 11% (db)**	**Moisture of 14% (db)**
1	1547.9 ljk	1617.2 hf	1671.4 fc
6	1574.2 kh	1653.6 gef	1762 cb
11	1582.2 jh	1685.5 ec	1818.5 ba
16	1610.8 igh	1720.9 dc	1853.5 a

Note: The same letters are not significantly different at the 5% significance level.

3.5. Soil sinkage

The effect of manure rate on soil sinkage was significant at the 5% significance level, while that of moisture contents and number of tire passes was significant at the 1% significance level (**Table 7**). Increasing the number of tire passes and soil moisture entailed an increase in soil sinkage. The maximum sinkage of 13.37 cm occurred at the soil moisture of 14%. Soil sinkage increased 3.2 cm due to the increment of tire passes from 1 to 16 (**Table 7**).

Table 7. Analysis of variance (ANOVA) table for the effect of manure, moisture and number of passes on soil sinkage

Factor	DOF	Sum of squares	Mean Square	F Value
Treatment	47	493.5	10.5	5.37**
Manure	3	16.3	5.4	2.78*
Number of passes	3	213.8	71.2	36.46**
Moisture	2	182.3	91.1	46.65**
Manure × Number of passes	9	6.5	0.72	0.37^{ns}
Manure × Moisture	6	19.78	3.29	1.69^{ns}
Number of passes × Moisture	6	22.16	3.69	1.89^{ns}
Manure × Number of passes × Moisture	18	32.60	1.81	0.93^{ns}
Error	96	187.6	1.95	
Total	143	681.2		

Note: ** = statistically significant (P < 0.01); * = statistically significant (P < 0.05); $^{n.s}$ = not significant.

Table 8 shows the soil sinkage means for three main factors. The increase in manure application rates reduced the soil sinkage while the maximum soil sinkage of 12.38 cm occurred in the no-manure treatment; the sinkage was reduced to 12.29, 12.02 and 11.52 cm as manure application rate increased to 45, 60 and 90 Mg ha^{-1}, respectively. The minimum sinkage value of 10.13 cm occurred in the first pass of the tire, increasing to 11.93, 12.83 and 13.33 as the pass number increased to 6, 11 and 16, respectively. Soil sinkage increase was 17.76%, 26.65% and 31.58% following the increasing number of tire passes from 1 to 6, 11 and 16, respectively. Botta et al. (2009) investigated soil sinkage for tractor passes in the soil under conventional tillage and direct sowing using two different weights of the tractors. Soil sinkage was 6.8, 7.3, 8.5 and 14.5 cm in the tire pass number of 1, 3, 5 and 10, respectively. The greater soil sinkage values for both tractors were produced on soil under conventional tillage because of the high compressibility of the loose soil. Also, soil sinkage was 10.62 cm at a moisture content of 8%, reaching 12.17 and 13.37 cm as soil moisture increased to 11% and 14%, respectively.

Table 8. Anova statistics for the effect of manure, moisture, number of passes on soil sinkage

Manure application rate, Mg ha^{-1}	soil sinkage, cm	Number of passes	soil sinkage, cm	Moisture (db), %	soil sinkage, cm
0	12.38 a	1	10.13 d	8	10.62 c
45	12.29 b	6	11.93 c	11	12.17 b
60	12.02 c	11	12.83 b	14	13.37 a
90	11.52 d	16	13.33 a		

Note: Different letters show there is statistically significant difference, P < 1%.

3.6. Prediction model for soil bulk density and soil sinkage

Regression analyses were also carried out to establish a functional relation between independent and dependent variable to develop multiple regression models. The developed multivariate liner equations from regression analysis are presented in **Equation (2) and (3)**. Models were proposed to predict bulk density and soil sinkage at clay soil with determination coefficient (R^2) of 0.959, 92.66, respectively. Different models were evaluated in predicting bulk density value and the model with high square value was selected.

(2) BD = 1995 + 1.96 D + 63.33 M + 4.99 P - 1.12 FM - 1.189 D.M -0.2867 D.P - 0.0478 D.FM -0.00923 P.M.FM

(3) Sinkage = 7.77 - 0.0326 FM + 0.142 P + 0.282 M

where BD is the soil bulk density, kg m^{-3}; FM the amount of farmyard manure Mg ha^{-1}; P the number of passes; M soil moisture; D is the soil depth, cm.

Analysis of variance of the multiple regression models for bulk density and soil sinkage is given in (**Table 9**). Regression equations for bulk density and soil sinkage were validated with the measured data.

Table 9. Analysis of variance of the multiple regression model for bulk density and soil sinkage

	Source of variation	Degree of freedom	Sum of squares	Mean square	F-value
Bulk density	Regression	5	5699358	1139872	241.41**
	Residual	426	2011466	4721.75070	
	Total	431	7710824		
sinkage	Regression	5	596.1	119.22	501.68**
	Residual	138	32.79	0.23	
	Total	143	628.9		

Note: ** = statistically significant (P < 0.01).

The observed and predicted values determination coefficients (R^2) were 0.81 and 0.59 for bulk density and soil sinkage, respectively (**Figures 8-9**). Patel and Mani (2011) predicted a model for bulk density and cone penetration resistance in tractor passes test with varying normal loads on soil compaction at the experimental farm. This research includes more effective parameters such as farmyard manure application and soil moisture content which were not considered by Patel and Mani (2011).

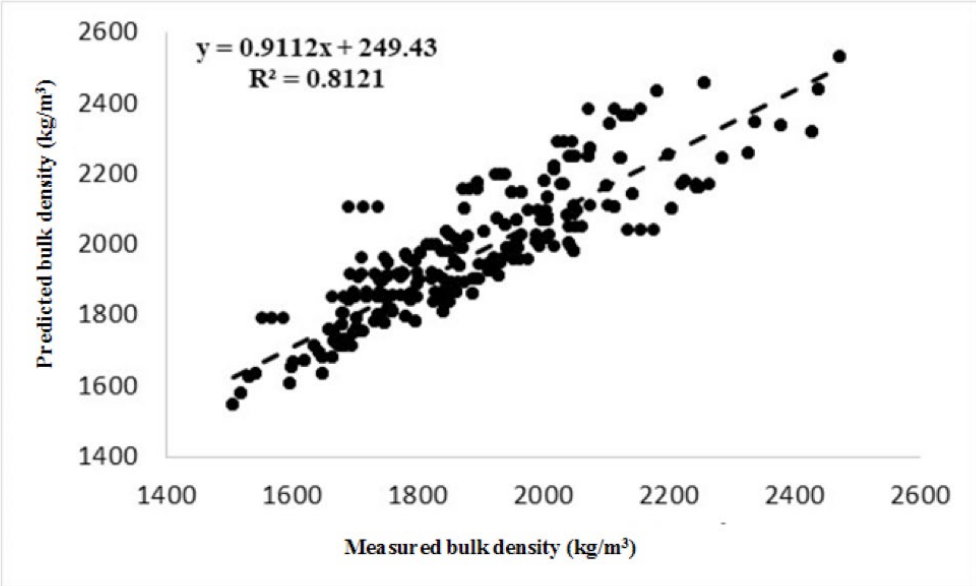

Figure 8. Correlation between values predicted and measured bulk density by **Eq. (2).**

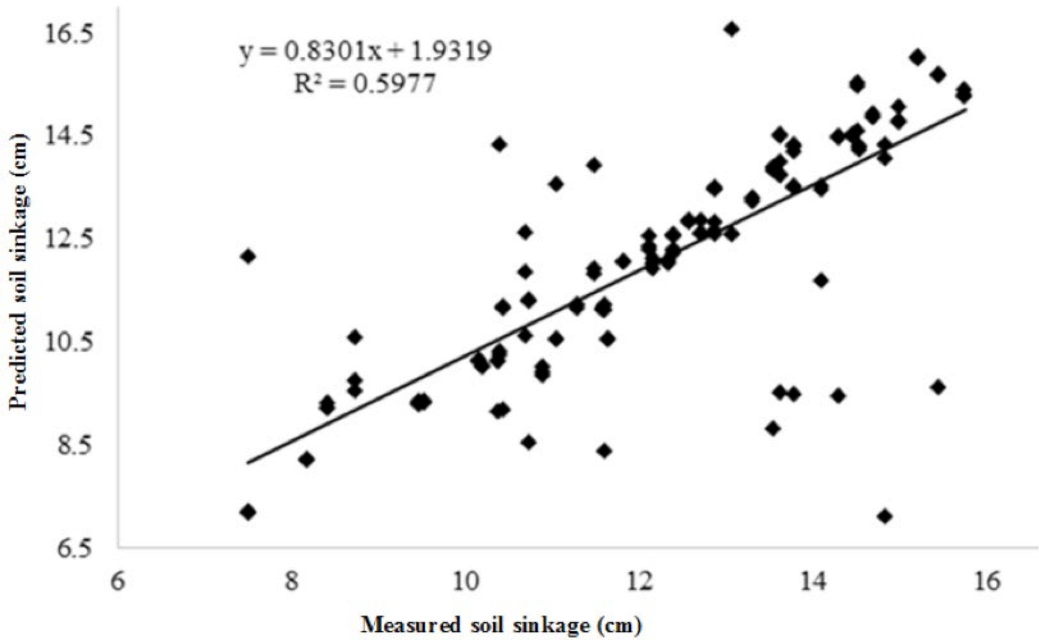

Figure 9. Correlation between values predicted and measured soil sinkage by **Eq. (3).**

4. Conclusions

The following conclusions were drawn from soil bin experimental study to evaluate soil compaction as affected by farmyard manure, moisture content and multiple tire pass at different depths. The results of this study clearly indicated that manure application decreased soil compaction and soil sinkage:

1- Soil behavior under a tractor tire using a displacement transducer system (DTS) showed that incorporation manure decreased final soil displacement in vertical and horizontal directions and increased lateral displacement. Accordingly, the conclusion is that any manure amount increases soil elasticity and DTS is a proper method for investigating and measuring soil compaction. A determination value of 0.94 was found between bulk densities measured via cylindrical cores and DTS.

2- The relative effects of manure on compaction depend on the rate of its application. The decreasing rates in bulk density values at 90 Mg ha^{-1} was 14.7% in comparison to zero manure treatment. An increase in soil moisture and the number of tire passes augmented soil compaction. Soil bulk density increased by 7.21% as the tire passes increased from 1 to 16, and by 7.92% as moisture increased from 8% to 14%. It was found that clay soil is very sensitive to tire traffic at moisture levels close to the critical moisture level. Then, agricultural operations in clay soil must be carried out at the minimal soil moisture recommended for farm operations.

3- The soil sinkage occurrence pattern was similar to the soil bulk density change. Soil sinkage was reduced when manure was incorporated into the soil. It decreased by 6.94% following the application of 90 Mg ha^{-1} manure in comparison to no-manure treatment. Soil sinkage increased as the soil moisture and tire pass number increased.

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