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Critical Moisture Content, Bulk Density Relationships and Compaction of Cultivated and Uncultivated Soils in the Humid Tropics

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Authors' contributions

This work was carried out in collaboration between both authors. Author BEU designed the study, performed the statistical analysis, wrote the protocol and wrote the first draft of the manuscript. Author JE managed the analyses of the study and the literature searches. Both authors read and approved the final manuscript.

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ABSTRACT

Soil compaction affects soil fertility through increasing bulk density and soil strength. It also decreases infiltration rate, total porosity and amount of water stored in the root zone for crop use. In this study, we evaluated the optimum moisture contents (OMC) in relation to maximum dry density (MDD) and compaction of cultivated and uncultivated soils. The study was carried out on four land use types viz: uncultivated: Velvet tamarind (*Dialium quineese*), rubber plantation (*Hevea brasiliensis*) and cultivated: 5-year fallow and 10-year continuous cultivated soil to maize crop. Proctor test for the maximum dry density-moisture content relationship was carried out, including some hydraulic and structural properties of the soil, and their effect soil compaction. Results showed that optimum moisture content (OMC) for compaction relate to the maximum dry density (MDD). In which case, dry density increased with water content to a maximum and decrease as moisture content increased above the optimum. Soil organic matter (SOM) content and particle size distribution highly affected the MDD and OMC. The MDD and OMC were: 1.92 g cm^{-3} and 10.4%, 1.95 g cm^{-3} and 11.2%, 1.91 g cm^{-3} and 12.3%, and 1.87 g cm^{-3} and 12.8% for velvet tamarind, 5-year fallow, CC and rubber plantation soils respectively, at 0-15 cm depth. Changes in field bulk densities at similar depths were in the order of velvet tamarind < rubber < 5-year fallow < CC. There were highly significant ($p < 0.01$) relationships between MDD, total porosity, Ksat and SOM and negative relationships between these parameters and OMC. Thus, continuous cultivation increased MDD and reduced OMC for compaction. Two- season fallow periods with legume could improve soil hydraulic properties and maintain the MDD of sandy soils at minimum.

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1. INTRODUCTION

Soil bulk density is an intermediate index of soil compaction and ecological properties such as porosity and hydraulic conductivity, with respect to their mutual relations [1,2]. These relationships are constantly being modified by soil moisture content, which according to Silver [3] affected soil susceptibility to the action of mechanical forces [3]. The effects of antecedence moisture content on soil compaction have been discussed. For example, soils that were completely dry were not compacted to its maximum or optimum density due to the friction between the soil particles [4,5]. They further reported that, as the moisture content increased, the lubricating effect of water on soil particles allowed the particles to move easily into a state of compaction. At compaction state, soil aggregates are pressed closer together, resulting in a greater mass per unit volume. Hence, compaction tends to reduce the soil pore volume, resulting in less space for air and water in the soil [6]. Since soil dry bulk density is the mass of oven dry soil per unit volume, the relationship between soil compaction and its capacity to store and transport water or air is obvious. For this reason, the dry bulk density of soil one of the most frequently used parameters to characterise the state of soil compaction [7]. The use of bulk density as an indicator of soil compaction revealed that soil was vulnerable to compaction with increasing water contents to a limiting range, after which the density decreased with additional water content [7].

Susceptibility of soils to compaction depends on factors which influence soil particle interactions and soil texture [8]. These factors include clay to sand ratio [9], soil structure [2] and soil water content. This way, the susceptibility of soil to compaction is related to soil water content. The amount of water retained by the soil organic matter helps the soil to rebound against compaction [10].

A number of literature reported that, critical limits of moisture content for compaction have not been well studied in some tropical soils [11,12]. They agreed that low organic matter soils dominant in the hot humid tropics are usually susceptible to compaction. Therefore, it is important to improve our understanding on the critical and/or limiting moisture content of some tropical soils in relation to compaction and dry bulk density. Such knowledge would help in decision making on the type of tillage and soil management options to prevent soil degradation. The broad objective of this study was to evaluate the maximum dry density in relation to the optimum moisture content for compaction of cultivated and uncultivated soils on coastal plain sands. We also quantified some structural and hydraulic properties and related them to optimum soil moisture content and maximum dry density. Such information would provide valuable input on soil compaction in relation to moisture content, especially, in some fragile tropical soils under continuous cultivation.

2. MATERIALS AND METHODS

2.1 Site Description and Sampling

The experiment was carried out at the University of Port-Harcourt environment (Lat $4^{o}15^{1}$N and Long $7^{o}45^{1}$E) in the rainforest zone of southern Nigeria. Total annual rainfall in the area is in excess of 2400 mm, with two peaks in the months of June and September [13]. Mean monthly temperature ranges between 22° and 32^{o}C, with minimum and maximum relative humidity of 35% and 78% respectively during cropping season [14]. The soil is derived from coastal plain sands and classified as *Arenic acrisol* [15]. Two cultivated sites and two uncultivated sites were selected. The cultivated sites were: (A) Fifteen hectare (15 ha) land area under 5-year fallow, previously cultivated to maize and cassava (5-year fallow), (B) Twenty–five hectare (25 ha) land area under 10-year continuous cultivation to maize and cassava (CC), while, uncultivated sites were: (A) Twenty hectare (20 ha) rubber plantation (Rubber) and (B) Twenty-five (25 ha) reserved area under black velvet tamarind (Velvet tamarind). A few characteristics of the sites are in Table 1. Each land area was divided into 4 replicates of 50 m x 50 m based on the physiographic position of the land, since the slope of the land would affect the soil water content, and other physical properties of the soil. Five undisturbed core and five bulk soil samples were collected from each replicate at 0-15 cm and 15-30 cm depths in 4 replicates. In total, 160 core and 160 bulk soil samples were collected in the whole area for laboratory analysis.

2.2 Laboratory Analysis

2.2.1 Proctor test for bulk density - moisture content relationship

Soil samples weighing 2.5 kg were wetted to five different moisture contents. Wet sub-samples of homogenized soils were compacted in three layers in a compaction chamber of 944 cm^3 in volume with each layer receiving 25 blows of a 2.5 kg falling hammer from a height of 30 cm. The mass of wet-compacted soils (mt) in the chamber were determined. Two sub-samples of the compacted soils were collected and weighed to obtain the fresh weight (mf). The samples were oven-dried at 105º C for 24 hours and weighed to obtain dry weight (ms). The difference in weight was used to determine the average gravimetric water content (w), wet (ρ) and dry (ρd) soil bulk density (g cm^{-3}) as follows:

$$w = \frac{(mf - ms)}{ms} \quad (1)$$

$$\rho = \frac{mt}{944\ cm3} \quad (2)$$

$$\rho d = \frac{\rho}{(1+w)} \quad (3)$$

where, w is gravimetric water content, mf is mass of wet soil, ms is mass of dry soil, mt is mass of wet compacted soil, ρd is dry soil bulk density, and ρ is wet soil bulk density

2.2.2 Bulk density, total porosity and hydraulic conductivity

The field bulk density was determined by the method as described in details by Black and Hartge [16] as:

$$\text{Bulk density} = \frac{mass\ of\ oven{-}dried\ soil}{volume\ of\ bulk\ soil} \quad (4)$$

Total porosity was calculated with core samples using the method of Flint and Flint [17] as;

$$\%\ \text{Total porosity} = \frac{volume\ of\ water\ at\ saturation}{volume\ of\ bulk\ soil} \quad (5)$$

Saturated hydraulic conductivity was measured by the constant-head permeability technique as described by Klute and Dirksen [18] and calculated using the transposed Darcy's equation for vertical flow of liquids [19]. In this method, leachate volume was measured over time until flow was constant at which time the final flow rate was determined from the equation:

$$Ksat = \frac{Q}{AT} \times \frac{L}{\Delta H} \quad (6)$$

Where, Ksat is saturated hydraulic conductivity (cm hr^{-1}), Q is volume of water that flow through a cross sectional area A (cm^2), T is time elapse (s), L is length of core (cm), ΔH is hydraulic head difference (cm).

2.2.3 Determination of particle size distribution and soil organic matter content

Particle size distribution was determined with air-dried soil sample sieved through 2 mm mesh by the method of Gee and Bauder [20] after complete dispersion with sodium hexametaphosphate. Total organic carbon was determined by the wet oxidation dichromate method and titration with 0.5 M NaOH [21]. Total organic matter (TOM) was obtained by multiplying the organic carbon (TOC) values by the Van Bemelen factor of 1.724 [22].

2.3 Data Analysis

For each location analysis of variance (ANOVA) was used, followed by multiple comparisons of the parameters measured using the SAS software [23]. Means were separated by the least significant difference using Fisher's protected test [24] at 5% probability. Correlation analysis was used to determine the relationships between

Table 1. Characteristics of the sites used for the study

Land use	Characteristics
5 year fallow	The area has been under fallow for about five years, crops grown are maize and cocoyam. Organic manure is used to improve soil fertility
CC	The area has been under continuous cropping to maize, cassava and fluted pumpkin for about 10 years. Spent mushroom substrate and poultry manure have been used to boost soil fertility
Rubber (*Hevea brasiliensis*)	The area is a secondary forest that has not been cleared for over 20 years. The forest consists of rubber trees and shrubs.
Velvet tamarind (*Dialium guineese*)	A secondary forest that has been in use for over thirty years, consisting of the black velvet tamarind bush, undergrowths and shrubs.

water retention properties and some physical properties. Significant correlation coefficient was tested at 5% probability.

3. RESULTS

3.1 Particle Size Distribution, Bulk Density and Total Porosity of the Soils

In Table 2, the soil is sandy loam at 0-30 cm depth. Sand fraction ranged between 651 and 681 g kg^{-1} in the top 0 – 15 cm and 623 and 670 g kg^{-1} at 15.30 cm depth. Significant ($p < 0.05$) different in silt content at 0-15 cm depth did not change the optimum moisture range for compaction. Significant differences in sand and clay contents were found at 15-30 cm depth among the land use types. Bulk densities were significantly ($p < 0.05$) lower in the 5-year fallow, velvet tamarind and rubber plantation soils compared with that in continuous cultivation (CC). Bulk density values ranged between 1.41g cm^{-3} in velvet tamarind soils and 1.69 g cm^{-3} in CC, indicating the significance roles of these plants in modifying soil bulk density. The topsoil total porosity was higher in forested soils. Mean values were 28% in rubber plantation, 25 and 21% in 5-year fallow and CC respectively.

Soil organic matter (SOM) and saturated hydraulic conductivity (Ksat) were relatively higher SOM in forested soils (Table 3). At 0-15 cm depth, SOM ranged between 11.7 and 15.0 g kg^{-1}, and 10.7 and 13.01 g kg^{-1} at 15-30 cm depth. Soil organic matter in the topsoil was in the order of velvet tamarind > rubber > 5-year fallow > CC in the topsoil. Velvet tamarind being a popular plant in bush fallow farming systems in most tropical environment increased SOM which subsequently, increased the MWD of water stable aggregates and saturated hydraulic conductivity.

Significantly ($p < 0.05$) variations in Ksat were found across all land use types, with values ranging between 38.7 cm hr^{-1} and 28.7 cm hr^{-1} in Velvet tamarind and rubber soils respectively. These values were 340% and 235% respectively, higher than that in CC soils. The very low Ksat values of 8.57 cm hr^{-1} and 1.7 cm hr^{-1} found in CC soils at 0-15 cm and 15-30 cm depths respectively, could have implications on the soil air capacity.

3.2 Moisture Content– Wet and Dry Bulk Density Relationship

The moisture - density relationship for the different land use at various moisture content are shown in Figs. 1 and 2. The overall soil moisture-density curves have maximum dry density range of 1.84 - 1.95 g cm^{-3} for corresponding optimum moisture content (OMC) range of 10.3 - 13.4 %. At 0 – 15 cm depth, the average OMC for Velvet tamarind and rubber plantation, representing forested soils were 10.3 and 13.4% at corresponding dry density (MDD) values of 1.95 and 1.84 g cm-^{3} respectively (Fig. 1).

Cultivated soils, represented by the 5-year fallow and CC showed OMC of 11.2 and 12.5 % at corresponding MDD values 1.89 and 1.88 g cm-^{3} respectively at 0 – 15 cm depth .At 15-30 cm depth, the average MMC for Velvet tamarind and rubber plantation were 10.4 and 12.8% at corresponding MDD values of 1.92 and 1.87 g cm^{-3} (Fig. 2).

The results further demonstrated that at a certain level of compaction efforts, increase in moisture content increased the dry density to a maximum (MDD) after which the dry density decreased with further increase in moisture content. This typical behaviour of soils during compaction to a critical point otherwise known as the OMC or limiting moisture range and corresponding MDD is indication that vehicular movements or cattle grazing could reduce the soil quality criteria by increasing soil dry density at certain limiting moisture ranges.

Soil compaction was further characterised by the percentage clay content in the subsoil in Table 2. Results showed that the degree of compaction was moderate in all land use types due to increased clay content in the subsoil. In Fig. 1, the dry bulk density decreased by about 5% when OMC for compaction increased by 23%. Generally, limiting moisture content for maximum compaction increased the dry bulk density in the order of velvet tamarind > 5-year fallow > rubber plantation > continuous cultivation. At 15-30 cm depth (Fig. 2), clay contents were relatively higher; so that the optimum moisture content for compaction maintained a marginal decrease in the dry bulk density.

Table 2. Particle size-distribution, bulk density, and total porosity of the soils

Land use	Sand ($g\ kg^{-1}$)	Silt ($g\ kg^{-1}$)	Clay ($g\ kg^{-1}$)	Textural class	Bulk density ($g\ cm^{-3}$)	Total porosity (%)
			0-15 cm			
5-year fallow	661	207	132	SL	1.48	25
CC	681	200	119	SL	1.69	21
Velvet tamarind	670	216	114	SL	1.41	28
Rubber	651	241	109	SL	1.42	28
LSD (0.05)	NS	35	NS		0.21	2.7
			15-30 cm			
5-year fallow	626	227	147	SL	1.40	26
CC	670	214	116	SL	1.68	20
Velvet tamarind	626	234	140	SL	1.41	27
Rubber	623	222	155	SL	1.42	29
LSD (0.05)	22.5	NS	31.6		0.23	3.16

NS-non significant at p > 0.05, SL- sandy loam

Table 3. Soil organic matter and saturated hydraulic conductivity of the soil

Land use	Organic matter ($g\ kg^{-1}$)	Ksat ($cm\ hr^{-1}$)	Permeability index*	Permeability class*
		0-15 cm		
5-year fallow	12.1	20.42	5	Moderately rapid
CC	11.7	8.57	1	Very slow
Velvet tamarind	15.0	37.70	6	Rapid
Rubber	13.8	28.70	5	Moderately rapid
LSD (0.05)	1.21	9.2		
		15-30 cm		
5-year fallow	10.7	10.46	2	Slow
CC	11.01	1.74	1	Very slow
Velvet tamarind	12.15	25.71	5	Moderately rapid
Rubber	12.11	9.25	2	Slow
LSD (0.05)	1.04	3.2		

*Ksat- saturated hydraulic conductivity *- Soil Survey Staff [25] Classification,*
LSD (0.05)- Least significant different at p < 0.05

3.3 Relationships among Optimum Moisture Content, Maximum Dry Density and Some Properties of the Soil

There were highly significant positive relationships between the optimum moisture content (OMC) and porosity, Ksat and organic matter content (r = 0.870, 0.609 and 0.586), ($p < 0.01$) respectively (Table 4). This implies that increased in OMC led to concomitant increase in total porosity. Similarly, soil organic matter increased saturated hydraulic conductivity, whereas, MDD showed significant negative relationship with organic matter content and hydraulic conductivity (r = - 0.58 and – 0.557 at $P < 0.01$) respectively. As dry bulk density increased, Ksat decreased.

4. DISCUSSION

In Table 2, the low field bulk density in fallow soils consequently led to concomitant increases in Ksat and aggregate stability. Organic matter built up by the legume plant during the 2-season fallow may have contributed to such increases. The moisture content-dry density relationships found in this study further confirmed the widely held assertion that additions of water to soil increased force of cohesion within the soil particles, when water acting as lubricant

[26]. The lubrication effect, however, continued to a limiting moisture range when water combined with the remaining air within the soil pores to fill the pore spaces. At that stage, the soil would attain its MDD and OMC. Further increase in the moisture content after the OMC, tends to increase the volume of voids, resulting in lower density and soil strength [27-29].

However, the decrease in bulk density at higher moisture contents confirmed that further addition of moisture to the soil created greater pore-water pressures, which made the soil less compacted [27]. The observed low densification of the soils at higher moisture content is consistent with [29,30] that capillary effects due to the high moisture content yielded tension stress that opposed compaction. High SOM found in the Velvet tamarind and 5-year fallow soils may have led to the low densification compared to the cultivated soils [31,32]. This is also consistent with [11,27] that SOM usually create a high number of macro pores which could facilitate higher amounts of water holding capacity.

Implication is that when tillage operations are carried out in the field at such moisture contents, it could lead to soil compaction. This is also consistent with an earlier report by [10] that built-up of SOM in soils increased water retention, thus, helping soils to rebound against compaction. When the pore diameter was reduced by compaction, water and gas fluxes decreased, leading to reduction in soil air capacity. Saturated hydraulic conductivity (Ksat) and total porosity as ecological properties were higher in velvet tamarind and 5-year fallow soils most probably due to accumulation of plant litter and high SOM content which caused rapid flow of water into and within the soil. Under saturated conditions, the water flow would mainly occur in the macro-pores, further confirming that positive correlation between Ksat and porosity was commonly obtained in soils with high organic matter content [33]. These properties are usually affected by soil compaction.

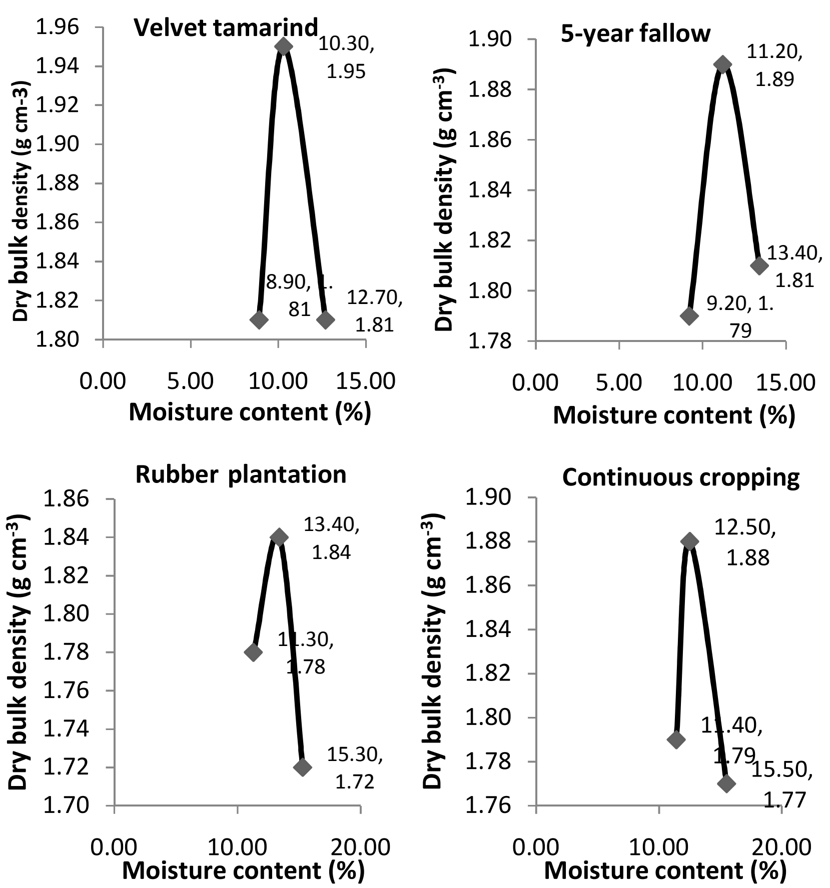

Fig. 1. Moisture-density relationship of cultivated and forested soils at 0-15 cm

Table 4. Relationship among optimum moisture content (OMC), maximum dry density (MDD) and some properties of the soil

	Correlation coefficient (R) N = 30					
Soil parameters	**Sand**	**Silt**	**Clay**	**Porosity**	**Ksat**	**OM**
OMC	-0.12	0.27	-0.17	0.87**	0.61**	0.59**
MDD	0.14	-0.14	0.13	-0.69**	-0.56**	-0.58**

***- significant at (p > 0.01), Ksat– Hydraulic conductivity OM- Organic matter, OMC- Optimum moisture content, MDD- Maximum dry density, (r = 0.349 at 5% and r = 0.449 at 1% level of significance)*

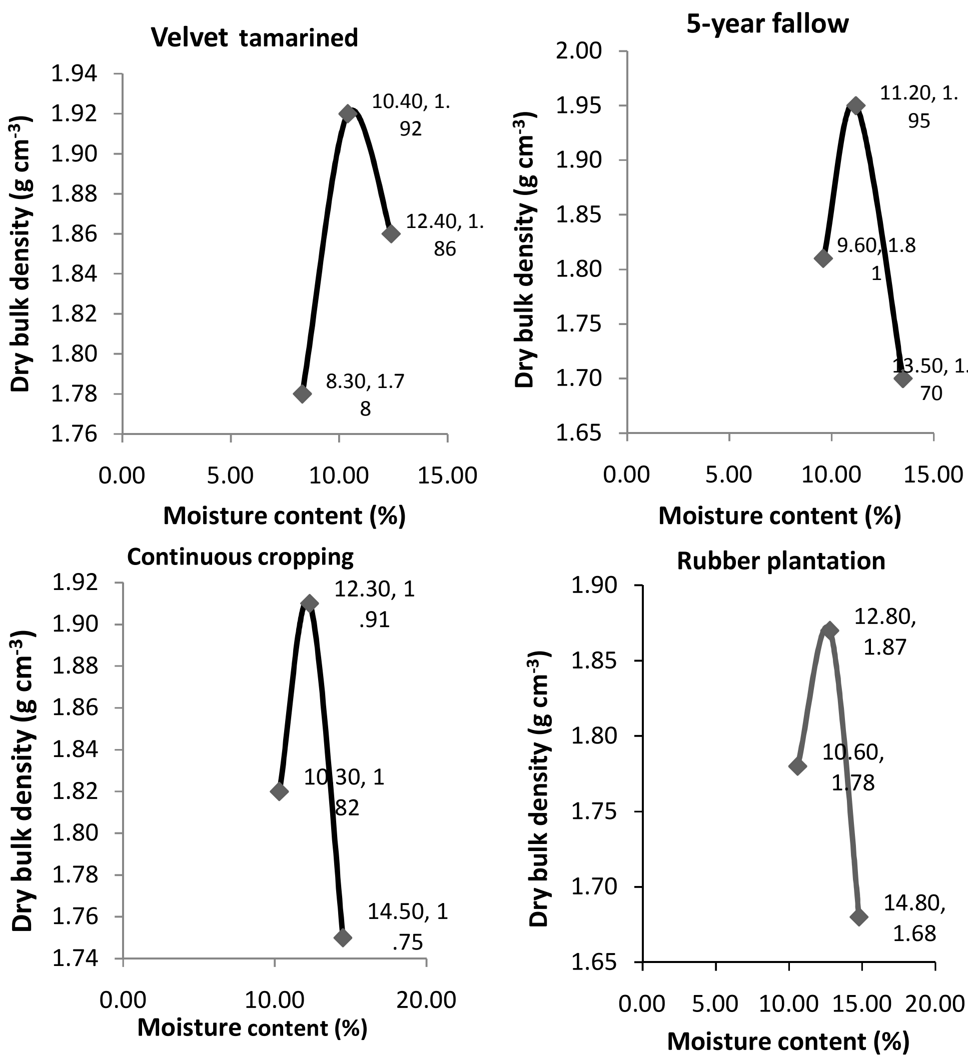

Fig. 2. Moisture-density relationships of cultivated and forested soils at 15 30 cm

Proctor test (Figs. 1 and 2), showed that compaction increased bulk density at the threshold moisture content such that roots of certain plants may be restricted so also crop establishment. The continuous cultivation soils showed rapid response to compaction, more attributed to high sand particle fraction which characterized continuous cultivated soils through the loss of silt-clay fractions. This is also consistent with the discussions of Reichart et al. [2] that the differences in sensitivity of soils to compaction varied with the particle size-distribution, total porosity and saturated hydraulic conductivity. At minimum water content the velvet tamarind, 5-year fallow and rubber plantation soils can support loads arising from possible wheel traffic and tillage equipment. The positive relationships between porosity, Ksat and OM had earlier been discussed [32,33]. Increase in SOM led to increase in saturated hydraulic conductivity and total porosity, especially when OM acts as aggregating agent. The negative relationships between MDD and Ksat and OM were not surprising because compaction reduced macro-pores which invariably reduced permeability and have deleterious consequences on root penetration and seedling emergence (2). This may induce surface runoff and increase soil erosion.

5. CONCLUSION

Significant conclusions drawn from this study are that: Compaction increased dry bulk density and decreased total porosity and saturated hydraulic conductivity. The OMC for compaction was influenced by soil organic matter and particle size distribution. The lowest OMC and highest MDD were obtained in Velvet tamarind soils due to relatively high soil organic matter associated with such soils. The highest OMC and corresponding highest MDD was found in rubber plantation soils. Relationships showed a negative correlation between OMC and MDD. The maximum dry density (MDD) also showed a negative correlation between MDD with total porosity, Ksat and SOM. Soil organic matter associated fallowed and velvet tamarind helped soils to rebound against compaction. Continuous cultivation increased the soil dry density under increased moisture content load effort. Thus land use and management practices that would leave soil organic matter on the soil surface, retain soil moisture would reduce compaction and sustain the soil quality.

COMPETING INTERESTS

Authors have declared that no competing interests exist

REFERENCES

1. Bulinski J, Niemczyk H. Effects of method of agricultural outfit running on the field on soil properties and sugar beet yielding. Ann. Warsaw Agric. Univ. Agric. Eng. 2001;41:39–44.
2. Reichert JM, Suzuki LEAS, Reinert DJ, Horn R, Hakansson I. Reference bulk density and critical degree-of-compactness for no-till crop production in subtropical highly weathered soils. Soil Tillage Res. 2009;102:242-254.
3. Silva VR. Soil physical and water parameters under different soil compaction state. Doctorate Thesis, Santa Maria. Universidade Federal de Santa Maria. 2003;191.
4. Carter MR. Soil quality for sustainable land management, organic matter and aggregation interactions that maintain soil functions. Agron. J. 2002;94:38-47.
5. Hamza MA, Anderson WK. Soil compaction in cropping systems: A review of the nature, causes and possible solosions. Soil Tillage Res. 2005;82:121-145.
6. Panayiotopoulos KP, Papadopoulou CP, Hatjiioannidou A. Compaction and penetration resistance of an Alfisol and Entisol and their influence on root growth of maize seedlings. Soil Tillage Res. 1994; 31:323–337.
7. Ish aq M, Ibrahim M, Hassan A, Saeed M, Lal R. Subsoil compaction effects on crops in Punjab, Pakistan: II. Root growth and nutrient uptake of wheat and sorghum, Soil Tillage Res. 2001;60:153–61.
8. Defossez P, Richard G. Models of soil compaction due to traffic and their evaluation. Soil Tillage Res. 2002;67:41–64.
9. Reichert JM, Reinert DJ, Braida JM. Soil quality and sustainability of agro systems. G. Ambiente. 2003;27:29-48.
10. Hamza MA, Anderson WK. Response of soil properties and grain yields to deep ripping and gypsum application in a compacted loamy sand soil contrasted with a sandy clay loam soil in Western Australia. Aust. J. Agric. Res. 2003;54: 273–282.
11. Beutler AN, Centurion JF, Silva AP, Roque CC, Ferra MV. Optimal relative bulk density for soybean yield in oxisols. Braz. J. Soil Sci. 2005;29:843-849.
12. Beutler AN, Centurion JF, Silva AP, Roque CC, Ferraz MV. Soil compaction and least limiting water range in dry land rice yield Braz. J. Agric. Res. 2004;39:575-580.
13. Beutler AN, Centurion JF, Centurion MAPC, Silva AP. Effect of compaction on

soybean cultivar yield in Haplustox. Braz. J. Agric. Res. 2006;30:787-794.
14. NIMET (Nigeria Meteorological Agency): Annual report 2014, Port Harcourt, Nigeria. 2014;539-579.
15. USDA–United States Department of Agriculture: Soil taxonomy. USDA-NRCS, Washington, DC, USA; 2012.
16. Black GR, Hartage KH. Bulk density. In: Klute A. (Ed.). Methods of soil analysis. Part 1, 2nd ed. Physical and Mineralogical Methods. Agron. Monogr. 1986;9:363-375.
17. Flint LE, Flint AL. Pore-size distribution. In: Done JH, Topp GC. (Eds.). Methods of soil analysis. Part 1. Physical methods. Soil Sci. Soc. Am. Madison WI. 2002;246–253.
18. Klute A, Dirksen C. Hydraulic conductivity and diffusivity: Laboratory methods. In: Klute A. (ed.). Methods of soil analysis, Part 1, 2nd edn. Agron. Monogr. No 9. ASA-SSSA, Madison, WI. 1986;687-734.
19. Reynolds WD, Elick DE, Youngs EG, Amoozegar A, Bootink NW. Saturated and field-saturated water flow parameters. In: Dane JH, Topp GC, editors. Methods of soil analysis, part 4. Madison (WI): Soil Sci. Soc. Amer. 2002;797–878.
20. Gee GW, Bauder JW. Particle size analysis. In: Methods of soil analysis, part 1 (Klute, A. ed), 2nd ed. Agronomy Monograph No 9. ASA-SSSA. Madison, WI. 1986;383–411.
21. FAO: Methods of analysis for soils of arid and semi-arid regions. Rome; 2007.
22. Van der Ploeg RR, Bohm W, Kirkham MB. On the origin of the theory of mineral nutrition and the law of minimum. Soil Sci. Soc. Am. J. 1999;66:1055-1062.
23. SAS–statistical analysis system: Institute SAS/STAT User's Guide, 4th ed., Vol.1.SAS Inst. Cary, NC, USA; 2001.
24. Gomez KA, Gomez AA. Statistical procedures for agricultural research. 2nd ed., Wiley Interscience Publication, Singapore; 1984.
25. Soil Survey Staff. Soil survey manual. USDA, Soil conservation service, Agricultural a Handbook No. 18, Print Office, Washington, DC, USA; 1993.
26. Udom BE, Adesodun JK. Soil penetrating quality in cultivated and forested coastal plain sands of southern Nigeria. Archives of Agronomy and Soil Science. 2016;62: 963-971.
27. Canarache A. Factors and indices regarding excessive compactness of agricultural soil. Soil Tillage Res. 1991; 19:145-165.
28. Proctor RR. Design and construction of rolled earth dams. Engineering News Record. 1933;3:245–248,286–289,348–351,372–376.
29. Gurtug Y, Sridharan A. Prediction of compaction characteristics of fine grained soils. Geotechniques. 2002;52(52)761-763.
DOI: 10.1680/geot,2002.52.10.761
30. Baker AT. Soil compaction and agricultural production. Soil Tillage Res. 2014;182–187.
31. Udom BE, Omovbude S, Abam PO. Topsoil removal and cultivation effects on structural hydraulic properties. Catena. 2018;165:100-105.
32. Mesquita MGBF, Moraes SO. The dependence of the saturated hydraulic conductivity on physical soil properties. Ci. Rural. 2004;34:969-969.
33. Udom BE, Ogunwole JO. Soil organic carbon, nitrogen and phosphorus distribution bin stable aggregates of an ultisol under contrasting land use and management history. J. Plant Nutr. Soil Sci. 2015;178:480-487.

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