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THE IMPACT OF TRACTOR POWER AND MULTIPLE PASSES ON SOIL COMPACTION AND CROP YIELD IN DIFFERENT SOIL TYPES

Buba Baba Shani[1]and Aliyu Musa[1]
[1]Department Of Crop and Soil Sciences, National Open University of Nigeria
Corresponding Author, Email: bshani@noun.edu.ng
Phone No: +234-803-457-4544

ABSTRACT

This study examined the impact of tractor power on soil compaction and crop yield in different soil types and climatic conditions. The experiment used a split-split plot design with three replications to test the effects of tractor power level (40, 60, 80, and 100 kW) and number of passes (1, 3, and 5) and soil type l compaction and crop yield. A four-wheel drive tractor with radial tires, tire inflation pressure of 120 kPa, and speed of 5 km/h was used on 10 m × 10 m plots with different soil types and climatic conditions. The results showed changes in soil stress, bulk density, porosity, water infiltration rate, yield, and quality by 15.6%, 8.7%, -6.5%, -18.2%, -11.4%, and 4.2% respectively at low tractor power; by 23.4%, 12.4%, -9.3%, -26.7%, -16.8%, and 6.1% at medium power; and by 31.2%, 16.3%, -12.1%, -35.4%, -22.3%, and 8.1% at high power. However, soil compaction increased with higher tractor power and passes, negatively impacting crop yield and quality. Lower tractor power and fewer passes resulted in better crop quality but lower yield compared to higher power levels. Recommendations included practices to mitigate compaction and improve soil/crop management to aid farmers in managing soil compaction and enhancing agricultural systems.

Keywords: soil compaction, tractor power, crop yield, soil types, climatic conditions

INTRODUCTION

Soil compaction is a major problem in modern agriculture, as it reduces soil quality and productivity by affecting soil physical, chemical, and biological properties. Soil compaction is caused by the application of external forces on the soil surface, such as those exerted by heavy machinery, animal trampling, or rainfall. The degree and extent of soil compaction depend on several factors, such as soil type, moisture content, organic matter, tillage system, and machinery characteristics (weight, tire size, inflation pressure, speed, and number of passes) (Shaheb et al., 2021). Soil compaction occurs when the applied stress on soil exceeds its natural strength, leading to a reduction in soil volume and an increase in bulk density. This phenomenon can be caused by natural factors such as rainfall and human activities like farming and construction (Arvidsson & Keller, 2011). Soil compaction is defined as the increase in soil bulk density and the concomitant decrease in soil porosity due to external mechanical forces**.** It impacts soil aeration, root penetration, and water movement, and is often exacerbated by repeated passes of heavy machinery (Horn et al., 2005). One of the most important machinery characteristics that influences soil compaction is tractor power. Tractor power determines the amount of energy available to perform various field operations, such as tillage, planting, harvesting, and transport. Tractor power also affects the size and weight of the tractor and the attached implements, which in turn affects the soil stress distribution and the soil deformation under the wheel tracks (Field & Long, 2018). Therefore, tractor power has a direct and indirect impact on soil compaction and its consequences.

Soil compaction affects crop growth and yields by limiting root penetration, water infiltration, nutrient availability, and gas exchange in the soil. Soil compaction also increases the risk of soil erosion, runoff, and greenhouse gas emissions, which have negative environmental implications. The magnitude and duration of these effects vary depending on the crop type, growth stage, and climatic conditions (Rosenzweig & Hillel, 1998). Soil compaction is a widespread problem in agricultural soils, especially under intensive mechanization and heavy field traffic. Soil compaction alters soil structure and reduces soil porosity, water infiltration, air permeability, and root penetration, which affects soil functions and crop productivity (Shaheb et al., 2021). Soil compaction can have negative impacts on crop growth and yield, as it reduces the soil porosity, water infiltration, aeration, drainage, and root penetration, and increases the soil bulk density, strength, and resistance (Eloud et al., 2015)

Several studies have investigated the effects of soil compaction on soil physical properties, soil hydraulic properties, soil biological properties, soil chemical properties, soil erosion, greenhouse gas emissions, crop growth and development, crop yield and quality, and farm economics). However, the relationship between soil compaction and these factors is complex and dynamic, as it depends on many interacting variables, such as soil type, soil moisture, soil organic matter, tillage system, crop type, crop stage, climatic conditions, and machinery characteristics. Among the machinery characteristics, tractor power is one of the most important factors that influence soil compaction, as it determines the amount of energy available to perform various field operations and the size and weight of the tractor and the attached implements (Shaheb et al., 2021). Gameda et al. (1987) found that increased axle loads from heavy machinery significantly increased soil compaction, reducing soil porosity and root growth. Similarly, Hamza and Anderson (2005) noted that soil compaction from machinery traffic led to increased bulk density and reduced crop

yields in various soil types. This underlines the necessity of managing machinery use to mitigate soil compaction effects.
Moreover, soil moisture content at the time of machinery use is another critical factor. Compaction effects are often more severe when soils are wet, as the soil particles are more easily compressed (Chamen et al., 2003). This highlights the importance of timing agricultural operations to avoid wet conditions that exacerbate compaction.
In addition to mechanical solutions, biological approaches such as the use of cover crops have been shown to alleviate soil compaction. Cover crops can improve soil structure by increasing organic matter content and promoting biological activity, which helps to naturally loosen compacted soils (Blanco-Canqui et al., 2015). This integrative approach of combining mechanical management with biological amelioration strategies is crucial for sustainable soil health and agricultural productivity.
Tractor power affects soil compaction in two ways: directly and indirectly. Directly, tractor power affects the soil stress distribution and the soil deformation under the wheel tracks, which depend on the tractor weight, tire size, inflation pressure, speed, and number of passes. Indirectly, tractor power affects the choice and performance of the tillage and planting implements, which affects the soil disturbance and the soil surface condition. Therefore, tractor power has a direct and indirect impact on soil compaction and its consequences (Shaheb et al., 2021). According to Shaheb and his colleagues (2021), different tractor power levels and number of passes have different effects on the soil properties and the water movement in various soils and moisture conditions. They found that the soil became more compacted and less porous, and the water entered the soil more slowly, when the tractor power level and the number of passes were higher. The magnitude and extent of these effects varied depending on the soil type and the soil moisture, as different soils have different mechanical and hydraulic properties and different susceptibility to compaction. Generally, clayey soils and wet soils were more prone to compaction than sandy soils and dry soils.
The growth, development, and yield of various crops in different soils and climates have also been examined and contrasted by several studies that investigated the impact of soil compaction caused by different levels of tractor power and number of passes. However, according to Nawaz et al., (2013), soil compaction reduces root growth, shoot growth, leaf area, photosynthesis, transpiration, nutrient uptake, biomass, and the yield of various crops, such as wheat, maize, soybean, cotton, rice, and potato. The magnitude and duration of these effects varied depending on the crop type, the crop stage, and the climatic conditions, as different crops have different morphological, physiological, and biochemical responses to compaction and different sensitivity to water and nutrient stress. Generally, crops at early stages and under drought and heat stress were more affected by compaction than crops at later stages and under optimal conditions. The relationship between tractor power, soil compaction, and crop yield is not linear, but rather nonlinear and threshold-based. This means that there is a critical level of tractor power, beyond which soil compaction becomes detrimental to crop yield, and below which soil compaction may have no effect or even a positive effect on crop yield. This critical level depends on the soil type, the soil moisture, the crop type, the crop stage, and the climatic conditions. Therefore, there is no universal optimal tractor power level for all situations, but rather a site-specific and situation-specific optimal tractor power level that minimizes soil compaction and maximizes crop yield. The relationship between tractor power, soil compaction, and crop yield is complex and dynamic, as it involves many interacting factors and feedback mechanisms. Moreover, the relationship may differ across different soil types and climatic conditions, which have distinct soil properties and crop responses. Therefore, there is a need for more comprehensive and systematic studies on this topic, especially in the context of climate change and food security. (Shaheb et al., 2021). Recent research highlights the intricate relationship between tractor power, soil compaction, and crop yield. Tractor power significantly influences soil compaction levels, which in turn affects crop productivity. High-powered tractors often increase soil compaction due to their weight and the pressure exerted on the soil, leading to reduced soil porosity, hindered root growth, and decreased water infiltration (Fang et al., 2023; Morris et al., 2023). These conditions can significantly impact crop yields, particularly in soils with high clay content where compaction effects are more pronounced.
To mitigate these negative impacts, several strategies have been proposed, including the use of lighter machinery, controlled traffic farming, and soil amendments such as organic matter and biochar to improve soil structure and resilience (Fang et al., 2023). Additionally, adopting precision agriculture techniques can help optimize tractor operations and minimize unnecessary soil compaction (Smith et al., 2023).
This study is justified by several reasons. First, it will contribute to the existing literature and knowledge on soil compaction and its management, as it will provide a comprehensive and systematic analysis of the effects of tractor power on soil compaction and crop yield in different soil types and climatic conditions. Second, it will provide practical and useful information and recommendations for farmers, agronomists, and engineers, as it will help them to select and operate the appropriate tractor power level and number of passes for different soil types and climatic conditions to prevent or mitigate soil compaction and improve soil quality and crop performance. Third, it will support the development and implementation of sustainable and profitable agricultural systems, as it will evaluate the economic and environmental impacts of different tractor power levels and number of passes for different soil types and climatic conditions.
The aim of this research is to investigate the impact of tractor power on soil compaction and crop yield in different soil types and climatic conditions. The specific objectives are: to measure and compare the soil stress distribution

and the soil bulk density under different tractor power levels and number of passes in different soil types to evaluate and compare the effects of soil compaction induced by different tractor power levels and number of passes on the growth, development, and yield of different crops in different soil types.

MATERIALS AND METHOD

The study area was the research farm of Faculty of Agricultural Sciences, the National Open University of Nigeria, Rigachikum, Kaduna State. The study was conducted in three experimental sites with different soil types: a sandy loam soil in a semi-arid region, a clay loam soil in a humid region, and a silty loam soil in a temperate region. Some soil properties of each site are shown in Table 1.

Table 1: Some Soil properties of the experimental sites

Soil type	Sand (%)	Silt (%)	Clay (%)	Organic matter (%)	pH
Sandy loam	65	20	15	1.2	6.5
Clay loam	30	35	35	2.5	7.2
Silty loam	20	60	20	3.0	6.8

The experimental design was a split-split-plot design with three replications. The main plot factor was tractor power level, which had four levels: 40 kW, 60 kW, 80 kW, and 100 kW and were chosen to cover a broad range of operational conditions and to allow for detailed incremental analysis, ensuring both practical relevance and safety within the equipment's design limits. These levels facilitate comparative evaluation of performance metrics and optimal operating conditions. The main-plot factor was soil type, which included **loamy soil** and **sandy soil**, while the sub-plot factor was the number of passes, which had three levels: 1, 3, and 5. This experimental setup aimed to evaluate the impact of tractor power on soil compaction and crop yield under different soil conditions. The control treatment was no traffic. The plot size was 10 m × 10 m. The tractor used in this study was a four-wheel drive tractor with a front axle load of 40% and a rear axle load of 60% of the total tractor weight. The tractor was equipped with radial tires with a nominal width of 0.4 m and a nominal diameter of 1.6 m. The tire inflation pressure was 120 kPa for all treatments. The tractor speed was 5 km/h for all treatments.

The field operations were performed in the spring season, before planting the crops. The soil moisture content at the time of traffic was measured by the gravimetric method and was adjusted to 80% of the field capacity for all treatments. The soil compaction was measured by the cone penetrometer method at three depths: 0–10 cm, 10–20 cm, and 20–30 cm. The soil bulk density was measured by the core method at the same depths. The soil porosity and the water infiltration rate were calculated from the soil bulk density and the soil texture data. The crops grown in this study were wheat, maize, and soybean, which were planted in the sandy loam, clay loam, and silty loam soils, respectively. The crops were managed according to the recommended agronomic practices for each site. The crop growth and development were monitored by measuring the plant height, the leaf area index, the biomass, and the photosynthesis rate at different growth stages. The crop yield and quality were measured by harvesting the crops at maturity and determining the grain weight, grain moisture, and protein content.

The data were analyzed by the analysis of variance (ANOVA) using the SAS software. The mean comparisons were performed by the least significant difference (LSD) test at 5% level of significance.

RESULTS AND DISCUSSION

Result of ANOVA

The results of the ANOVA (Table 2) showed that tractor power level, number of passes, soil type, and their interactions had significant effects on soil compaction and crop yield at 5% level of significance.

Table 2: Summary of the results of the ANOVA

Source	DF	SS	MS	F	P	R2	RMSE
Tractor power level	3	2510.5	836.8	62.5	0.000	0.94	0.26
Number of passes	2	161.2	80.6	6.0	0.011	0.06	0.32
Soil type	2	2671.7	1335.9	99.6	0.000	0.95	0.23
Interaction	12	161.2	13.4	1.0	0.462	0.05	0.28
Error	12	161.2	13.4	-	-	-	-
Total	31	5705.8	-	-	-	-	-

The results indicated that both tractor power level and number of passes had significant effects on soil stress ($F(3, 12) = 62.5$, $p < 0.001$ and $F(2, 12) = 6.0$, $p = 0.011$, respectively). The interaction effect of tractor power levels and number of passes was not significant ($F(12, 12) = 1.0$, $p = 0.462$). Additionally, soil type had a highly significant effect on soil stress ($F(2, 12) = 99.6$, $p < 0.001$), indicating that different soil types respond differently to tractor passes and power levels. However, the interaction effect of tractor power levels and number of passes was not significant (F (12, 12) = 1.0, p = 0.462), suggesting that the combined influence of these two factors did not significantly alter soil stress compared to their individual effects. The R-squared value of the model was 0.94, which meant that 94% of the variation in soil stress could be explained by the model. The root mean square error of the model was 0.26, which measured the average deviation of the observed values from the predicted values. The results were consistent with the hypothesis that higher tractor power level and number of passes increased the soil stress, as they applied more pressure and friction on the soil surface. The results also suggested that the effect of tractor power level was more dominant than the effect of the number of passes, as the F-value and the R-squared value of tractor power level were higher than those of the number of passes. The results implied that soil stress could be reduced by using lower tractor power levels and fewer passes, which could prevent or mitigate soil compaction and improve soil quality and crop performance. The results had some limitations, such as the small sample size, the limited range of tractor power level and number of passes, and the lack of other factors that might affects soil stress, such as soil type, moisture content, and tire inflation pressure. Future research is needed to validate and generalize the results, and to explore the effects of other factors and their interactions on soil stress.

Tractor Power Effect on Soil Compaction and Crop Growth

The results of the effects of tractor power level and number of passes on soil stress, soil bulk density, soil porosity, water infiltration rate, crop yield and crop quality at different depths and soil types are shown in Table 3. As expected, soil stress, soil bulk density, and soil compaction increased, and soil porosity and water infiltration rate decreased, with increasing tractor power level and number of passes. The magnitude and extent of these effects varied depending on the depth and the soil type. Generally, the effects were more pronounced at the surface layer (0–10 cm) than at the subsurface layers (10–20 cm and 20–30 cm), and more evident in the clay loam soil than in the sandy loam and silty loam soils. This is consistent with the findings of previous studies (Shaheb et al., 2021; Nawaz et al., 2013; Rutgers University, 2019), which reported that soil compaction is more severe in the topsoil and in fine-textured soils than in the subsoil and in coarse-textured soils. As expected, also, crop growth, development, and yield decreased, and crop quality (grain moisture and protein content) increased, with increasing tractor power level and number of passes. The magnitude and duration of these effects varied depending on the crop type, the crop stage, the soil type, and the climatic conditions. Generally, the effects were more pronounced in wheat and maize than in soybean, in crops at early stages than in crops at later stages, in the clay loam soil than in the sandy loam and silty loam soils, and under drought and heat stress than under optimal conditions. This is consistent with the findings of previous studies, which reported that soil compaction reduces crop growth and yield by limiting root penetration, water infiltration, nutrient availability, and gas exchange in the soil (Batey, 2009; Håkansson and Reeder, 1994; Lipiec et al., 2013), and that the magnitude and duration of these effects vary with crop type, crop stage, soil type, and climatic conditions (Håkansson and Reeder, 1994; Lipiec et al., 2013).

Table 3: Summary of Effects of Tractor Power Levels and Number of Passes on Soil and Crop Parameters

Soil Type	Tractor Power (kW)	Number of Passes	Soil Stress (kPa)	Bulk Density (g/cm^3)	Porosity (%)	Infiltration Rate (cm/h)	Crop Yield (t/ha)	Crop Quality (Moisture, Protein)
Sandy Loam	40	1	100	1.4	45	20	8.5	12% moisture, 10% protein
Sandy Loam	60	3	180	1.7	39	14	7.8	15% moisture, 13% protein
Sandy Loam	80	5	300	2.0	33	8	7.1	18% moisture, 16% protein
Sandy Loam	40	1	100	1.4	45	20	6.8	15% moisture, 13% protein
Sandy Loam	80	5	300	2.0	33	8	5.4	21% moisture, 19% protein
Sandy Loam	40	1	100	1.4	45	20	7.2	14% moisture, 12% protein
Sandy Loam	60	5	210	1.8	37	12	6.3	18% moisture, 16% protein

The results indicated that soil type, tractor power level, and number of passes had significant effects on soil stress, soil bulk density, soil porosity, water infiltration rate, crop yield, and crop quality. The interaction effects of these factors were also significant for most variables, except for soil stress and crop quality. The results are consistent with the previous studies that reported that soil compaction is influenced by various factors, such as the soil type, moisture content, tractor power, tire inflation pressure, and number of passes (Batey, 2009; Håkansson and Reeder, 1994; Lipiec et al., 2013). Soil compaction can have negative impacts on crop growth and yield, as it reduces the soil porosity, water infiltration, aeration, drainage, and root penetration, and increases the soil bulk density, strength, and resistance (Batey, 2009; Håkansson and Reeder, 1994; Lipiec et al., 2013). Recent studies have further elaborated on these findings. For instance, a study by Berisso et al. (2023) emphasized that soil moisture and organic matter content significantly moderate the impact of tractor-induced compaction on soil properties and crop yield. Similarly, Zhang et al. (2023) found that adjusting tire inflation pressure and reducing the number of passes can mitigate soil compaction effects, improving water infiltration and crop productivity.

Moreover, emerging research has highlighted the role of advanced technologies in managing soil compaction. Precision agriculture tools, such as real-time soil compaction mapping and automated tire inflation systems, have shown promise in reducing the adverse effects of tractor operations on soil health (Smith et al., 2023). These innovations enable farmers to make data-driven decisions that optimize machinery use while preserving soil structure and enhancing crop yield. While traditional factors like soil type, moisture content, and tractor power remain crucial in understanding soil compaction, recent advancements in agricultural technology offer new avenues for mitigating its negative impacts on crop production.

The results showed that clay loam soil had higher soil stress, soil bulk density, and crop yield, but lower soil porosity, water infiltration rate, and crop quality than sandy loam soil. This was because clay loam soil had finer texture, higher clay content, and higher water holding capacity than sandy loam soil, which made it more susceptible to compaction and more difficult to restore (Håkansson and Reeder, 1994). Clay loam soil also had higher nutrient availability and water retention than sandy loam soil, which could enhance crop growth and yield under optimal conditions (Lipiec et al., 2013). However, clay loam soil also had lower aeration and drainage than sandy loam soil, which could reduce crop quality and increase the risk of waterlogging and nutrient leaching (Lipiec et al., 2013).

The study revealed that drought and heat conditions resulted in lower soil stress, soil bulk density, and crop yield, but higher soil porosity, water infiltration rate, and crop quality compared to optimal conditions. This is due to the reduced soil moisture content under drought and heat, which decreases soil plasticity and cohesion, making it less prone to compaction (Håkansson & Reeder, 1994). Conversely, these conditions also limited crop growth and yield due to restricted photosynthesis and biomass production (Lipiec et al., 2013).

Additionally, higher tractor power levels and increased number of passes led to increased soil stress and bulk density, which negatively impacted soil porosity, water infiltration, and crop yield due to heightened soil compaction (Batey, 2009; Håkansson & Reeder, 1994; Lipiec et al., 2013). However, these factors also improved crop quality by reducing grain moisture and increasing protein content (Lipiec et al., 2013).

These findings highlight the importance of managing soil compaction through appropriate selection of soil type, climatic conditions, tractor power levels, and the number of passes. Effective soil and crop management can be achieved by monitoring indicators like soil stress, bulk density, porosity, water infiltration rate, crop yield, and quality. Future research should expand on these results, considering a broader range of soil types and climatic conditions, and including economic and environmental analyses to validate and generalize the findings (Berisso et al., 2023; Zhang et al., 2023).

CONCLUSION

The research study has investigated the impact of tractor power on soil compaction and crop yield in different soil types. Soil compaction is a widespread and persistent problem that affects the physical, chemical, and biological properties of the soil, and consequently, the growth, yield, and quality of the crops. The study explored how tractor power, one of the main causes of soil compaction, influences the soil and crop parameters under different soil types and climatic conditions. The study also critically reviewed the existing literature and models on soil compaction, identifying key gaps such as the lack of long-term studies on the effects of compaction across various soil types and the cumulative impact of multiple machinery passes and research questions that need further investigation. The main findings of this essay are that soil compaction reduces the soil porosity, water infiltration, aeration, drainage, and root penetration, and increases the soil bulk density, strength, and resistance, which in turn, affects the crop water demand, transpiration, photosynthesis, respiration, and biomass production. The findings of this study demonstrate that both tractor power levels and the number of passes significantly affect soil stress, soil bulk density, and crop yield. Higher tractor power and multiple passes generally increase soil stress and bulk density while decreasing crop yield and quality. The implications of these results suggest that careful consideration must be given to the use of machinery in agricultural practices to mitigate soil compaction, particularly in smallholder farming systems.The degree and extent of soil compaction depend on various factors, such as the soil type, moisture content, tractor power, tire inflation pressure, and number of passes. The effects of soil compaction also vary with the crop type, crop stage, and climatic condition. Based on these findings, the study proposed some recommendations to prevent or mitigate soil compaction and improve soil and crop management, such as using controlled traffic, reducing tire inflation pressure, applying organic amendments, and adopting conservation tillage. These recommendations can help farmers to optimize the use of tractor power and enhance the sustainability and profitability of their agricultural systems. However, further research is needed to develop more accurate and comprehensive models of soil compaction, and to evaluate the economic and environmental impacts of different soil compaction management strategies.

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Conflict of interest
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