Modelling soil compaction effects on maize growth and yield in a sandy loam soil

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Abstract: A mathematical model was developed for the prediction of soil compaction effects on the growth and yield of maize crop in a sandy loam soil in tropical climates. Field investigations were carried out at the teaching and research farm of Rivers State University, Port Harcourt, Nigeria. A plot of land measuring 18 m x 4 m was divided into five sub-plots of equal dimensions of 3 m×3 m and labelled as: plot 1 – uncompacted and untilled; plot 2 – uncompacted but tilled; and plots 3, 4 and 5 - tilled and compacted to varying degrees of tractor passes, viz 2, 4 and 6 tractor passes respectively. A Massey Ferguson (MF) 90 model disc plough was used for the tillage and an MF 260 model tractor used for the soil compaction treatments. Irrigation, weed and pest control were done equally on all plots when necessary. The maize crops were planted in the month of October and grew to maturity fourteen weeks thereafter. Field measurements gave values of soil bulk densities and moisture contents as 1.20, 1.17, 1.23, 1.28 and 1.35 g cm^{-1} and 5.17%, 6.02%, 4.89%, 4.43% and 3.39% respectively for plots 1-5. The height and yield of the maize crop at the fourteenth week for the plots 1-5 are respectively 0.941, 1.380, 0.872, 1.146 and 1.402 m and 1192, 2859, 1195, 1311 and 2320 kg ha^{-1}. The model was developed based on the response of the maize crop growth and yield to the different levels of compaction treatment, using dimensional analysis. The field results showed that at p<0.05, there is a statistically significant effect of soil compaction on the growth and yield of maize in a tropical sandy loam soil; and the model predictions correlated experimental data up to about 99.5%.

Keywords: soil compaction, maize growth, maize yield, sandy loam soil, tropical climate

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1 Introduction

As the bid for farm mechanization continues to increase in Nigeria, so also would consideration be given to the consequences of an increased use of farm machinery in agricultural operations. It is now trite knowledge that when off-road vehicles are used on agricultural fields, they cause compaction of the soil; the degree of compaction being "related to soil type, soil moisture and machinery traffic (number of passes and contact pressure)" (Ohu and Folorunso, 1989; De-Jong-Hughes et al. 2001; Duiker, 2004; Sudduth et al., 2008; Nawaz et al, 2013). Furthermore, Chamen et al. (2003) stated that "The severity of soil compaction on crops is a function of soil type, soil water content, vehicle weight, speed, ground contact pressure, number of passes and their interactions with cropping frequency and farming practices".

Soil compaction is the compressing of soil particles together by an external force, thereby eliminating the pore spaces and reducing the soil volume and this bears serious consequences on the productivity of the soil and environmental quality. Soil compaction occurs when an applied soil stress exceeds the soil strength (Lipiec et al, 2000). Soil compaction risks increase with increased mechanization and the drive for greater productivity (Jones et al, 2000). In recent times commercial agricultural production practices mainly depend on

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vehicular traffic (Ohu et al., 2009). With the progressive increase in the sizes and weights of these agricultural vehicles, there is a corresponding increase in their tendencies to compact and hence damage the soil, which is the very medium responsible for producing and supporting agricultural crops.

According to Duiker (2004) and Hanna and Al-Kaisi (2009), when soil is compacted, the major change that occurs to the soil is in its bulk density, defined as "the mass of oven-dry soil in a standard volume of soil, often given as grams per cubic centimeter (g cm^{-3})" (Duiker, 2004). Generally, with compaction, there is usually a complete alteration of the physical properties of the soil, with notable changes in the soil bulk density, soil strength, porosity and hydraulic properties such as infiltration rate and hydraulic conductivity. Mada et al. (2013) investigated the effect of soil compaction on soils in Southern Adamawa State, Nigeria and observed that soil "compaction due to heavy tractor traffic changes the numerical values of soil bulk density". It increases the soil bulk density and consequently retards or diverts the flow of water in the soil resulting in ponding or excessive runoff. This is because there is a reduction in the hydraulic properties of the soil, like infiltration and percolation, which are determined as functions of time, in rates. While infiltration is the entering of water from the soil surface into the soil, percolation is the gradual movement of the water downward inside of the soil. The reduction of the soil infiltration rate usually "has a serious consequence to water quality and sediment transport, particularly on sloping soils" (Hanna and Al-Kaisi, 2009). Horn and Hartge (1990) stated that soil compaction is dependent on the duration of the applied load. This implies that for tractors and other harvesting machinery that move relatively fast, soil compaction is worsened by the repeated passes of these equipment.

It has been variously asserted that the changes that occur in the soil physical properties as the soil is compacted have adverse effects on the growth and development of planted crops, like limiting yields and inhibiting effective site management for crops (Passioura, 2002; Rooney et al., 2004; Sudduth et al., 2008; and De-Jong-Hughes et al., 2001). Jayan et al. (2006) reported that soil compaction affects the emergence of maize crop. Igoni and Ayotamuno (2016) found that "Maize yield on a sandy loam soil in a humid tropical environment in Nigeria is reduced by compaction induced in the soil by tractor wheel passes. The compaction delays early shoot emergence, root formation, and stunts overall plant performance".

Maize (*Zea mays*) is a food grain of the tropics, "grown in the rain forest and derived savannah zones of Nigeria" (Olaniyi and Adewale, 2012). It has increased tremendously in its economic value over the years. Maize, which has been in the diet of Nigerians for centuries, has transited from subsistence-level cultivation to a commercial level, in so much that "many agro-based industries depend on it as raw material" (Iken and Amusa, 2004). Maize is a major cereal crop in Nigeria and actually the second most important cereal crop in Nigeria after sorghum (FAO, 2013). In 2014, the Central Bank of Nigeria estimated growth in maize crop production as 1.2% (CBN, 2014). Abba (2017) reported that Nigeria had an average maize production of 8.0 million tons per annum, positioning it as the largest producer of maize in Africa. The report further stated that the average yield per hectare is between 2.0 and 2.5 tons for conventional farming practices and 6 tons for improved practices. In contemporary times when improved/mechanized farming is envisioned, this yield per hectare would translate to a field coverage/land usage of at least 1.33 million hectares. However, a study by National Agricultural Extension and Research Liaison Services (NAERLS) in collaboration with the Federal and States' Ministries of Agriculture and Rural Development in 2017, showed that maize production increased from 10,813,980 tonnes in 2016 to 12,107,580 tonnes in 2017, representing an increase of 11.96% (NAN, 2018).

Evidently, the type of soil in which maize crop is cultivated plays a significant role in its yield and growth. Maize is not suited to soils that are acidic, salty or very wet. The soil texture should be intermediate: sandy, sandy-loam to sandy-clay loam (Ministry of Agriculture, Food and Rural Affairs, 2009). In Nigeria, in spite of the economic importance of maize, compaction limits its production. Maize crop yields in compacted soils are mostly associated with the extent and function of the root system. The ability of the roots to penetrate strong soils can increase with increasing root density (Panayiotopoulos et al., 1994). Thus, when the soil is compacted the maize crop requires greater pressure to extract moisture and nutrients from the soil.

The effects of topsoil compaction on maize crops may be reduced in few years when the soil is mould-board-ploughed (Arvidsson and Hakansson, 1996), but that of the subsoil compaction persist much longer and may even be more or less permanent (Etana and Hakansson, 1994). Mechanical loosening to improve the structure of the subsoil is expensive and has often proved unsuccessful and, in some cases, even negative (Hakansson and Reeder, 1994). Thus, there is no established or specified number of tractor passes for varying soil types and corresponding maize crop yield. Available models and measurements on soil compaction and crop growth responses are geared towards soil stresses caused by vehicular weights and their dependence on the ground contact pressure (Hakansson, 2000).

In Nigeria, with an estimated land size of 1.33 million hectares for the cultivation of maize with mechanized devices, it is expedient to monitor levels of farm machinery usage on the field and the compaction induced thereby, in relation to the growth and yield performance of the crop. Therefore, the objective of developing this predictive model is to enable agricultural producers determine appropriate combinations of the physical properties of a compacted sandy loam soil that would give optimal growth and yield of maize.

2 Materials and methods

2.1 Description of study area

The field work of this research was carried out in the teaching and research farm of Rivers State University, Port Harcourt, Nigeria, while the bench work was at the laboratory of the Department of Soil and Crop Sciences of the same University. Port Harcourt is the capital city of Rivers State in Nigeria in western Africa. It is located on latitude 05°21′N and longitude 06°57′E. The area is characterized by a humid tropical climate, with a high humidity of 80% and moderately high temperature of between 25^{o}C and 30^{o}C (Fubara-Manuel et al., 2017). The climate is sub-divided into two main seasons of wet (May–October) and dry (November–April), with a mean annual rainfall of 2,280 mm (Fubara-Manuel et al., 2000). The soil type is predominantly sandy loam. Figure 1 is a map showing the location of this investigation.

2.2 Materials

The materials used included an 18 m×4 m plot of land, a Massey Ferguson (MF) 260 model tractor, an MF 90-disc plough, non-hybridized maize seeds, pesticide, core sampler, hydrometer, irrigation cans and grass mulches.

2.3 Experimental design

The experimental plot was allowed fallow for two years and then cleared manually at the time of use. The plot was divided into five sub-plots dimensioned 3 m× 3 m each with an in-between furrow of 0.5 m. The furrow was created for effective irrigation of the crops. The sub-plots were labeled 1-5. Plot 1 which served as the experimental control was left in its original state while plots 2-5 were ploughed using tractor mounted MF 90-disc plough. Plots 3, 4 and 5 were subsequently subjected to varying tractor compaction treatments using the MF 260 model tractor. Plot 3, had two tractor passes as its compaction treatment while plot 4, had four passes as its treatment and plot 5, had six tractor passes as its compaction treatment; while plot 2 was left in the tilled state without compaction (Douglas, 2002). After the compaction treatments, soil samples were randomly taken at five different points in each plot at depths of 0.3 m respectively. The soil bulk density was determined using the core method. The soil particle size analysis was determined using the hydrometer method described by Foth (1990). From the obtained results of the particle size analysis, the soil textural classes were determined using the United States Department of Agriculture textural triangle. The soil moisture content was determined using the gravimetric method described by the American Society of Agricultural Engineers standards, ASAE (1984).

Two sets of non-hybridized maize seeds were planted at 0.05m depth with an inter-row spacing of 0.75 m and intra-row spacing of 0.25 m, which are the generally recommended planting specifications for maize in Nigeria (AGRORAF, 2017; Ibirogha, 2018). Manual method of weed control was adopted for the experiment and the experimental plots were uniformly irrigated. The irrigation of the plots was done manually twice daily at 6 am and 6 pm, using a 20 litre (0.002 m^3) watering bucket, from where equal amounts of the irrigation water were poured into the inter-row and border furrows. The evaporative moisture control method adopted was the grass mulch system. At the ninth week of growth, the field was treated with Karate 0.8% ULC pesticide as a pest control measure.

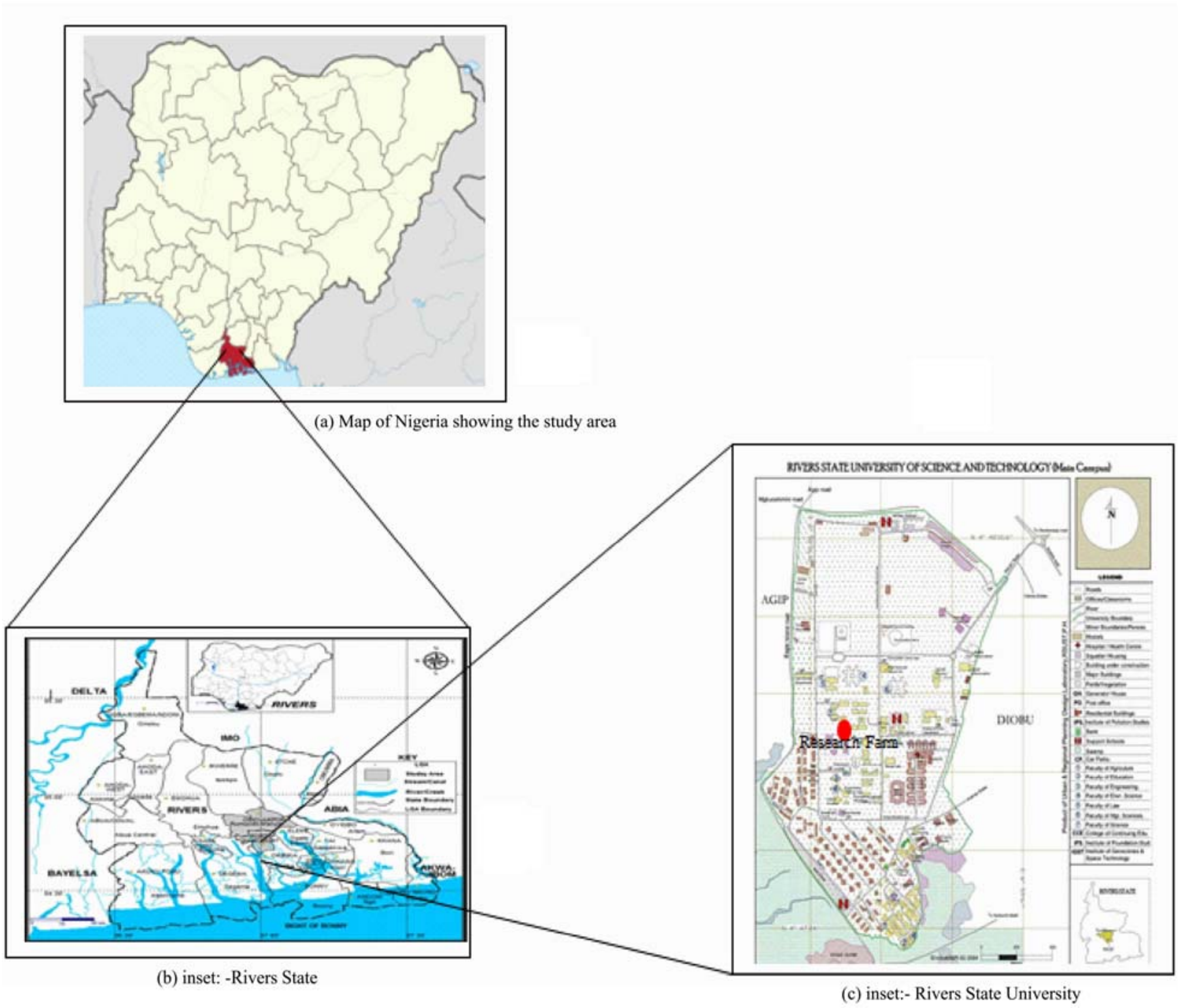

Figure 1 Map of the study area

Source: Department of Urban & Regional Planning, Rivers State University, 2019.

The plant heights were measured at weekly intervals from the third week of growth using measuring tape. The crops viability was noted and the leaf area also determined. After fifteen weeks of growth, the crop wet root mass for each plot was determined. The yield was determined through the cobs above ground matter. The cobs were then dried for one week with an electronic drying oven, model YF 101-3A and the maize grains manually shelled and weighed with a digital weighing balance, model ADAM AAA 250LE. Data obtained from the experimentation was analyzed using the analysis of variance (ANOVA) test following the procedure prescribed by Gomez and Gomez (1984).

2.4 Model development

The model was developed using the Rayleigh's modeling method of dimensional approach to experimental analysis. The dependent variable and a set of independent variables were identified from the experimental data; and by dimensional homogeneity a functional relationship was established between the dependent and independent variables.

3 Results and discussion

3.1 Results of soil analysis

Table 1 shows results of the soil analysis for the determination of soil type, bulk density and moisture content for the five different experimental plots.

Table 1 Results of soil analysis

Plots No.	Tractor passes	% sand	% silt	% clay	Soil types	Bulk density (g cm^{-3})	Moisture content (%)
1	0 (untilled)	57.7	25.1	17.2	Sandy loam	1.20	5.17
2	0 (tilled)	58.2	23.4	18.1	Sandy loam	1.17	6.02
3	2	57.8	24.1	18.1	Sandy loam	1.23	4.89
4	4	57.2	23.8	20.0	Sandy loam	1.28	4.43
5	6	57.6	20.6	21.8	Sandy loam	1.35	3.39

From Table 1, the soil type is predominantly sandy loam, as the soil has higher percentage of sand (>57%), followed by silt (>20%) and then clay (≤21.8%). The soil bulk density varied directly with the number of tractor passes on the plots. Thus, an increase in soil compaction results in a corresponding increase in the soil bulk density. This variation conforms with the findings of Mirreh and Ketcheson (1972) and Iraj et al. (2012) on the effect of mechanical manipulation of soil on its physical properties. Furthermore, the soil moisture content showed that as the soil compaction increases, the moisture content decreases. For the non-compacted soil, tilled soil had higher moisture content (6.02%) compared to the non-tilled soil (5.17%). This difference may be attributable to the evaporation of the soil water in the untilled soil before the water had time to infiltrate the soil. On the other hand, for the tilled uncompacted soil, the infiltration may have been relatively faster and the percolation gradual. On the whole, the uncompacted soils had the highest moisture contents. These variations existed irrespective of the fact that the volume of irrigation water applied to the plots at all times was the same. These results corroborate the conclusion of Guihua and Ray (2011).

Notably, as the soil is being compacted by the tractor passes, the soil structure is automatically altered, changing the configuration of the soil pores at the surface, thus limiting passage of the irrigation water. For this reason, the water applied to the field rather results in ponding of the plots, with little infiltration into the soil, while the remaining water evaporates, leaving a black streak on the compacted soil surface. The high temperatures of the tropics hasten evaporation of irrigation water, leaving behind a soil with poor moisture distribution. This poor moisture infiltration into the soil affects the overall plant performance, because the amount of soil moisture available to the roots of the maize crop will be limited.

3.2 Maize crop responses

Tables 2 and 3 respectively show experimental values for the level of plant height measured on the five different plots with time, indicated in number of weeks after planting; and growth and yield parameters in relation to soil compaction treatments.

Table 2 Maize crop height

Plot No.	Plant height (m)											
	3 WAP	4 WAP	5 WAP	6 WAP	7 WAP	8 WAP	9 WAP	10 WAP	11 WAP	12 WAP	13 WAP	14 WAP
1	0.360	0.470	0.560	0.722	0.752	0.790	0.843	0.874	0.879	0.898	0.930	0.941
2	0.376	0.572	0.710	1.020	1.023	1.030	1.296	1.280	1.272	1.440	1.380	1.380
3	0.330	0.500	0.631	0.790	0.810	0.810	0.837	0.855	0.741	0.863	0.872	0.872
4	0.291	0.393	0.494	0.610	0.650	0.693	0.745	0.810	0.855	0.900	1.124	1.146
5	0.290	0.331	0.470	0.763	0.763	0.766	0.880	0.913	0.934	1.131	1.143	1.402

Note: WAP - Weeks After Planting.

Table 3 Maize crop responses to tractor compaction treatments

Plots No.	Tractor passes	Dry matter maize yield (kg ha^{-1})	Wet root mass (kg ha^{-1})	Leaf area (m^2)		
				1 MAP	2 MAP	3 MAP
1	0 (untilled)	1192	309	0.0527	0.0840	0.1150
2	0 (tilled)	2859	2431	0.0998	0.1097	0.1974
3	2	1195	683	0.0667	0.0863	0.1112
4	4	1311	1022	0.0502	0.0735	0.1490
5	6	2320	2378	0.0446	0.0757	0.1561

Note: MAP – Month(s) After Planting.

From Table 2, maize crops at the untilled and uncompacted soil, labelled plot 1, had 0.941 m as the average maximum crop height at the fourteenth week of growth. While crops on the soil with no compaction treatment but tilled had 1.380 m as the average maximum height at that same period. Furthermore, crops on soils with compaction treatments of 2, 4 and 6 tractor passes had plant heights of 0.872, 1.146 and 1.402 m at the fourteenth week of growth respectively. It was observed that the best maize crop growth in terms of plant height was at plot 5. This result agrees with the findings of Adamu and Ezeaku (2002), when they said that soil structural modification optimizes soil conditions for seed germination and growth. The plots with treatments of two and four tractor passes (plots 3 and 4) showed slightly reduced growth when compared to the other plots. This indicates that compaction of the soil due to the tractor passes had a slight detrimental effect on the maize crop growth. This could have been caused by the reduction in soil pore space and the inability of the plant root to effectively penetrate the soil to extract nutrients and moisture, considering also that by this time of the year the soil moisture may not be available within the root zone of the crops. In the Table 2 it was also observed for plot 2 that the plant heights from the 10 WAP up to the 13 WAP were declining rather than increasing. This appears to be recording error in the field, which, however, did not alter the conclusions from the data analysis.

The Table 3 showed that the maize crop leaf area in plot 2, measured in months after planting (MAP), was the highest, with a leaf area of 0.1974 m^2 for three MAP. For plots 1, 3, 4 and 5, leaf areas of 0.115, 0.1112, 0.1490, and 0.1561 m^2 at the third MAP were recorded. These observations showed that more sunlight was trapped by crops on plot 2 followed by those on plot 5. Notably, the yield of crops is directly related to the photosynthetic activities using sunlight as energy source. Thus crops with higher leaf area tend to yield more when compared to those with less leaf area, provided the crops had better access to moisture and nutrients.

The crops on plot 2 had the best yield with dry matter yield of 2859 kg ha^{-1} followed by crops on plot 5 with 2320 kg ha^{-1}. Plots 1, 3 and 4 respectively had dry matter yields of 1192, 1195 and 1311 kg ha^{-1}. From this, the optimal average dry matter yield for the crop was obtained from plot 2, with a soil bulk density of 1.17 g cm^{-3}. This is contrary to deductions by Igoni and Ayotamuno (2016), for the same set of data, that the optimal soil bulk density was 1.35 g m^{-3}. It appears their conclusion was based on the plant height data, which does not on its own directly determine the yield performance, especially as much as the dry matter maize yield. The performances of the maize crop can be attributed to their leaf areas and accessibility to nutrients and moisture through their roots. These results showed that a minimal level of soil compaction by tractor wheel traffic can aid better crops performance. Therefore, the findings of this work completely contradict the position of Stepniewski et al. (1994) that maize crop performance may not be negatively affected by compaction.

Using Analysis of Variance (ANOVA) 2010 model to investigate if any significant difference exists in the effect of soil bulk density on the dry matter yield and wet root mass of the maize and the soil moisture content, it was observed that at p<0.05, the p-value was 0.000385. This showed that a reasonable level of significant effect exists due to the impact of the soil compaction caused by the tractor traffic on the maize crop growth and yield.

3.2 The Model

The dependent variable in this investigation is the crop yield and the independent variables, which affect the yield, but which in themselves are also altered by the compaction induced in the soil by tractor wheel passes, are soil bulk density, moisture content, plant height, leaf area and wet root mass.

By Raleigh's configuration, representing the dependent variable as a function of the independent variables, then:

$$Y_c=k(\rho_b, m, H_p, A_l, W_r) \tag{1}$$

where, k is a dimensionless constant; Y_c is the crop yield (kg ha^{-1}); ρ_b is soil bulk density (g cm^{-3}); m is moisture content (%); H_p is plant height (m); A_l is leaf area (m^2) and W_r is wet root mass (kg ha^{-1}).

Using a, r, s, c, and d as exponential constants, then:

$$Y_c = k(\rho_b^a, m^r, H_p^s, A_l^c, W_r^d) \tag{2}$$

$$ML^{-2}T^0=k[(ML^{-3})^a(M^0L^0T^0)^r(L)^s(L^2)^c(ML^{-2})^d] \tag{3}$$

To satisfy dimensional homogeneity, the mass, length and time dimensions must equate on either side of the equation. So that, relating Equation (2) to (3) gives:

$$Y_c = k(\rho_b^a, m^0, H_p^{a-2c}, A_l^c, W_r^{1-a}) \tag{4}$$

From where
$$Y_c = km^0W_r\left[\left(\frac{\rho_b H_p}{W_r}\right)^a\left(\frac{A_l}{H_p^2}\right)^c\right] \tag{5}$$

And
$$Y_c = kW_r\left[\left(\frac{\rho_b H_p}{W_r}\right)^a\left(\frac{A_l}{H_p^2}\right)^c\right] \tag{6}$$

Substitute f for k at a=1 and c=1, since a uniform-soil type is used for the experiment, then:

$$Y_c = fW_r\left[\left(\frac{\rho_b H_p}{W_r}\right)\left(\frac{A_l}{H_p^2}\right)\right] \tag{7}$$

$$Y_c = fW_r\left[\left(\frac{A_l\rho_b H_p}{W_r H_p^2}\right)\right] \quad (8)$$

$$Y_c = f\left[\left(\frac{A_l\rho_b}{H_p}\right)\right] \quad (9)$$

$$(Y_c)_i = (f)_i\left(\frac{A_l\rho_b}{H_p}\right) \quad (10)$$

Equation (10) is the model equation relating maize crop yield to some independent variables affected by soil compaction as leaf area, bulk density and plant height. The model shows that the crop yield is directly proportional to the product of the leaf area and bulk density, but inversely proportional to the plant height. Then there is the constant of proportionality, *f*, which is a dimensionless parameter that varies with (*i*) the number of tractor passes and soil moisture content. Using the experimental data for validation, the value of '*f*' is found as:

$$(f)_i = 320.194(moisture\ content)_i^2 \text{ zeta} \quad (11)$$

where, zeta is an error term that varies as $1 \leq$ zeta ≤ 3 with increasing compaction.

3.3 Validation of the model

The model was validated using data obtained from field and laboratory experimentations. A graphical comparison of the measured and predicted data for dry matter yield of the maize crop (kg ha^{-1}) in relation to the number of tractor passes using the model developed in Equation (10), is presented in Figure 2

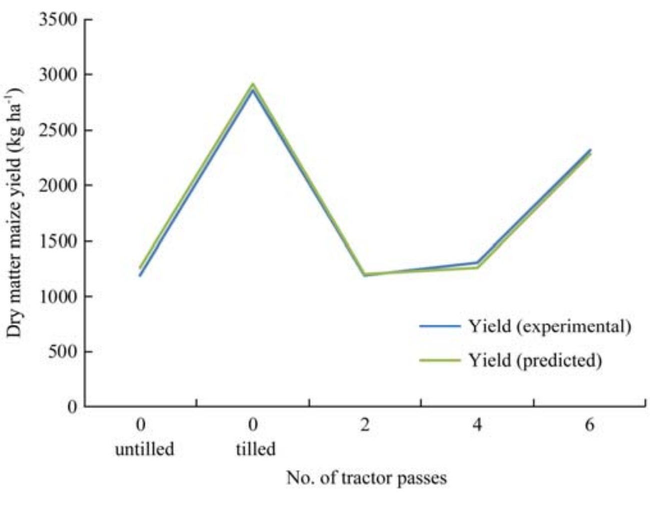

Figure 2 Validation of the predictive model with experimental data

For the plots with no tractor pass to two tractor passes, the model prediction showed about 99.7% correlation with the measured data. For the plots with four tractor passes, the model prediction was about 98.8% in correlation with the measured data. For the plots with six tractor passes, the model prediction was about 99.4% in correlation with the measured data. On the whole, the model prediction on the dry matter yield of the maize crop (kg ha^{-1}) in relation to the number of tractor passes was an average of 99.5% when compared with the measured data. This indicates that the model can be used effectively to tract maize crop yield on soils with various levels of compaction.

4 Conclusion

Nigeria is the top-most producer of maize in Africa and the product has tremendous economic relevance in the development of the country. Aside from presenting as a staple cereal in the food chain of the citizenry, it serves for several other industrial purposes. The growth and yield of the maize crop in a sandy loam soil in tropical Nigeria is affected by soil densification resulting from tractor wheel passes. Compaction of soil due to the tractor traffic on it does not alter the soil textural class, but rather affects the maize crop yield. For optimum maize crop production, the bulk density of the soil should not exceed 1.17 g cm^{-3} contrary to an earlier allusion to 1.35 g cm^{-3}. The model developed in this work can be used to predict and monitor maize crop performance on both the compacted and un-compacted soils. Therefore, it is possible to regulate maize crop performance in terms of growth and yield in relation to varying degrees of compaction. Consequently, it is recommended that the soil for maize cultivation be prepared to the desired level of compaction, in order to obtain optimal yield and growth performance of the maize. Furthermore, the soil moisture content after the soil compaction treatment, before planting of the maize, should be regulated following the model prediction.

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