Effect of soil physical properties on performance of agricultural field machinery in south eastern Nigeria

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Abstract: A research was conducted at the demonstration farms of Michael Okpara University of Agriculture, Umudike, Abia State and Veterinary School, Ezzangbo, Ebonyi State in 2017; to assess the effect of soil physical properties on the performance of some selected agricultural field machineries in the tropical region of Nigeria. Results of the effect of the soil textural class/type on implement performances revealed that the average efficiency of the implements was highest on sandy-clay soil with average efficiency of 87.35% and the least was loamy-sandy soil that gave an average efficiency of 86.21%. It was observed from the results that the highest average moisture content of 17.7% was recorded for all the soils before tillage; but after tillage; ploughing recorded 16.3% moisture content; harrowing, ridging, pulverization and planting in that order had 15.45%, 14.70%, 14.23% and 14.12% respectively. The reduction in moisture content during the field operations promoted workability of the soils. The highest moisture contents are observed for the plough as compared to other implements was attributed to high compaction associated with ploughing operation which decelerates infiltration rate. Results further showed that the bulk density of the soils reduced with the application of the implements. Prior to the field operations, the average bulk density of the soil was 1.62 g cm^{-3}, but when the implements were applied, there was shortfall in the bulk densities in which ploughing recorded 1.49 g cm^{-3}, harrowing (1.40 g cm^{-3}), ridging (1.33 g cm^{-3}), rotovator (1.29 g cm^{-3}) and planter (1.35 g cm^{-3}). The reduction in the bulk density of the soil enhances the field performances of the implements by reducing the resistance to the penetration of the implements and also improves the soil for proper root penetration. The effect of porosity on the implements performance followed opposite trend as bulk density. The lowest porosity was observed in untilled soil with average porosity of 48.30%; on the application of the field machineries, the porosity of the soils increased to 49.68% after ploughing, 53.43% after harrowing, 54.11% after pulverization, 54.14% after ridging and 53.67% after planting. The increase in porosity of the soil during operation provided it was within the acceptable limit for machine operation which improved the workability of the soils, enhanced the water infiltration rate and implemented penetration to the soil. Finally, the statistical analysis (ANOVA) conducted on the effect of soil physical properties on the implement performances showed significant difference at 5% level of probability.

Keywords: field machineries, performances, physical properties, soil, tropical region

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1 Introduction

Soil condition is a major factor that affects the performance of field machineries; for instance, when the soil compaction increased, the bulk density increased and consequently the soil penetration resistance became high (John et al., 1987). When soil conditions are poor for machine operations, the rate of operation is affected; forward speed must usually be reduced. This condition will improve field efficiency but it is not, of course, a desirable operating condition (Alnahas, 2003). An extreme time loss can occur in harvesting if the crop has been windblown to such a position that it can be approached from only one direction. Soil conditions that affect

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machine operations are mostly vegetative cover, topography and soil physical properties such as soil moisture, soil texture and structure: porosity and bulk density. Measures of agricultural machine performance are the rate and quality at which the operations are accomplished (Hunt, 2013). According to Belel and Dahab (1997), tillage operations are soil-related procedures; soil type and condition are cardinal factors affecting the field performance of a tractor through their effects on the powered implement and tractor traction. Smith (1993) observed that the performance of plough varies considerably according to the type of soil, its moisture content, weed growth, crop residues and shape of the field. The soil physical characteristics which affect crop production and tillage requirements, are hard to be studied or assessed directly; these involve size, shape, and arrangement of solids and continuous voids, and forces relevant to physical soil characteristics. Structural stability is usually assessed in terms of different properties including total porosity, pore size distribution, available water content, and bulk density (Lal, 1995). According to John et al. (1987), when the soil compaction increased, the bulk density increased and the soil penetration resistance became high, consequently, the implements in the firm soils require a greater draft force to overcome a considerable amount of soil resistance, thus the draft force required to pull the implement in firm soil condition was greater than that of loose condition. High bulk density, higher slippage and increased fuel consumption, and decreased operating speed should be achieved in the firm soil (Alnahas, 2003). Simple correlation analysis showed that, the draft accounted for 77.3% of the availability of the slippage and 63% of the availability of fuel consumption (Belel and Dahab, 1997). They observed that, the implement in firm soil conditions had better efficiency than in loose ones. Osman (1994) maintained that there were many factors that affect the draft of an implement. The draft of blades in the wet sand was about 45% higher than that in the dry sand, showing the effect of cohesion in increasing the draft, while the draft in the clay soil was greater than sandy soil by 17%, showing the effect of soil type on draught. Salokhe and Shirn (1992) stated that increase in soil moisture content and disc angle, decreased the specific draft requirement. Dahab and Mohamed (2002) obtained similar results that there were significant differences in traction performance between tested implements due to soil moisture content and tire inflation pressure. Bukhari and Balock (1982) noticed that wheel slip was increased in clay loamy soil, when the speed of ploughing increased. Energy consumption depends on many factors including soil type and strength, tilling depth, forward speed and quality of tillage. Kepner et al. (1982) explained the effects of soil type as they reported that clay soil has a higher break up energy requirement than sandy loamy soils. For any given soil, energy requirements increased with bulk density (Shebi et al., 1988).

There is no data available from operations under local conditions to be able to quantify the effect of soil physical characteristics on machine performances in the tropics. Therefore, It is essential to evaluate the effect of soil physical characteristics on the efficiencies of the tractor coupled implements under field conditions. This research on various agricultural operations with some tractor coupled implements is aimed at obtaining data on the effect of soil physical characteristics on the field efficiencies of the machineries under field conditions in the study area.

2 Materials and Method

2.1 Materials

2.1.1 Description of experimental areas

The experiments were conducted at the demonstration farm of veterinary school, Ezzangbo, Ohaukwu L. G. A. Ebonyi State and demonstration farm of department of Agricultural and Bio-Resources Engineering, college of engineering and Engineering technology, Michael, Okpara University of Agriculture, Umudike, Abia State

The experimental sites have an average area of 8100 m^2 each. The land area was divided into four units of 45×45m each for random observations. Each unit was separated by a distance of 2.5 m from the other to avoid interaction between the plot borders and to be equally used as head lands for the commencement of the experimental operations. A random distribution of treatments within the plots was carried out and the experiments were arranged in a randomized complete block design (RCBD).

The tests were conducted in May, through June, July and August which coincide with planting season of the year, 2016; and which also offer the tractor and the coupled implements an exposure to a wide range of soil conditions.

2.1.2 Description of machine used for the test

A Massey Ferguson of model MF430E and capacity of 55.2kW (74hp) was used for the study. The same operator was used for the operation of the machine throughout the test to ensure minimal variations in operation skill/style throughout the study. The coupled implements that were studied include ploughs, harrows, rotovators, ridgers, and planters.

2.1.3 Apparatus used

The following apparatus were used for the study:-

i. Stop watch: used to keep time of operation;

ii. Measuring tape: used for linear measurement of land, working distance and working width of the machine;

iii. Wooden metre rule: used for measuring depth of cut for tillage and seed planting

iv. An electric oven of Model n30c Gen Lab size: used to determine the moisture content of the soil;

v. Mechanical soil sieve: used for soil textural class (soil type) test;

vi. Core- cutter apparatus: used to collect soil sample for bulk density measurement;

viii. A weighing balance: used to measure the weight of soil samples during the tests.

2.2 Methods

2.2.1 Determination of soil physical properties

Soil samples freshly tilled and free of organic matter, stones, stumps or plant roots was collected from different parts of the experimental site, to a depth of 0-20 cm and were bulked together to form a composite sample (Okeke et al, 2016), for laboratory test. The core- cutter apparatus was used specifically to collect soil sample for bulk density measurement. Other soil properties that were tested include soil moisture, texture, and soil structure and porosity.

2.2.2 Determination of soil moisture contents

The oven-dry method of moisture content determination was used to determine the moisture content of the soil samples in the various sites used for the study. The weight of initial samples of soil (wet soils) collected from the site and the weight of oven-dry samples of the same soils (dry soils) was determined in the laboratory and the moisture content was evaluated from the expression

$$M_C = \frac{W_S - D_S}{D_S} \times 100\% \tag{1}$$

where, M_C = moisture content of the soil, %; W_S = weight of wet soil (initial soil sample), kg; D_S = wight of oven-dry soil, kg.

2.2.3 Determination of soil textural class (soil type)

The mechanical soil analysis method was used. In the process, a freshly tilled soil free from gravel, stones, plant roots/stumps and organic matters was collected with an air tight container for a quantitative determination of the particle sizes (sand, silt and clay) in the laboratory. The soil sample was properly oven-dried and finely ground, to free all the separate particles. The total weight of the soil sample was accurately measured; and was passed through a series of mechanical sieve with mesh of different sizes ranging from 2.0 to 0.002 mm in diameter. The weight of the contents of each sieve after mechanical shaking was determined separately and expressed as a percentage of the initial weight of the fine sample; and the textural class of the soil was finally determined using the textural triangle (USDA, 2010).

2.2.4 Determination of soil bulk density

The cylindrical core-cutter method was used to determine the soil bulk density and evaluated from the expression suggested by Murthy (2012)

$$\rho = \frac{W_S}{V_S} \tag{2}$$

where ρ = bulk density, g cm^{-3}; W_S = weight of dry soil sample, g; V_S = volume of dry sample of soil, cm^3 (equal to the volume of the cylindrical cutter).

2.2.5 Determination of soil structure

The disruptive method for assessing soil structure as adopted by Diaz-Zorita (2002) was used to determine the soil structure of the area; by drop shatter technique in which the bulk sample of the soil is broken into smaller natural units/fragments of peds along planes of weakness by dropping the soil sample from various heights into a hard surface (Hadas and Wolf, 1984); and the shape of peds formed is observed and recorded.

2.2.6 Determination of soil porosity

The soil porosity was evaluated from Equation (3) suggested by Danielson and Sutherland, (1986)

$$\text{Porosity} = 1 - \frac{\text{Bulkdensity}}{\text{average density of soil particles}} \times 100\% \tag{3}$$

Density of soil particles was determined from the expression adopted by Murthy (2012) as:

$$\gamma_W = \frac{Wt}{Vt} \tag{4}$$

where, γ_W = unit weight of soil sample, KN m^{-2}; Wt = wet weight of soil sample, KN; Vt = total volume of soil sample, m^3.

2.2.7 Determination field efficiency

The field efficiency was determined from the expression suggested by Kepner et al (1982)

$$\varepsilon = \frac{100Te}{Tt} \tag{5}$$

where, ε = field efficiency, %; T_e = actual working (productive) time, hr; T_t = total working time = (T_e +T_d), hr; T_d = delay or idle time.

2.2.8 Determination of the Effective Field Capacity

The effective field capacity was determined from the expression suggested by Hunt (2013)

$$C = \frac{Swe}{c} \tag{6}$$

where, C = effective field capacity, ha hr^{-1} [a hr^{-1}]; S = speed, km hr^{-1} [mi hr^{-1}]; w = rated width of implement, m [ft]; e = field efficiency as a decimal; c = constant, 10.

2.2.9 Determination of theoretical field capacity

The theoretical field capacity was determined by rearranging the expression suggested by Gbadamosi and Magaji (2003) for field efficiency and obtained a new relationship for theoretical field capacity as follows:

According to Gbadamosi and Magaji (2003),

$$\varepsilon = \frac{Ce}{Ct} \tag{7}$$

By rearrangement,

$$C_t = \frac{Ce}{\varepsilon} \tag{8}$$

where, C_t = theoretical field capacity, ha hr^{-1}; Ce = effective field capacity, ha hr^{-1}; ε = field efficiency, decimal.

2.2.10 Data collection and analysis

Data was collected from the various parameters tested which include, soil physical properties, operation time, machine working width, operation speed, depth of cut, and machine performances; under different soil conditions and the effect of soil characteristics on the performances of the implements. This data was analyzed using tables with descriptive statistical methods and ANOVA from which the effect of soil physical properties on the field performances of the various machineries were adjudged.

3 Result and discussion

3.1 Effect of soil type on implement performance

The result of the effect of soil type on implement performance is presented in Table 1. The sandy-clay soil was the highest average performance efficiency for all the implements with overall average efficiency of 87.35%; followed by clay-loam that gave average efficiency of 86.53% and least was 86.21% obtained on loamy sandy soil. That could be due to low aggregation stability, high moisture content and low decomposed organic matter found in sandy-clay than other soil type as observed by Alnahas (2003). This is in agreement with the observations of Belel and Dahab (1997) that soil type and condition are specific indicators that affect the field performance of the tractor through their effect on the hitched implement and tractor traction. It also confirms the findings of Smith (1993) who stated that the performance of plough varies considerably according to the type of soil. Kepner (1982) had a similar observation and reported that clay soil has a higher break up energy requirement than sandy loam soil. Furthermore, the wheel slip which affect machine performance increase in clay loamy soil than other soil types when the speed of ploughing is increased as observed by Bukhari et al. (1988). Result of this research is also consistent with the observation of Abdul Razzag and Sabir (1992) that disc plough has increased field efficiency at increased rate when working on a coarser textured soil. The statistical analysis conducted on the effect of soil type on implement performance (Table 2) shows a significant difference at

5% probability level.

Table 1 Effect of soil textural class/ type on implement performances

Soil textural class	Implement performances (field efficiency, %)				
	plough	Harrow	Ridger	Rotovator	Planter
Clay-loam	87.41	82.06	84.41	87.13	86.18
Clay-loam	86.48	87.75	87.33	88.23	88.30
Loamy-sandy	87.47	85.83	87.51	84.91	85.31
Sandy-clay	85.12	86.85	86.64	87.78	86.35
Sandy-clay	88.07	89.12	88.03	87.64	87.92
Average	**87.11**	**86.32**	**86.78**	**87.14**	**86.81**

Table 2 ANOVA of the effect of soil textural class/type on the implement performances

Sources of variation	d.f	SS	MS	F. Cal	F.Tab	
					5%	1%
Soil type	4	180,817.32	45,204.33	3.997*	2.87	4.43
Implement	5	180,964.03	36,192.01	4.001*	2.71	4.10
Error	20	180,931.14	9,046.56			

Note: * significant at 5% probability level; ** significant at both 5% and 1% probability levels.

3.2 Effect of moisture content on implement performance

Results of soil moisture content before and after field operations are shown in Table 3. The highest average moisture content of 17.74% was recorded before tillage. After tillage, ploughing recorded 16.30% moisture content, harrowing, ridging, pulverization and planting in that order recorded 15.45%, 14.70%, 14.23% and 14.12% respectively. The statistical analysis (Table 4) showed significant difference between the values of moisture content for different implements at 5% level of probability. This is in agreement with results obtained by Omar et al (2015), Makki (2002). The moisture content levels are recorded in the study area within the machine workable limit. Result of this research work is consistence with the observations of Salokhe and Shirn (1992) that the increased in moisture and disc angle decrease the specific draft requirement as observed. The higher moisture content was observed for the plough as compared to other implements may be attributed to high compaction (which decelerates infiltration rate) associated with ploughing operation.

3.3 Effect of bulk density on implement performance

Results of Table 5 revealed that the bulk density reduced with the application of tillage implements. Prior to the field operation, the average bulk density of the soil was 1.62 g cm^{-3} but when the implements were applied, there was reduction or improvement in the bulk densities in which ploughing recorded 1.49 g cm^{-3}, harrowing (1.40 g cm^{-3}), ridging (1.33 g cm^{-3}), rotovator (1.29 g cm^{-3}) and planter (1.35 g cm^{-3}).The reduction or lower bulk density recorded when the implement were applied as compared to the initial bulk density (i.e when the implements have not been applied) is evidence of the improvement of the soil for crop growth, root development and a better yield. That is why tillage is the first agricultural operation upon which depends the success of the agricultural season, because it is the preparatory stage of seedbed which is the critical stage in plant life. This also confirms the observations of Olatunji (2011). The statistical analysis (Table 6) of the effect of bulk density on implement performances shows a significant difference between the values of bulk densities for different implements at 5% probability level.

Table 3 Effect of moisture content (%) on the implement performances

Soil type	Before tillage	Plough	Harrow	Ridger	Rotovator	Planter
Clay-loam	18.9	17.12	16.22	14.24	14.20	13.23
Clay-loam	16.3	15.24	14.81	14.43	13.93	13.84
Loamy-sandy	17.4	16.20	15.43	14.48	13.53	14.48
Sandy-clay	15.7	14.31	13.46	13.27	13.18	12.86
Sandy-clay	20.4	18.63	27.32	17.09	16.33	16.21
Average	**17.74**	**16.30**	**15.45**	**14.70**	**14.23**	**14.12**

Table 4 ANOVA of the effect of moisture content on the implement performances

Sources of variation	d.f	SS	MS	F. Cal	F.Tab	
					5%	1%
Moisture content	4	8,281.47	2,070.37	4.600**	2.87	4.43
Implement	5	6,843.80	1,368.76	3.041*	2,71	4.10
Error	20	8,501.20	450.06			

Note: * significant at 5% probability level; ** significant at both 5% and 1% probability levels.

Table 5 Effect of bulk density (g/cm^3) on the implement performances

Soil type	Before tillage	Plough	Harrow	Ridger	Rotovator	Planter
Clay-loam	1.68	1.54	1.49	1.40	1.35	1.38
Clay-loam	1.68	1.51	1.42	1.36	1.30	1.36
Loamy-sandy	1.47	1.39	1.28	1.21	1.18	1.22
Sandy-clay	1.64	1.50	1.41	1.36	1.31	1.41
Sandy-clay	1.64	1.49	1.40	1.32	1.29	1.40
Average	**1.62**	**1.49**	**1.40**	**1.33**	**1.29**	**1.35**

Table 6 ANOVA of the effect of bulk density of the soil on the implement performances

Sources of variation	d.f	SS	MS	F. Cal	F.Tab	
					5%	1%
Bulk density	4	69.144	17.286	5.009**	2.87	4.43
Implement	5	57.40	11.480	3.327*	2.71	4.10
Error	20	69.016	3.451			

Note: * significant at 5% probability level; ** significant at both 5% and 1% probability levels.

3.4 Effect of porosity on implement performance

Table 7 shows the effect of porosity on implement performances. It is observable from the results that the effects of porosity on the performance of the implements follow the same trend as bulk density. The lowest porosity values were observed in zero tilled soil (before tillage) with average porosity value of 48.30%. This is in line with Omar et al (2015) and Makki (2002). The highest porosity was recorded on the loamy-sandy soil followed by sandy-clay and least was obtained on the clay-loam soil. Results obtained showed that the higher the bulk density, the lower the porosity; according to Chen et al (1998), this is due to the variation in the structural conditions of the soil. During the field operation ridger gave the highest average porosity value of 54.14%. The plough, harrow, rotovator and planter in that other gave average porosities of 49.68%, 53.43%, 54.11% and 53.67% respectively. Statistical analysis (Table 8) indicated a significant difference between the values of porosities and the implements at both 5% and 1% probability levels as observed by Alnahas (2003).

Table 7 Effect of porosity (%) on the implement performances

Soil type	Before tillage	Plough	Harrow	Ridger	Rotovator	Planter
Clay-loam	37.40	45.22	48.18	48.20	48.82	48.13
Clay-loam	37.40	45.27	49.63	49.64	48.34	49.32
Loamy-sandy	50.80	55.25	57.25	57.28	57.25	58.22
Sandy-clay	48.30	51.26	57.31	57.36	58.07	55.18
Sandy-clay	48.30	51.38	57.52	58.20	56.55	56.53
Average	**48.30**	**49.68**	**53.43**	**54.14**	**54.11**	**53.67**

Table 8 ANOVA of the effect of porosity of the soil on the implement performances

Sources of variation	d.f	SS	MS	F. Cal	F.Tab	
					5%	1%
Porosity	4	92,619.79	23,154.94	3.983*	2.87	4.43
Implement	5	78,144.57	81,212.82	13.969**	2.71	4.10
Error	20	116,270.75	5,813.59			

Note: * significant at 5% probability level; ** significant at both 5% and 1% probability levels.

4 Conclusion and recommendations

The implements recorded the highest performance when working on sandy-clay soil. This was attributed to low aggregation stability, high moisture content and low decomposed organic matter found in sandy-clay soil.

Higher moisture content observed after ploughing as compared to other implements was as a result of high compaction associated with ploughing operation which retards infiltration rate.

The higher the bulk density was, the higher the soil compaction and the higher the resistance to penetration the soil offers to the implement was. However, the application of the implements improves the soil bulk densities.

The higher the porosity was, the lower the bulk density was, due to the variation in the structural conditions of the soil, which enhances high speed of implement operation with low working efficiency.

Results of this research work will help the farmers to know the effect of some soil physical properties on the performances of various agricultural field machineries and to select the right equipment for their agricultural activities.

Differences exist in soil conditions among different agricultural or ecological areas; it is therefore recommended that more studies should be conducted in every agricultural zone to provide data on machine/ implement performances based on soil conditions for increased production, minimize production costs, reduce loss/wastage of energy, time and waste of agricultural products.

Finally, this study did not cover all the agricultural field machineries. Researchers are also recommended to make a detailed time study in other machineries not covered in this work in other to provide database in the effect of soil physical properties on their performances as to guide farmers here and other agricultural zones in machine/implement selections.

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