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Full Length Research Paper

Effect of agricultural machinery on physical and hydraulic properties of agricultural soils

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The study assessed effect of farm machinery on both physical and hydraulic properties of agricultural soils used for rice cultivation in northern Ghana. Two tractor models were used for the field experiment with field tests and soil sampling points classified as tractor tyre passage area (TTPA), ploughed area (PA) and unploughed area (UPA). The study used Randomised Complete Block Design (RCBD) with 3 blocks, 3 treatments, 9 replications and data were analysed using Graph Pad Prism, 8 software and Microsoft Excel 2016. Soil aggregate composition varied for the 3 study sites and sampling locations with a sandy loam soil textural class. Soil dry bulk density ranged from 1.11 to 1.61 g cm^{-3} with TPA recording 1.42 to 1.61 gcm^{-3} indicating high level of soil compaction. Unsaturated hydraulic conductivity of 2.01 × 10^{-4} to 1.05 × 10^{-3}, 1.61 × 10^{-4} to 6.50 ×10^{-4} and 1.89 × 10^{-4} to 7.19 × 10^{-4} cm s^{-1} were recorded for PA, TTPA and UPA respectively. Low unsaturated hydraulic conductivities were recorded for TTPA compared to other treatments. Overall, average cumulative infiltration revealed a relatively lower infiltration for TTPA compared to PA and UPA. Specific TTPA for a typical ploughing activity was estimated as 2107. 0 and 2895.5 m^2 ha^{-1} for two tractor models, translating to 28.6 and 21.0% ha^{-1}. respectively. The study recorded appreciable soil compaction resulting from a typical tractor plough activity on agricultural soils which might negatively impact soil water conductivity as well as plant growth and development.

Key words: Soil compaction, tractor plough, hydraulic conductivity, soil water infiltration, soil bulk density.

INTRODUCTION

In modern agriculture, farm machinery is an integral part; however, it causes soil compaction. Soil compaction affects soil physical properties as it increases soil bulk density leading to reduction of soil water infiltration rate (Chyba et al., 2014; Mašek et al., 2016). Infiltration rate is influenced by agricultural traffic and its intensity and infiltration characteristic of the soil guides in the assessment of soil compaction. Traffic intensity increases soil bulk density negatively affecting soil infiltration parameters compared to non–trafficked soil (Hamza and Anderson, 2005; Raper and Kirby, 2006).

According to Keller et al. (2019), soil compaction caused by vehicular traffic negatively affects the important soil functions such as water flow and aeration, nutrient cycling, agricultural and forestry production, and habitats for soil organisms.

Javůrek and Vach (2008) noted that machine passes on soil causes compression and reduces soil porosity, and creating barriers to water and air movement and roots penetration. Compaction adversely affects crop

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productivity and significantly reduces crop yield (Brady and Weil, 1999). Beutler and Centurion (2004) indicated that soil compaction reduces root growth through physical processes like lower aeration and decreasing water and nutrients absorption causing significant yield decrease.
Hamza and Anderson (2005) reported that soil compaction increases soil strength and decreases soil physical fertility through decreasing storage of water and nutrients supply leading to additional fertilizer requirement and increasing production cost.

According to Horn et al. (1995), the first wheel of tractor pass promotes more compaction than subsequent passes which destroys larger pores (pores > 50 μm) with the initial traffic and then numerous smaller pores in compacted soil, and are more resistant to deformation and compaction, increasing the soil's ability to support applied loads. Reports in literature indicate that compaction by traffic reaches 0.20 m by heavier machines (Hamza and Anderson, 2005). Lipiec and Hatano (2003) reported that, unsaturated hydraulic conductivity is low on loose soils, which reduces water and nutrient movements towards the roots, because of the greater space among soil particles.

Agricultural machinery in the savanna ecosystems, especially the use of tractors for ploughing leaves large tracts of land compacted due to their weights. Assessment of the effect of this machinery on the compacted soils of farmlands through monitoring of the physical and hydraulic properties such as soil water infiltration, bulk density, and soil grain size is important in land preparation and crop cultivation for maximum yields. This necessitated the current study in the northern savannas of Ghana.

MATERIALS AND METHODS

Study area

The study was carried out on selected rice fields at (3) different locations in the Tolon District in Northern Region of Ghana, namely; Golinga Irrigation Project (GIP), SARI Experimental Rice Fields (SERF) and Dindo Community Rice Field (DCRF). A map showing the study rice fields is presented in Figure 1.

The Tolon District is located between latitude 9º15' N and 10º 02' N, and between longitude 0º 15' W and 1º 25' W. It lies within the Guinea Savannah Agro-ecological zone with tropical semi-arid climate and is characterized by tropical savannah woodland and perennial grass species. Soils are generally sandy loam, except in lowland areas where alluvial soils are found (Baatuuwie et al., 2011). The district is characterized by a unimodal rainy season and total annual rainfall of 1,000-1,300 mm. Temperatures are consistently high with values ranging from 25 to 36ºC (Abdul-Ganiyu, 2011). The rainy season is the period of intense farming activity and tractor ploughing is the main primary tillage practice in rice, maize, groundnut and cowpea farming in the district (Boakye-Danquah et al., 2014).

Data collection

The materials and equipment used for the field experiment and data collection were Mini-Disk infiltrometer, Pro Check Decagon-EC-5 soil moisture meter (Decagon Inc., Pullman, WA), tractors and their ploughs, soil auger, core samplers, mallet, sampling bags, measuring tape (30 m metallic tape) and Global Positioning System (Garmin Map64S).

The impact of the tractor ploughing activity on soil bulk density, hydraulic conductivity and soil water infiltration rates were monitored at the (3) study sites.

The study used Randomised Complete Block Design (RCBD) with (3) blocks, (3) treatments and (9) replications that is, each block was divided into (3) zones/replications namely; upstream, midstream and downstream for infiltration test and soil sampling for dry soil bulk density and particle size analysis. The treatments were Tractor Tyre Passage Area (TTPA), Ploughed Area without passage (PA) and Unploughed Area (UPA).

Characteristics of farm tractors used for the study

The models of the tractors used for the study were John Deere 3020 (JD3) and Mahindra 705 DI (MD7) and the detailed characteristics of the tractors used for the study are presented in Table 1.

Field conduct of soil infiltration and soil sampling

The infiltration of water was recorded for 30 seconds interval at an optimal suction setting of 2 cm for all the sampling sites. The infiltration test was conducted at visible Tractor Tyre Passage Area (TTPA), Ploughed Area without passage (PA) and Unploughed Area (UPA).

Nine undisturbed soil samples were taken at depths of 0 - 30 cm at different sampling points that is, TTPA, PA and UPA for dry bulk density determination and soil particle size distribution determination. The methods used for determination of soil infiltration rate, unsaturated hydraulic conductivity, soil dry bulk density and soil particle size distribution are presented in Table 2.

Determination of specific tractor tyre passage area (TTPA)

A mathematical equation (Equation 1) was developed during the study for the calculation of the specific area covered by the rear tractor tyre in a typical ploughing activity for an hectare of land. The average number of travels by the tractors was thus noted by count. Estimate of TTPA was made for a single rear tyre with the assumption that a typical tractor plough operation has one tyre on the PA and the other at UPA. The standard specification of the rear tractor tyres used for the study is presented in Table 1.

$$TTPA = RTW \times NT \times DT \qquad (1)$$

Where:
TTPA - Tractor Tyre Passage Area (m^2)
RTW - Rear Tyre Width per Tractor Model (m)
NT - Number of Travels per hectare
DT - Distance of Travel (m)

Data analysis

Data were analysed for the average levels of the various parameters at the respective study areas. Two-way analysis of variance (ANOVA) was performed at 5% level of significance to compare the level of significance for variation among the various sampling sites and the selected study areas. Tukey's multiple comparisons test was carried out for the separation of means. GraphPad Prism 8 software and Microsoft Excel 2016 were used

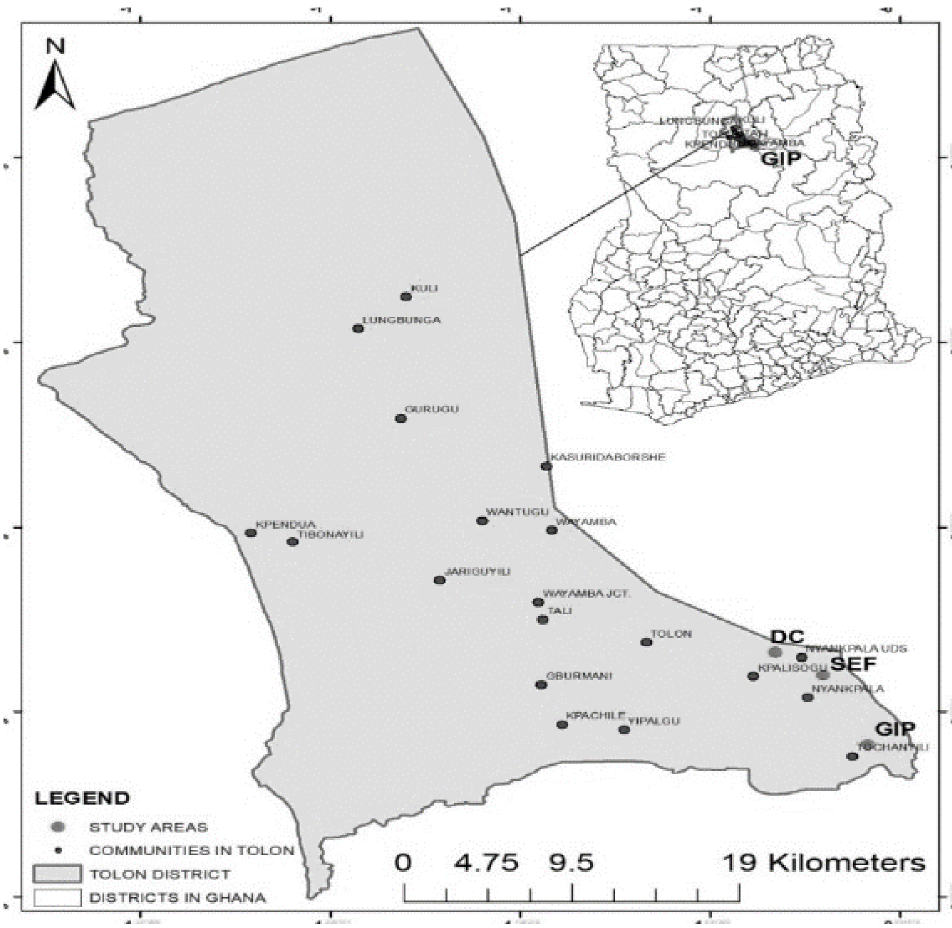

Figure 1. Map of Tolon district showing study rice fields.

Table 1. Coordinates of study sites, characteristics of tractors and soil moisture content.

Parameter	Study site		
	Golinga irrigation project (GIP)	**SARI experimental rice field (SERF)**	**Dindo community rice field (DCRF)**
Latitude (°)	N 09.35760	N 09.40518	N 09.42095
Longitude (°)	W 000.95086	W 000.97384	W 000.99801
Average VSMC (%)	18.1	37.3	46.1
		Tractor characteristics	
Model	John Deere 3020	Mahindra 705 DI	
Length (cm)	351.79	350.0	
Width (cm)	228.0	200.0	
Height (cm)	168.91	152.4	
Operating weight (tonnes)	3.49 – 3.60	NA	
Ballasted weight (tonnes)	4.35	NA	
Rear tyre (cm)	13.6 x 38.0	16.9 x 28.0	
Front tyre (cm)	6.5 x 16.0	7.5 x 16.0	
Operating weight of tractor (kg)	3490.4 - 3603.8	2610.0	
No. of travel per plough per acre	41.0	44.0	
Power take-off (PTO) (HP)	71.26	60	

VSMC: Volumetric soil moisture content.

Table 2. Methods for determination of soil parameters.

S/N	Parameter	Analysis method	Reference
1	Soil Infiltration rate	Mini disk infiltrometer (MDI)	Sihag et al. (2018)
2	Unsaturated hydraulic conductivity	Wind's evaporation	Tamari et al. (1993)
3	Soil dry bulk density	Core sampler	Blake and Harte (1986) and Cresswell and Hamilton (2002) Equations
4	Particle size distribution	Hydrometer	Bouyoucos (1963)

Table 3. Soil texture of sampled soils.

Study Site	Sampling zone	Sand (%)	Silt (%)	Clay (%)	Textural class
SERF	Upstream	55.92	33.84	10.24	Sandy loam
	Midstream	55.92	33.84	10.24	Sandy loam
	Downstream	63.92	27.84	8.24	Sandy loam
DCRF	Upstream	63.92	27.84	8.24	Sandy loam
	Midstream	75.92	17.84	6.24	Sandy loam
	Downstream	61.92	28.84	9.24	Sandy loam
GIP	Upstream	53.88	32.91	13.21	Sandy loam
	Midstream	49.50	35.11	15.39	Sandy loam
	Downstream	47.21	27.57	25.22	Sandy loam

SERF - SARI Experimental Rice Field: DCRF - Dindo Community Rice Field: GIP - Golinga Irrigation Project.

for the data analysis and plotting of graphs.

RESULTS AND DISCUSSION

Soil particle size and texture

Although, there were variations in the soil aggregate composition for the three study sites and sampling locations, the textural class for all the soils was noted to be sandy loam.

In the SARI Experimental Rice Fields (SERF), sand particles recorded a high of 63.92% in the downstream compared to a low concentration of 55.92% for both the midstream and upstream. Silt and clay particle concentrations were noted as 33.84 and 10.24%, respectively for both upstream and midstream of SERF whilst the downstream recorded 27.84 silt and 8.24% clay concentrations.

In the Dindo Community Rice Field (DCRF), soil particles varied from a low of 6.24% clay in the midstream to a high of 9.24% clay in the downstream. Silt in DCRF varied from 17.84 in the midstream to a high level of 28.84% in the downstream whilst sand particles recorded a low of 61.92 in the downstream to a 75.92% high concentration.

For the Golinga Irrigation Project (GIP), 53.88% sand, 35.11% silt and 25.22% clay were recorded for the upstream, midstream and downstream respectively as high levels of particle concentration whilst 47.21% sand, 27.57% silt were recorded in the downstream and 13.21% clay in the upstream for the GIP. Details of soil texture and soil particles variation are presented in Table 3. Variations in soil particles distribution were not observed for ploughed area, unploughed area and path of travel of tractor tyres during the ploughing activity.

Soil dry bulk density as affected by tillage activities

Soil bulk density is a very important parameter that influences soil water infiltration, seed germination, plant development and vigour (Bergamin et al., 2015). The study assessed the difference in soil bulk density for the TTPA, PA and UPA and the results are as presented in Figure 2. Results of dry bulk density of the soils indicated that bulk densities were high for areas where the tractor tyre had passed over and noted as TTPA to range from 1.42 to 1.61 g cm^{-3} for the GIP and SERF, respectively. These were notably higher than the dry bulk densities for the ploughed area for the same sites. The least bulk density was recorded in the PA for all 3 study sites and ranged from 1.11 to 1.20 gcm^{-3}. It is clear from Figure 2 that high soil dry bulk densities of between 1.44 and 1.57 gcm^{-3} recorded indicated high level of soil compaction.

The results of ANOVA showed a significant difference

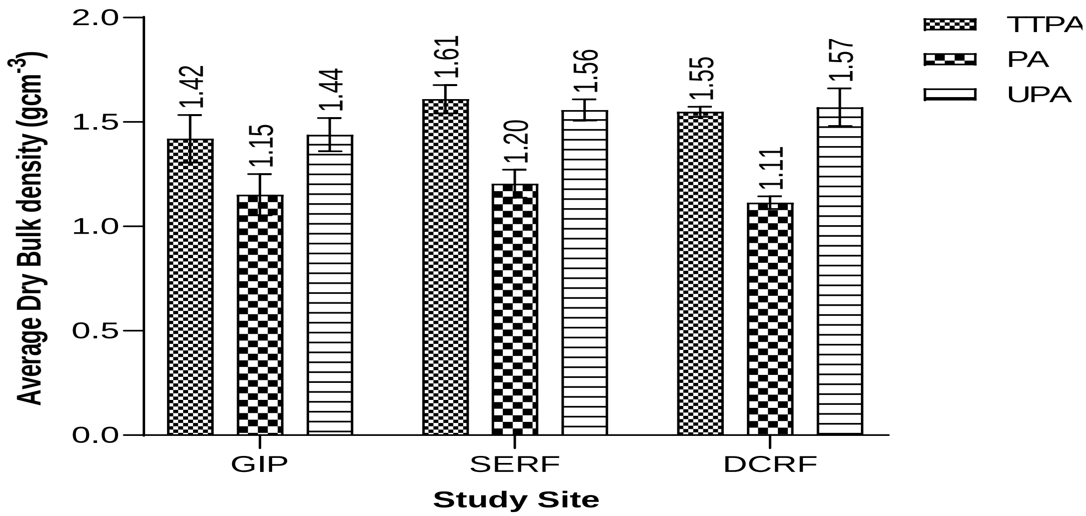

Figure 2. Soil dry bulk density as affected by tillage activities. Error bar represent standard deviation.

Table 4. ANOVA for soil dry bulk density.

ANOVA		MCT	
Comparison	***P*-Value**	**Study site**	***p*-value**
Study site	0.0022**	GIP vs. SERF	0.0029**
Sampling site	0.0001****	GIP vs. DCRF	0.0837*ns*
Interaction	0.1571*ns*	SERF vs. DCRF	0.5137*ns*

* Significantly different; p- probability; ns- no significant difference; MCT- Multiple Comparisons Test.

among the different study and sampling sites at p-values of 0.0001 and 0.0022 respectively (Table 4). However, the results from the multiple comparisons test revealed that the significant differences exist between GIP and SERF only with *p*-value of 0.0029.

Shah et al. (2017) reported that bulk density increases with an increase in soil compaction, as compacting forces squeeze the volume of soil via eliminating pore spaces. External stress such as high axle load reduces aggregate stability of soil, thus increasing bulk density of soil. It is also well documented that increase in bulk density caused reduction in maize yield by 30% in Argentina (Ressia et al. (1998). Other consequences associated with increase in bulk density due to compaction are high penetration resistance, less infiltration, high run off and more soil erosion (Shah et al., 2017).

Effect of tillage on soil hydraulic conductivity

Aside SERF, the highest unsaturated hydraulic conductivity was recorded for the ploughed areas of GIP and DCRF at respective averages of 1.05×10^{-3} cm/s and 2.01×10^{-4} cm/s (Figure 3). The mean hydraulic conductivities for the Tractor Tyre Passage Area (TTPA) were noted to be low for all the study sites as compared to the ploughed and unploughed areas with the minimum of 1.61×10^{-4} cm/s at DCRF as evidenced in Figure 3. This implies that the conduct or flow of water across the soil profile for the various layers was impeded resulting from the weight of the tractors. Also, the mean hydraulic conductivity for the TTPA and UPA recorded were lower than the ploughed area which recorded a mean hydraulic conductivity of 1.05×10^{-3} cm/s.

The average hydraulic conductivity showed a highly significant difference for the different study sites (*p*-value of 0.0001) but not for the sampling sites (*p*-value of 0.3208) as presented in Table 5. The significant difference however, existed between GIP and the other sites at a *p*-value of 0.0001. This can be explained by the difference in tractor type used for the study and the relatively high tillage activities characterized by the GIP as compared to the other sites.

The finding of this study agrees with the results of a similar study carried out by Chyba et al. (2014) which reported that non-compacted soil recorded higher values of saturated hydraulic conductivity (5.62 mm h^{-1}) than the soil compacted by a tractor with a trailer (1.12 mm h^{-1})

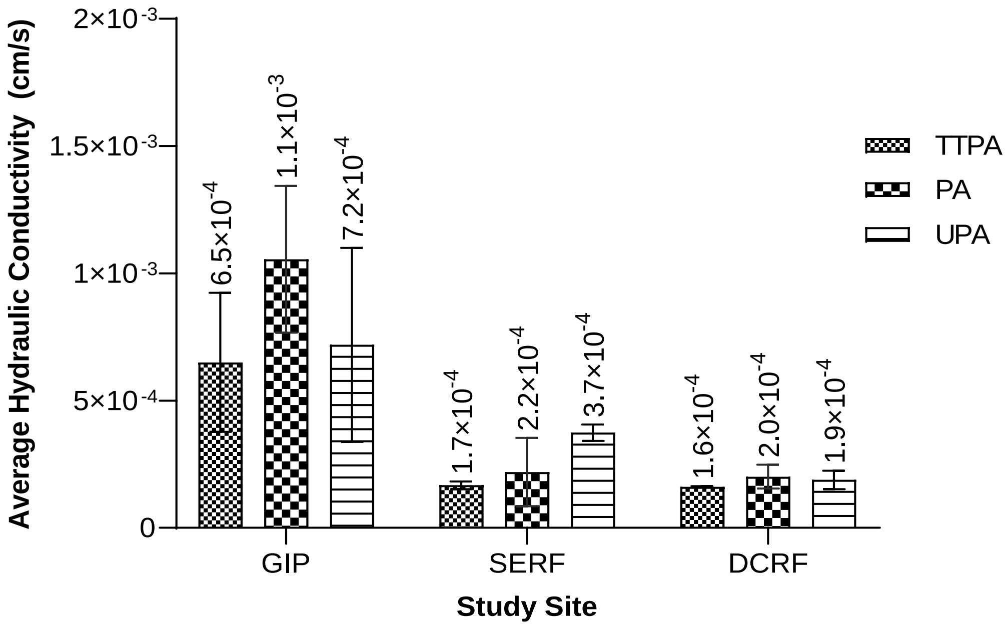

Figure 3. Hydraulic conductivity of soils as affected by tillage activities. Error bar represent standard deviation.

Table 5. ANOVA for soil hydraulic conductivity.

ANOVA		MCT	
Comparison	***p*-value**	**Study site**	***p*-value**
Study site	0.0001****	GIP vs. SERF	0.0001****
Sampling site	0.3208 *ns*	GIP vs. DCRF	0.0001****
Interaction	0.2511*ns*	SERF vs. DCRF	0.8394*ns*

*Significantly difference; p- probability; ns- no significant difference; MCT- Multiple Comparisons Test.

which equates to an 80% decrease in soil infiltration rate. Green et al. (2003) reported that saturated hydraulic conductivity is highly sensitive to soil deformation, especially soil compaction (Whalley et al., 1995) and alteration in porosity (Matthews et al., 2010). Similarly, Nayak et al. (2007) reported that a decrease in soil aggregate stability, increase in soil bulk density, and decrease in air voids result in decrease in hydraulic conductivity of soil. Moreover, Radford et al. (2000) noted that increase in soil strength due to compaction also reduces hydraulic conductivity.

Results from simulations by Keller et al. (2019) revealed an increase in soil stress levels with higher bulk density and mechanical penetration resistance and a decrease in soil hydraulic conductivity as a result of agricultural machinery weights.

Soil water infiltration of the study sites

With similar soil particle characteristics that is, sand 58.59, silt 31.84 and clay 9.57% like the DCRF, UPA of the SERF recorded high cumulative infiltration of 4.53 cm at the PA and TTPA exhibiting lower cumulative infiltration of 1.82 cm for the area.

Xue and Gavin (2008) indicated that infiltration rates are influenced by the initial moisture content, condition of the surface, hydraulic conductivity of the soil profile, texture, porosity, degree of swelling of soil colloids, organic matter, vegetative cover, duration of irrigation or rainfall and viscosity of water. Rao and Manna (2005) reported that, of all these factors, soil texture plays a predominant role in the infiltration rates of the soil.

Also, as can be seen in Figure 4, the Golinga Irrigation Project (GIP), recorded high cumulative infiltration of 5.18 cm in the PA compared to the TTPA of the ploughed area and the UPA which recorded cumulative infiltration values of 4.02 cm and 4.99 cm respectively.

The high clay content of 17.95 together with the 31.86 silt and 50.19% sand has been noted to influence the rate of infiltration in the soil of the study area.

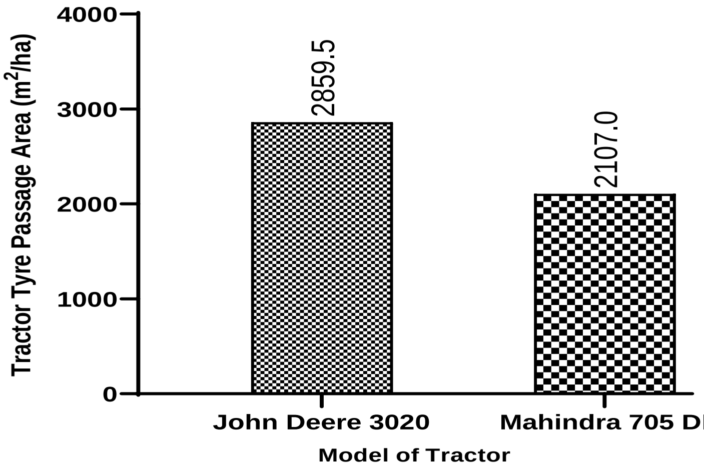

Figure 5. Average tractor tyre passage area for tractor models.

In the DCRF, high infiltration levels of 3.42 cm were recorded for the UPA compared to the PA (3.24 cm) and the TTPA of 2.14 cm. A good infiltration was relatively observed for the soil in the ploughed area whilst the TTPA exhibited a somewhat lower infiltration. The influence of infiltration in the study area may largely be affected by the soil particle composition, which was noted as sand (67.25%), silt (24.84%) and clay (7.91%). It can generally be noted that the intrinsic soil texture, that is, sandy loam, of the study sites has significant influence on the general hydraulic properties of the soil.

The finding of this study agrees with the assertion of Azooz and Arshad (1996) that, the disruption of soil structure and channels under conventionally tilled farmland led to a lower infiltration rate compared with an untilled treatment in northwestern Canada. Similarly, Chamen (2011) and Chyba et al. (2014) reported that a non-compacted soil has 4 to 5 times higher water infiltration rate than the soil compacted by agricultural machines.

With similar soil particle characteristics (sand: 58.59%, silt: 31.84, clay: 9.57%) like the DCRF, the UPA of the SERF recorded high cumulative infiltration while the PA and TTPA exhibited a low infiltration for the area. The final average cumulative infiltration depths for the SERF study area was in the order 4.53, 2.26 and 1.82 cm for UPA, PA and TTPA respectively (Figure 4).

Cropland as affected by tractor tyre passage

The average tractor passage area for the different tractor models was determined to be 2859.5 and 2107.0 m^2/ha for JD3 and MD7 respectively (Figure 5). These results translate into a respective 28.6 and 21.0% of a hectare of land affected by high level of soil compaction. The area affected by the impact of tractor tyre passage has been observed to be high and this will adversely affect crop seed germination, seedling establishment, growth and yield.

The results also indicate that the potential area of tractor tyre impact on the various soil physical and hydraulic parameters was slightly higher with the JD3 tractor which has a rear tyre size of 13.6 × 38.0 cm than that of the MD7 with a rear tyre size of 16.9 × 28.0 cm for a typical ploughing activity on agricultural land in the study area.

The higher percentage of affected area implies, tractor operators need training to help reduce farmland areas affected by the effect of tractor tyres in their path of travel.

Conclusion

The textural composition of the study soils was determined to be sandy loam and with the average dry soil bulk densities relatively high for both tractor tyre passage area and unploughed area while an appreciable lower level was noted for the ploughed area. The impact of soil compaction resulting from tractor plough was evident in lower hydraulic conductivity of tractor tyre passage area as compared to unploughed area for all the study soils. The study also found relatively high cumulative infiltration depths recorded for the soils in the ploughed area while the tractor tyre passage area exhibited a somewhat lower infiltration due to compaction. The unsaturated hydraulic conductivity measurements confirmed the negative effect of soil compaction on soil water infiltration.

The results of ANOVA revealed a significant difference for variation in average soil dry bulk density and hydraulic conductivity among the study sites which was evident between GIP and the other sites.

The higher tractor tyre passage area resulted from the JD3 tractor, thus indicating a wider potential area of tractor tyre impact on crop growth and establishment, soil physical and hydraulic properties as compared to the MD7 tractor for a typical ploughing activity on agricultural land in the study area. The results thus indicate an appreciable soil compaction as a result of a typical tractor plough activity on agricultural fields, which potentially has a negative impact on soil water conductivity as well as plant growth and development. The need for reduction of the area of land which is affected by tractor plough activity to allow proper, good growth and yield of crops will lead to increase in yield of crops in the study areas.

CONFLICTS OF INTEREST

The author has not declared any conflict of interests.

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