Effect of soil compaction on physico-mechanical properties of silt loam soils of Njoro, Kenya

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Abstract: In order to cope with the demand for more food for the continuously growing world population, it has become necessary to intensify farming leading to increased mechanization. The repeated movement of agricultural machines across the field has led to increased incidences of soil compaction. Although more studies undertaken on the effect of wheel traffic on soil compaction have used bulk density and penetration resistance as indicators, not much has been done on the effect of wheel traffic on mechanical properties of soil. The objective of this study was to establish the effects of soil compaction on selected soil physico-mechanical properties. A tractor of 4070 kg with an engine of 74.6 kW was used and the effect of repeated wheel passes on bulk density, penetration resistance, soil cohesion, angle of internal friction and soil strength studied. A factorial experiment in a completely randomized block design was used. Tests were conducted on 18 plots to investigate the effect of five tractor wheel pass treatments (1, 2, 3, 4 and 5) and a no wheel pass treatment on the soil properties at three depths (0 - 20, 20 - 30 and 30 - 40 cm) with three replications per plot. The results showed that increasing the intensity of traffic wheel passes and depth resulted in significant increase in bulk density (1291 to 1593 kg m^{-3}), penetration resistance (from 640 to 1340 kPa), soil strength (from 121.20 to 156.97 kPa), angle of internal friction (from 29° to 35°) and soil cohesion (from 6.84 to 8.42 kPa) at 5% level of confidence. It was concluded that although wheel passes subsequent to the first had a smaller effect on the studied properties, it is cautioned that additional passes may lead to increased tillage draft requirements.

Keywords: bulk density. cohesion, compaction, strength, tractor, wheel traffic

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1 Introduction

Farming has been intensified in recent days to cope with the demand for more food for the growing world population. This has resulted in increased mechanized farm operations. The increase of soil degradation by compaction has resulted from the intensive use of these machinery (Orzech et al., 2021). Soil compaction is an invisible form of soil degradation that is not easily detected on the soil surface (Ramazan et al., 2012).

Compaction of the soil occurs when an external stress applied on the soil surface exceeds the mechanical stability of the soil (Gürsoy, 2021). The applied stress alters the soil structure by pushing particles closer together. This reduces the volume of

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the pore spaces. Compaction limits root growth and resulting in reduced crop yields. Due to compaction, soil becomes more rigid leading to increased energy consumption during cultivation, increasing the traction forces and fuel consumption. This leads to increased emissions, which contribute to global warming (Bengough et al., 2011).

Hargreaves et al. (2019) documented the main causes of soil compaction as inadequate soil management, animal trampling, machinery traffic, impact of raindrops, intensive cropping, soil wetting, internal soil water tensions and the contact with machinery tyres. Studies have reported that the risk of undesirable changes in soil structure can be reduced by limiting the mechanical stress applied on soil (Biriş et al., 2011).

The consequences of soil compaction include limiting the growth of roots and inhibition of plant development leading to reduction of agricultural production (Tenu et al., 2012). Since deep compaction can persist for a long period of time, it can threaten soil productivity for a long time (Uceanu et al., 2008). Efforts to alleviate deep compaction by deep loosening of soil are expensive. Therefore, ploughing is being replaced with conservation tillage in modern farming to reduce the number and intensity of soil loosening operations (Orzech et al., 2021).

Soil structure changes due to soil compaction have previously been evaluated using bulk density and penetration resistance (Tim Chamen et al., 2015; Nawaz et al., 2013). Although many studies been carried out on the effect of soil compaction on bulk density and penetration resistance, not much is reported on the mechanical properties of soil. The study of soil mechanical properties is of importance because the dynamics of soil shear strength affect the driving resistance to agricultural machinery.

Soil shear strength is reflected from the physicochemical bonds (cohesion) and internal frictional resistance between particles (Amiri et al., 2019). Soil cohesion is dependent on the bonds between adjacent soil particles only (Gitau et al., 2006; Sadek et al., 2011). The angle of internal friction results from the interlocking of rough soil particles, therefore coarse-grained soils exhibit higher angles of internal friction than fine grained soils. The movement of soil particles while failing depends on the structural arrangement of particles in coarse-grained soils and the degree of bonding between adjacent particles in fine-grained soils (Zadeh, 2006).

This study had the objective of assessing the impact of soil compaction on selected soil physical and mechanical characteristics of silt loam soils.

2 Materials and methods

2.1 Experimental site

A wheeling experiment was performed in Njoro, Kenya, on arable field previously under corn maize with scattered stubble. The experimental field is located at latitude 0° 23’ South, longitude 35°35’ East and is 2,238 m above sea level. The site had 0 to 1% slope and had been utilized for many years using conventional tillage. The silt loam soil consisted of 37%, 51% and 12% of sand, silt and clay respectively. The moisture content during the experiments ranged from 23% to 32% on dry basis.

2.2 Experimental design and set up

The factorial design was generalized to two factors. The effect of five traffic levels (0, 1, 2, 3, 4 and 5) were determined at three soil depths of 0 - 20 cm (topsoil layer), 20 - 30 cm (hardpan layer) and 30 - 40 cm (subsoil layer). Five passes were chosen since studies have indicated that beyond the third pass of the well the change in soil properties is minimal.

Eighteen experimental plots were used each measuring 30 m long by 15 m wide with a 5 m wide buffer between adjacent plots (Figure 1). Wheel pass treatments made using a Massey Fergusson 455 *xtra* tractor of weight 4070 kg with an engine power of 74.6 kW (100 hp). The tractor had rear tyres of 9.00-16 F2 10PR, diagonals, inflated to a pressure of 150 kPa. The tractor was first run for one pass at a forward speed of 2.5 km h^{-1}. After the pass, soil samples were collected from three randomly selected locations at depths of 0 - 20, 20 - 30 and 30 - 40 cm. Multiple passes of 2, 3, 4 and 5 were made to determine their effect on bulk density, penetration resistance, cohesion, angle of internal friction and shear strength.

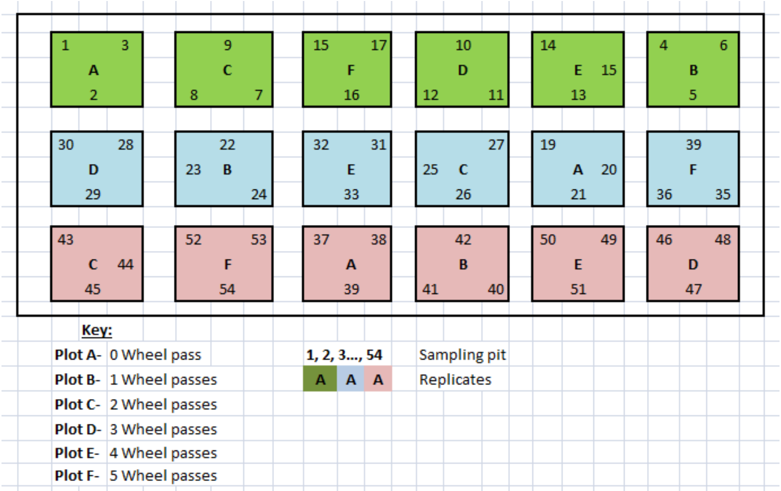

Figure 1 Experimental plots layout

2.3 Determination of soil properties

2.3.1 Bulk density

The core sampler with its content were weighed then dried in the oven at 105 °C for 24 hours to a constant weight. The mass of oven dry soil was measured using an electronic balance. Bulk density was then determined using the equation (Naghdi and Solgi, 2014):

$$\rho = W_d/V_c \qquad (1)$$

where, ρ is the bulk density (kg m^{-3}); W_d is weight of the dry soil (kg);V_c is volume of the soil cores (m^3).

2.3.2 Penetration resistance

An Eijkelkamp analogue cone penetrometer was pushed vertically into the soil and readings taken up to 12 cm depth of the penetrometer. The instrument had 0.25 and 0.5 cm^2 cones and compression springs of 50, 100, and 150 N. A slip ring on a graduated scale was slid along as the spring was compressed, indicating the maximum compression measured. Penetration resistance was calculated as (ASABE, 2006):

$$PR = 100\ C_s I/A_c \qquad (2)$$

where, *PR* is the penetration resistance (N m^{-2}); I is the impression on the scale (m); *Cs* is the spring constant (N m^{-1}); A_C is the area of the cone (m^2).

2.3.3 Determination of shear strength parameters

Undisturbed soil samples were collected from each plot by pushing sharpened, thin-walled stainless steel tubes of dimensions 38 mm internal diameter and 200 mm height. The rings were then removed, trimmed, covered with plastic lids and sealed. The sample was extruded out of the tubes and a 76 mm sample was cut off from the 200 mm sample (Gitau et al., 2008).

The digital system used in this study include a cabinet mounted triaxial cell, loading attachments and a pressure control panel as given by Gitau et al. (2006). The triaxial cell was designed to withstand pressures of up to 1.7 MPa. A constant cell pressure of up to 800 kPa was supplied by a compressor through a port.

The triaxial tests were performed on cylindrical soil specimens subjected to all-round effective confining stresses. Axial stresses were applied to the specimens through a loading rod in contact with the top of the specimen. The soil specimens were enclosed in rubber membranes and the ends placed between porous caps with drainage ducts. The effective confining stresses ranged between 50 and 500 kPa in increments of 50 kPa. Specimens were compressed and sheared in the axial direction at a rate of 0.25 mm min^{-1}.

The shear strength for the soil was determined from the Mohr–Coulomb failure equation (Gitau et al., 2006):

$$\tau = c + \sigma \tan \phi \qquad (3)$$

where, τ is the shear strength (kPa); c is the cohesion (kPa); σ is the effective normal stress (kPa); ϕ is the internal angle of friction (°).

For each soil sample, the effective normal stress and shear strength were plotted and the curves fitted with a straight line. Cohesion and internal angle of friction of the soils were determined graphically by construction of Mohr circles. The angle of the straight line was the internal friction angle, while the intercept of the straight line in the longitudinal coordinates was the cohesion.

2.4 Statistical analysis

A factorial experiment in a completely randomized block design was used in the study. The results of the experiments were analyzed using an analysis of variance (ANOVA). The fixed factors were number of tractor wheel passes and soil depth. The interaction between the factors was also analyzed. The least significance differences between means were conducted at a significance level of $\alpha = 0.05$.

3 Results and discussion

3.1 Bulk density

The soil bulk density was noted to generally increase as the number of tractor wheel passes and depth (Figure 2). An increase in bulk density was observed in the 0 - 20 cm depth layer with increase in number of passes. The minimum bulk density determined in this layer was 1291 kg m^{-3} for the untrafficked soil while the maximum bulk density value was 1580 kg m^{-3} after five passes. One pass caused 36% of this increase in bulk density.

The bulk density was higher in the 20 - 30 cm layer compared to the 0 - 20 cm layer. It was observed to increase from 1318 kg m^{-3} at no wheel pass to 1584 kg m^{-3} after five wheel passes. In the 30 - 40 cm layer the bulk density was observed to be higher than the top soil and was observed to increase from 1337 kg m^{-3} with no wheel traffic to 1593 kg m^{-3} after five passes. One wheel pass resulted in 50% of the observed change in bulk density.

It was noted in this study that bulk density increased with increasing traffic intensity. The higher bulk density produced under multiple tractor wheel passes could be due to decreases in soil volume as soil particles are pressed together and pore space. However, the ANOVA performed on the factors (Table 1) revealed that this change in bulk density was not significant at the 5% level of confidence.

The ANOVA indicated that the soil depth had a significant effect on bulk density. However, wheel the interaction between soil depth and wheel traffic did not have a significant effect on the bulk density. The increased bulk density with depth implied that soil compaction is a dynamic process that is transmitted to the lower depths through the soil matrix.

A higher increment of soil bulk density has been established to arise after the first pass than for subsequent passes. This finding agrees with those of Picchio et al. (2012) who have also reported that soil deformation caused by repeated tractor traffic was higher for the first three passes than for the subsequent ones.

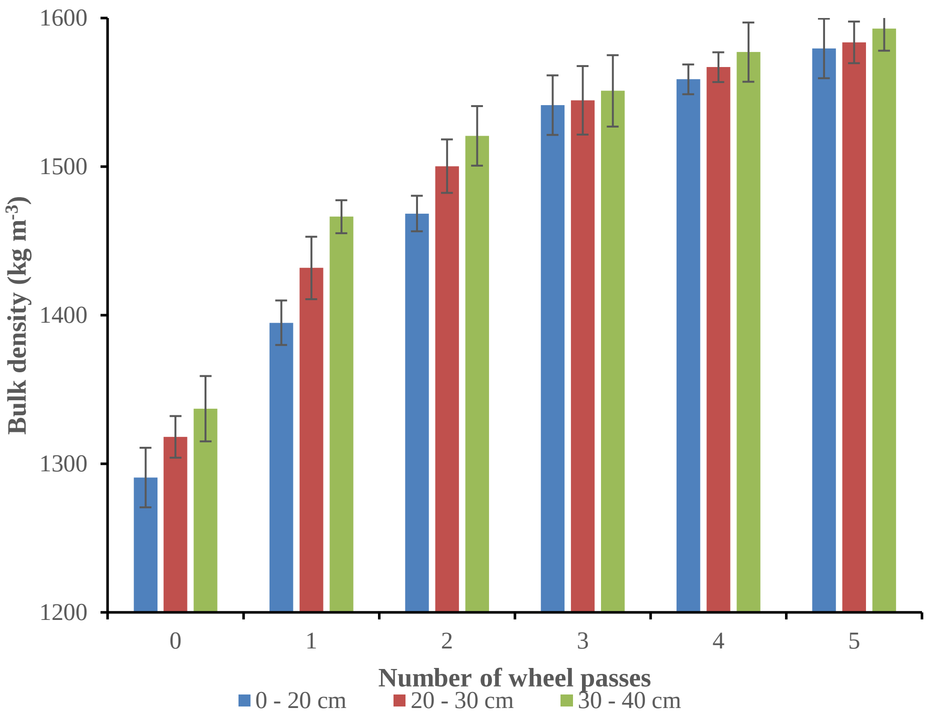

Figure 2 Bulk density as a function of wheel traffic frequency and soil depth

Table 1 ANOVA table for the variables studied

Source of variation	Degrees of freedom	Bulk density		Penetration resistance		Soil strength		Cohesion		Angle of internal friction	
		F ratio	*p* value	F ratio	*p* value	F ratio	*p* value	F ratio	*p* value	F ratio	*p* value
	18	4.259	0.201	7.624	0.120	2.203	0.341	7.421	0.123	4.00	0.212
	5	3.555	0.234	3.11	0.261	27.87	0.035	5.617	0.158	8.816	0.105
	2	33.78	0.029	142.2	0.007	1.592	0.429	3.501	0.237	221.5	0.045
	10	0.588	0.727	0.943	0.587	0.211	0.930	3.059	0.130	0.128	0.971

3.2 Penetration resistance

The initial penetration resistances of the experimental plots before wheel traffic treatments were determined as 640, 700 and 740 kPa at 0 - 25, 25 - 30 and 30 - 40 cm depths respectively (Figure 3). The penetration resistance in the 0 - 20 cm layer increased from 680 kPa in undisturbed soil 1230 kPa after five passes. One wheel pass caused a change in the soil penetration resistance of 15% of total change in penetration resistance.

Penetration resistance was generally higher in the 20 - 30 cm layer compared to the 0 - 20 cm layer. It increased with the increase in number of wheel passes from 700 kPa at no wheel pass to 1090 kPa after five wheel passes. The penetration resistance due to one wheel pass accounted for 15% of the total change in penetration resistance. In 30 - 40 cm layer, the penetration resistance was generally higher than the upper layers. The penetration resistance increased from 0.74 MPa at no wheel traffic to 1340 kPa after five passes. However, the change in penetration resistance due to wheel traffic intensity was not significant at the 5% level of confidence (Table 1).

The ANOVA conducted revealed that penetration resistance was significantly affected by the depth of sampling ($p < 0.05$). The effect of wheel passes and the interaction between wheel passes and depth were however not significant. The increase in penetration resistance with depth could be attributed to the fact that stresses are effectively transmitted to the lower depth levels in compacted soils. The test plot was a fallow land previously under maize cultivation and livestock grazing and a hard pan could have resulted from these previous land uses. Martínez et al. (2008) attributed penetration resistance increases with soil depth to years under management in no-tillage system which resulted in soil consolidation.

The findings agree with those of Taghavifar and Mardani (2014). According to Macrì et al. (2017), many plant species have their root growth limited by soil penetration resistance higher than 2500 kPa. This study established that this value had not been reached after five passes.

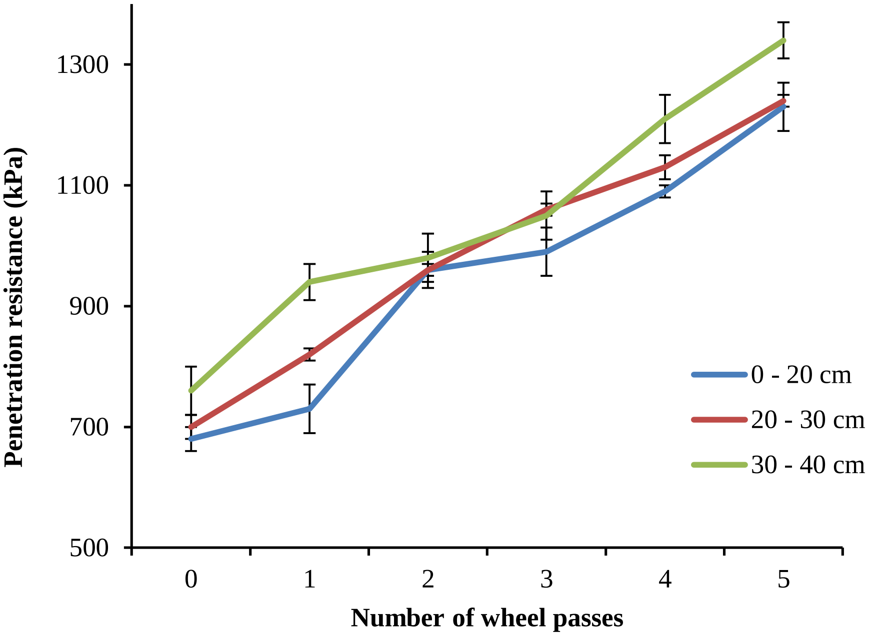

Figure 3 Variation of soil penetration resistance with depth and degree of compaction

3.3 Cohesion

The cohesion of the soil varies from place to place due to variation in the presence of cementing materials which helps to combine soil particles tightly. It was observed that the soil cohesion increased gradually with traffic intensity and normal load (Figure 4). The least value of cohesion was 6.84 kPa observed at the top soil layer (0 - 20 cm) at no wheel pass. The maximum cohesion of 8.42 kPa was observed at 30 - 40 cm depth after five passes.

The cohesion of soil in the 0 - 20 cm layer increased from 6.84 kPa with no wheel traffic to 8.05 kPa after five wheel passes. One wheel pass caused 17% of the change in soil cohesion caused by five passes. The soil cohesion of the 20 - 30 cm layer was observed to be generally higher than in the overlying layer. It increased from 7.15 kPa at no wheel pass to 8.14 kPa after five wheel passes. The cohesion of soil in the 30 - 40 cm layer was found to be higher than the two upper layers. It increased from 7.03 kPa for the un-trafficked soil to 8.42 kPa after five wheel passes.

The ANOVA revealed that these changes in cohesion due to depth, traffic intensity and their interaction (Table 1) were not significant at the 5% level of confidence. However, the marginal increase in soil cohesion with increased traffic could be attributed to the filling of large voids in the soil by the fine particles resulting from deformation of larger particles by the wheel. This finding was similar to that made by Secco et al. (2013).

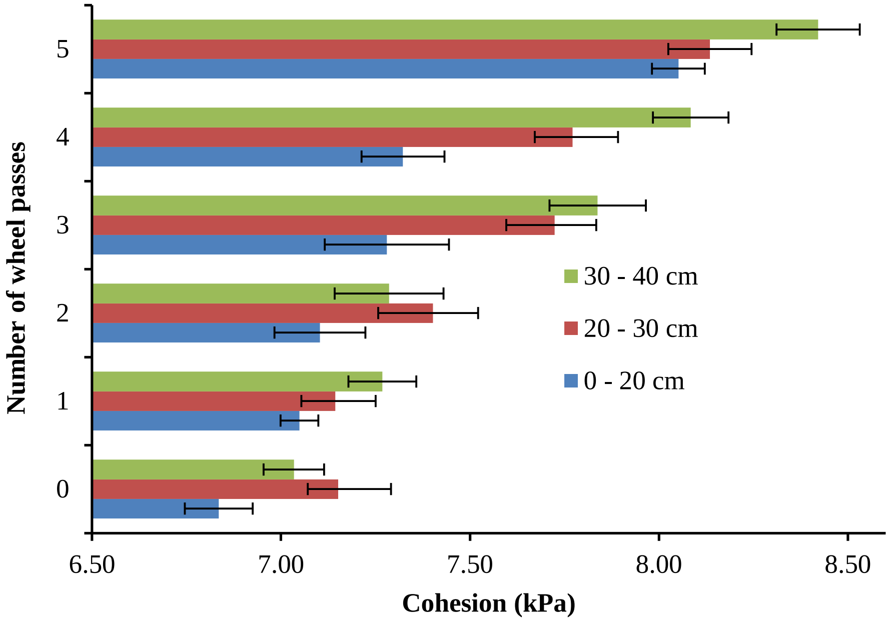

Figure 4 Soil cohesion at various depths due different wheel traffic frequency

3.4 Angle of internal friction

The results for determination of the angle of internal friction as affected by wheel passes (normal load) and depth are presented in Figure 5. The least angle of internal friction of soil was observed as 30 °for the undisturbed soil in 0 - 20 cm layer. A maximum value of 35 °was noted for the 30 - 40 cm layer after five-wheel passes.

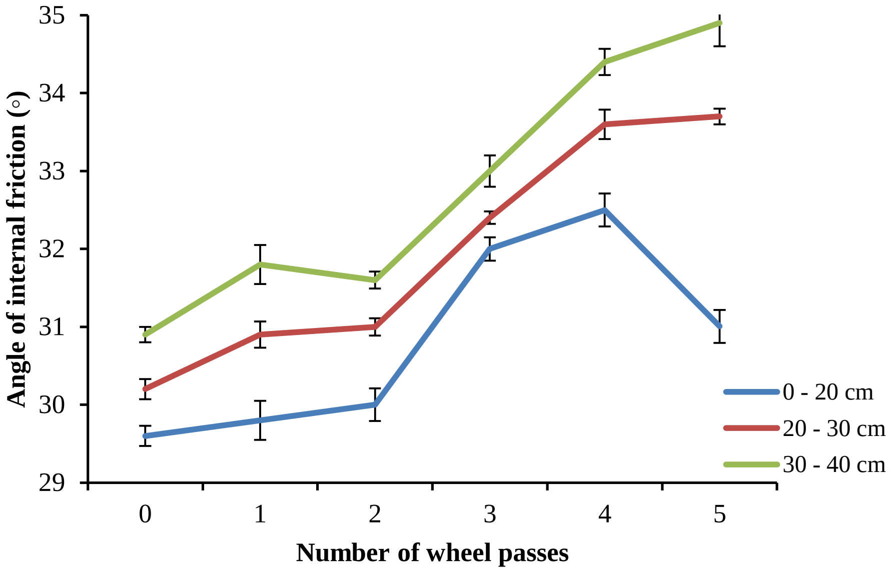

Figure 5 Variation of angle of internal friction with number of passes and depth

In the 0 - 20 cm layer was observed to increase from 30 °with no wheel traffic to 31 °after five wheel passes. The change in angle of internal resistance with wheel frequency was therefore not significant in this layer. The angle of internal friction of the 20 - 30 cm layer was marginally higher than in 0 - 25 cm layer, ranging between 30 °for untrafficked soil and 34 °after five wheel passes. One wheel pass resulted in 25% of the observed change in the soil angle of internal resistance.

The internal angle of friction of the 30 - 40 cm layer was higher than the two overlying layers. A minimum value of 31 ° was observed for the undisturbed soil while a maximum value of 35 ° was observed after five wheel passes. However, although the ANOVA conducted on the factors indicated that the angle of internal friction was significantly affected by depth, the change due to traffic wheel passes and the interaction between the factors were not significant at the 5% level of confidence (Table 1). This could have been because the internal friction angle changes mainly due to clay content and is independent of the structural state of a soil and does not exhibit spatial variation on the ground. The findings are in agreement with conclusions of Secco et al. (2013) who reported no significant variation in angle of internal friction with soil compaction.

3.5 Shear strength

As indicated in Figure 6, the soil shear strength increased with number of wheel passes and depth. The lowest shear strength was determined for untrafficked soils at the 0 -20 cm depth while the maximum shear strength of 157 kPa was recorded for the subsoil depth (30 - 40 cm layer). In the 0 - 20 cm soil layer, the least shear strength was determined as 121 kPa for the no wheel pass treatment. As wheel traffic intensity increased, a rise in soil shear strength was observed. The highest value of shear strength was recorded as 147 kPa after 5 passes. One wheel pass increased the soil shear strength by 15% of the observed increase due to the five wheel passes.

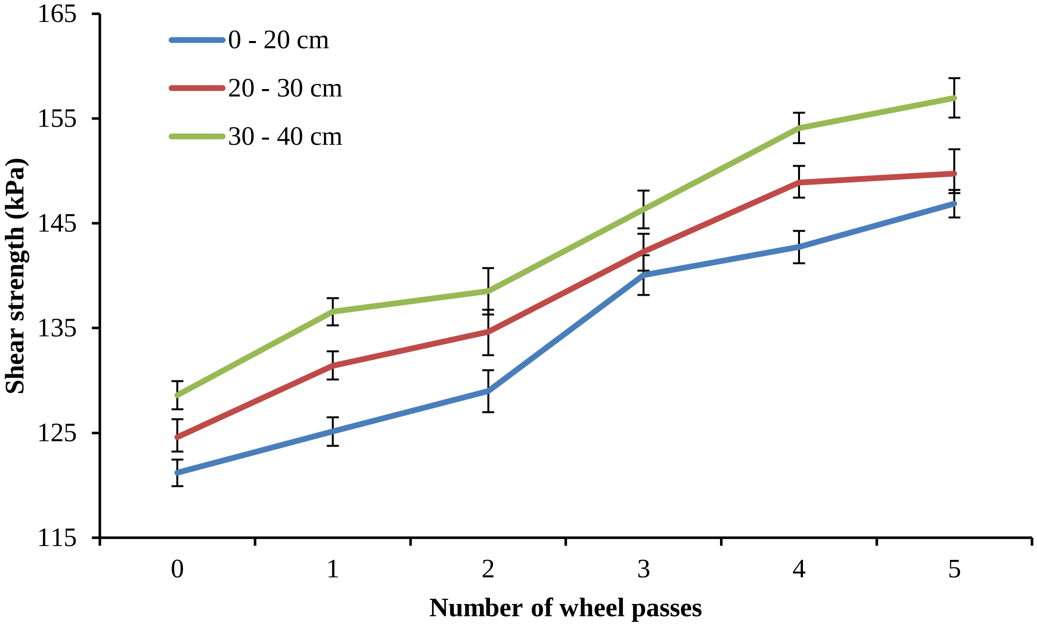

Figure 6 Soil shear strength as affected by number of wheel passes and depth

The shear strength of soil in the 20 - 30 cm depth was generally higher than in the 0 - 20 cm layer for any given number of wheel passes. The lowest value of 125 kPa was recorded for untrafficked conditions. The soil strength increased with number of wheel passes to 150 kPa after 5 passes.

For the 30 - 40 cm layer, it was observed that for any given traffic intensity, the shear strength was higher than for either 0 - 20 or 20 - 30 cm layers. The shear strength increased from 129 kPa for untacked soil to 157 kPa after five wheel passes.

The ANOVA revealed that soil shear strength was significantly affected by number of wheel passes at the 5% level of confidence. However, depth and the interaction between depth and number of wheel passes were not statistically significant. The increase in soil strength with depth could be attributable to the fact that stresses are effectively transmitted to lower soil layers when soils are compacted. Similar observations were made by Battiato and Diserens (2013) who showed that increasing the number of wheel passes on the same track increased depth of stress distribution on mineral soils.

3 Conclusions

It was established that bulk density, penetration resistance, cohesion, and angle of internal friction were pertinent to wheel traffic induced compaction. Increasing traffic passes from 0 to 5 wheel passes, resulted in increased bulk density, penetration resistance, soil cohesion and angle of internal friction. These results confirm the dynamic nature of soil compaction processes. This study found that after the third pass, there was no significant change in soil bulk density and penetration resistance of the soil. Although it was observed that after the third wheel pass subsequent passes have a smaller effect on soil properties, it should be cautioned that additional passes may increase soil compaction to levels that inhibit plant growth in addition to increased tillage draft requirements.

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