

## Research Article

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# Bulk density: An index for measuring critical soil compaction levels for groundnut cultivation

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**Abstract:** Assessing soil compaction using soil bulk density as an index for measurement could provide background information on the critical range of soil compaction for groundnut production in Nigeria. Therefore, field experiments were conducted in 2012 (year 1) and 2014 (year 2) to assess the effects of five levels of soil compaction ( $1.1 \text{ Mg m}^{-3}$  [control], 1.2, 1.3, 1.4, and  $1.5 \text{ Mg m}^{-3}$ ) on groundnut yield. The experiment was laid in completely randomized design with four replicates. Number of Pods (NP) and Fresh Pod Mass (FPM) of groundnut were estimated using standard procedures and subjected to ANOVA at  $\alpha_{0.05}$ . The NP of groundnut differed significantly among the treatments and was reduced by 70.1 and 76.0% in 1.4 and  $1.5 \text{ Mg m}^{-3}$  relative to  $1.1 \text{ Mg m}^{-3}$  in year 1, while corresponding low values were 40.4% ( $1.4 \text{ Mg m}^{-3}$ ) and 48.4% ( $1.5 \text{ Mg m}^{-3}$ ) in year 2. It was noteworthy that the NP in 1.2 and  $1.3 \text{ Mg m}^{-3}$  were statistically similar. Consequently, FPM of groundnut was in the order of  $1.1 > 1.3 > 1.2 > 1.4 > 1.5 \text{ Mg m}^{-3}$  in years 1 and 2, respectively. Hence, soil compaction at  $1.1\text{--}1.3 \text{ Mg m}^{-3}$  could be critical for groundnut cultivation.

**Keywords:** soil compaction, bulk density, field capacity, groundnut yield

## 1 Introduction

Soil physical conditions are important aspects of crop production due to their effects on soil productivity. These conditions determine certain factors that affect soil aeration and soil hydro-physical properties, consequently

influencing soil nutrient availability, crop nutrient uptake, root development and crop growth, and yield [1,2]. Thus, in the process of creating optimum conditions for plant growth, certain farm operations which involve soil manipulation are often carried out. Some of these operations may involve the use of heavy and/or light machinery which usually apply some degree of stress to soils due to their exerted mass, thereby compacting soils. Soil compaction is the process in which mechanical load of short duration results in reduction in soil pore volume and modification of pore structure [3].

Soil compaction is being recognized as an agricultural problem of increasing severity as it plagues many parts of the world, affecting crop production [4,5]. It is a major physical threat to soil fertility throughout the world, as many areas now have compacted subsoil due to increased soil working and poor timing of field operations [6]. For instance, the cumulative effects of vehicular trafficking and livestock treading on agricultural soils have been observed by several researchers to cause soil compaction [1,5,7–11]. In Nigeria, large expanse of agricultural land has been lost through increase in the use of tillage implements and improper agricultural practices [12], thus making soil compaction more difficult to correct [13].

Soil compaction caused by vehicular trafficking is a severe problem in tropical arable land as infiltration and water transmission are reduced and erosion is accelerated [14]. It also results in poor soil aeration and diffusive properties, nutrient transformations and uptake, and root growth and configuration [1,15]. Ref. [16] reported that soil compaction has led to excessive soil hardness, reduced infiltration rate, reduced soil aeration, and alteration of root distribution pattern, with resultant losses in crop yield. It generally leads to stunted plant growth due to moisture and nutrient stresses which may stem from limited pore space as plant root would exert a greater force to penetrate compacted soil layers [5,17–19].

Groundnut (*Arachis hypogaea* L.) is a native of South America [20]. It is the fourth-largest oil-seed crop in the world in terms of its annual production of 35.5 million tons, and it is cultivated in more than 100 countries [21]. Groundnut is one of the most popular commercial crops

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in Nigeria which accounted for 70% of their total export earning between 1956 and 1967 [22]. During this period, Nigeria was known for its magnificent groundnut pyramids, which became synonymous with the country's agricultural wealth. A pyramid could be built with as much as 15,000 full bags of groundnut. Although groundnut grows in virtually all the ecological zones in Nigeria, it is mostly grown in the savanna belt of Nigeria [23]. Its uses are diverse with about two-third of the world's production being crushed for oil which makes it an important oil seed crop [24]. It is an important source of dietary protein in many countries, and an oil seed crop of economic importance in Nigeria. The haulm and shells are important animal feed and sources of supplementary income during the dry season [25–27], and as such groundnut contributes to household food self-sufficiency as well as provides income-generating opportunities for smallholder farmers in Nigeria. Although FAOSTAT shows Nigeria's groundnut production accounts for 41% of the total West African groundnut production, a decline in its annual export has been reported in some studies [28,29]. Several factors including the vagaries of changing climate, particularly droughts and diseases of the late sixties, changes in ecological boundaries coupled with the discovering of mineral resources led to the collapse of the popular groundnut pyramids and a decline in exportation from about 26% before 1970 to 0% today [22,30].

Despite the foregoing, the depth of penetration and distribution of the roots of several crops including groundnut, corn, beans, and wheat varied widely with degree of compaction and nature of soil after compaction [16]. They also reported that vehicular traffic significantly reduced root length, root density, and root mass of maize. In this study, soil bulk density which is an indicator and a measure of soil compaction [31] was adopted for quantification of soil compaction. Though there is considerable amount of information on the effects of soil compaction on soil properties and crop yield, information on the response of groundnut to various degrees of soil compaction is still lacking. This study was therefore conducted to examine the growth and yield response of groundnut to different levels of soil compaction.

## 2 Materials and methods

### 2.1 Study area

The study was conducted between March and June, 2012 (year 1) and 2014 (year 2) at the screen-house of the

Department of Agronomy, University of Ibadan. The location has an elevation of 189 m above sea level, and it is situated between Latitude 07°21'06.4" N and Longitude 03°53'46.1" E. It is characterized by a humid tropical climate with a lengthy bimodal wet season that runs from March to October (having a break in August), and a dry season from November to February. The long-term mean total rainfall for Ibadan is about 1,200 mm [32], while the mean maximum and minimum temperatures are 26.5 and 21.4°C, respectively, and the relative humidity is 76% [33].

### 2.2 Experimental setup and design

The soil used for the study was obtained from the Teaching and Research Farm, University of Ibadan. The soil is an Alfisol that is classified at the local level as Ibadan series [34]. The plot from which the soil was obtained at the Teaching and Research Farm has been subjected to intensive farming of maize, okra, and yam for more than 15 years. Soil compaction of five levels of bulk density ( $1.1 \text{ Mg m}^{-3}$  [control], 1.2, 1.3, 1.4, and  $1.5 \text{ Mg m}^{-3}$ ) were used as treatments for the experiment. They were applied by weighing the mass of soil required for each desired bulk density value into wooden cuboid troughs measuring  $60 \text{ cm} \times 60 \text{ cm} \times 30 \text{ cm}$  (length  $\times$  breadth  $\times$  height). The mass of soil applied was determined by multiplying each desired bulk density value by the calculated volume to be occupied by the soils in each trough, using a desired height of 20 cm, as described in equations (1) and (2).

$$M_s = \rho_b \times V_b, \quad (1)$$

$$V_b = l \times b \times h, \quad (2)$$

where  $M_s$  is the mass of soil;  $\rho_b$  is the bulk density,  $V_b$  is the soil bulk volume,  $b$  is the breadth of the trough occupied by the soil, and  $h$  is the desired height (20 cm) for the soils for each treatment.

Thus, given the desired volume of  $72,000 \text{ cm}^3$  to be occupied by soils of each bulk density treatment, 79,200 g of soil was applied for bulk density of  $1.1 \text{ Mg m}^{-3}$  which served as the control, while 86,400, 93,600, 100,800, and 108,000 g of soil were applied for bulk density treatments of 1.2, 1.3, 1.4, and  $1.5 \text{ Mg m}^{-3}$ , respectively. These were then compacted to the desired height of 20 cm by exerting a mass of 30 kg using a pressboard. The treatments were setup in a completely randomized design and replicated four times to give a total of 20 experimental units. Two seeds of groundnut were sown to a depth of 3 cm per hole

in each trough after compaction, and this was later thinned to one plant per stand at 2 weeks after planting. Figure 1 shows groundnut plants under different soil compaction levels at 2 and 4 weeks after sowing (WAS) in wooden troughs.

Soil samples were randomly collected at 0–15 cm depth from ten spots with the aid of a shovel. The soil

samples were homogenized by bulking them together to form a composite sample. Sub-samples were extracted from the composite sample for laboratory analysis. The sub-samples were air-dried, crushed with mortar and pestle to break clods present, and sieved through 2 and 0.5 mm mesh for laboratory analysis of soil physical and chemical properties, respectively.

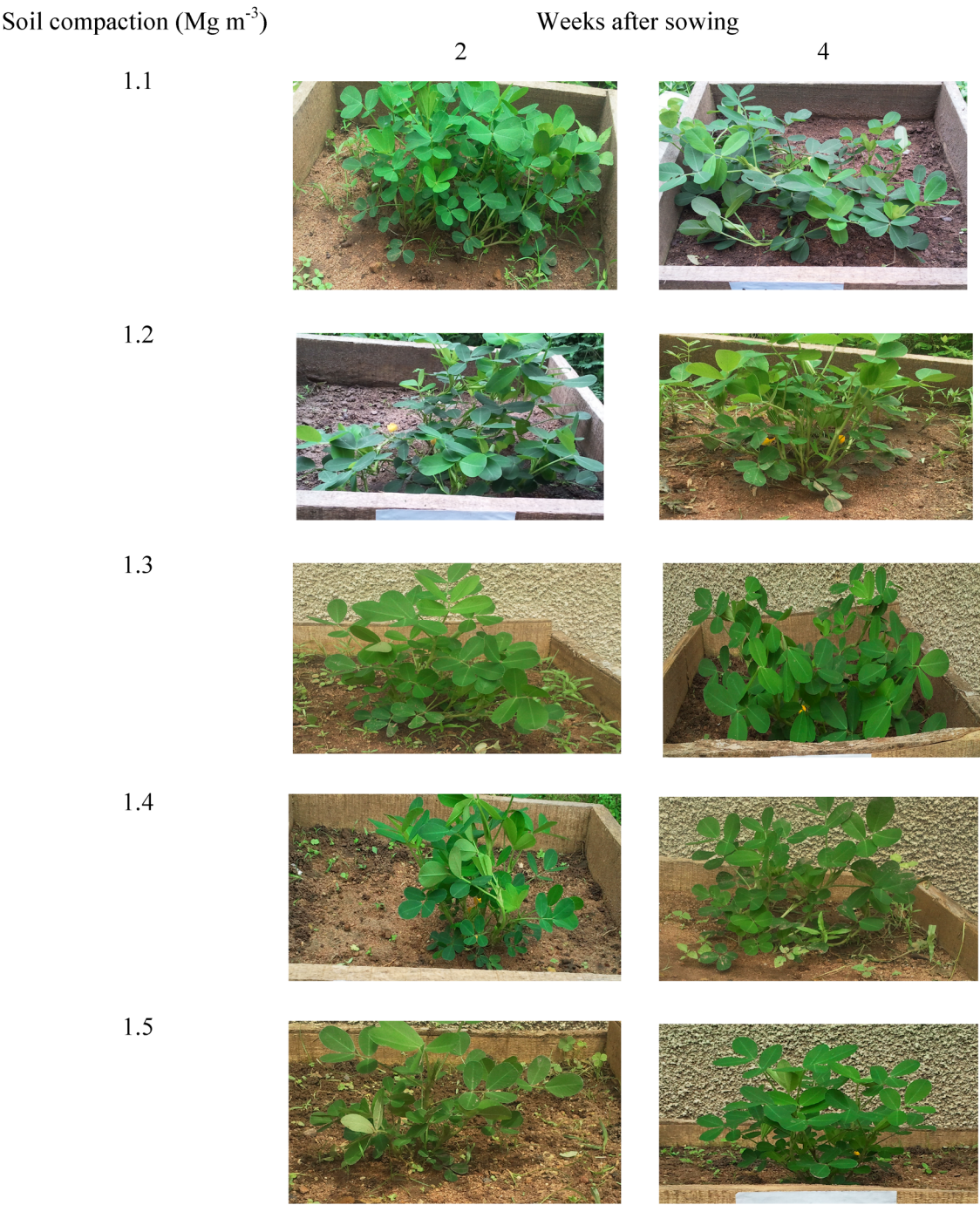


Figure 1: Groundnut plants as affected by soil compaction at 2 and 4 weeks after sowing.



## 2.3 Soil analysis

Soil chemical parameters such as soil pH was determined using a glass-electrode pH meter in a 1:1 soil and water mixture [35]; organic carbon was determined using the Walkley-Black wet-oxidation method [36]. Total nitrogen was analyzed using the macro-kjeldahl digestion-distillation apparatus [37], while ascorbic acid molybdate blue method was used in the colorimetric determination of available phosphorus [38]. Exchangeable bases (potassium, calcium, magnesium, and sodium) and extractable micronutrients (manganese, iron, zinc, and copper) were determined using the ammonium acetate and 0.01 N HCl procedure [39]. Calcium and magnesium were determined from soil extract using 0.01 M EDTA titration method, while sodium and potassium were determined by flame photometer [40]. The atomic absorption spectrometer was used to determine the micronutrients. Particle size analysis was carried out using the hydrometer method, with 20% sodium hexametaphosphate as the dispersant [41], while saturated hydraulic conductivity was determined using the constant-head permeameter [42], and field capacity was determined using the tension table assembly [43].

## 2.4 Plant sampling

Data on plant growth parameters such as plant height, number of leaves, leaf area, and stem diameter were taken at 2 weeks interval from 2 to 10 WAS. Plant height was measured with a meter rule from the surface of the soil to the tip of the highest part of the plant, while leaf area was measured with LI-COR Biosciences LI-3100C Area Meter, and stem diameter was measured with a digital vernier caliper at 2 cm from the surface of the soil. The yield parameters measured at harvest were number of pods per plant and mass of pods per plant, while total biomass (pods, shoot, and roots before detaching), below-ground biomass, leaf mass, stem mass, and mass of above-ground biomass were taken on fresh and dry mass basis after harvest. Dry biomass was determined by oven-drying the harvested plant parts to constant weight at 65°C.

## 2.5 Statistical analysis

Data analysis was carried out using the GenStat Discovery Statistical Package (8th Edition). All data collected were subjected to analysis of variance (ANOVA), while significantly

different means were separated using Duncan Multiple Range Test (DMRT) at  $\alpha_{0.05}$ .

# 3 Results

## 3.1 Baseline properties of the experimental soil

The results of the soil physical and chemical analysis prior to planting are presented in Table 1. Texturally, the soil used for the study was sandy loam. In year 1, its chemical constituents revealed that the soil was slightly acidic with a pH value of 6.4 and a total nitrogen content of 1.2 g kg<sup>-1</sup>. It had an organic carbon content of 11.4 g kg<sup>-1</sup> and available phosphorus of 11.4 mg kg<sup>-1</sup>, while its potassium, calcium, and magnesium values were 0.41, 1.28, and 0.96 cmol kg<sup>-1</sup>, respectively. In year 2, the results of the chemical analysis of the soil revealed that the soil was slightly acidic with a pH value of 6.0 and a total nitrogen content of 2.0 g kg<sup>-1</sup>. It had an organic carbon content of 33.9 g kg<sup>-1</sup> and available phosphorus of 68.3 mg kg<sup>-1</sup>, while its potassium, calcium, and magnesium values were 2.51, 11.07, and 0.13 cmol kg<sup>-1</sup>, respectively.

**Table 1:** Physical and chemical properties of the experimental soil

Parameter	Year 1	Year 2
Particle size distribution (g kg <sup>-1</sup> )		
Sand	764	764
Silt	160	160
Clay	76	76
Textural class	Sandy loam	Sandy loam
pH (1:1, soil:H <sub>2</sub> O)	6.4	6.0
pH (1:1, soil:KCl)	5.4	5.0
Total nitrogen (g kg <sup>-1</sup> )	1.2	2.0
Organic carbon (g kg <sup>-1</sup> )	11.41	33.9
Available phosphorus (mg kg <sup>-1</sup> )	11.41	68.3
Exchangeable bases (cmol kg <sup>-1</sup> )		
Potassium	0.41	2.51
Sodium	0.40	0.28
Calcium	1.28	11.07
Magnesium	0.96	0.13
Exchangeable acidity	0.08	0.30
Extractable micronutrients (mg kg <sup>-1</sup> )		
Manganese	nd	160.0
Iron	nd	413.0
Zinc	nd	15.9
Copper	nd	5.1

nd: not determined.

### 3.2 Saturated hydraulic conductivity and field capacity

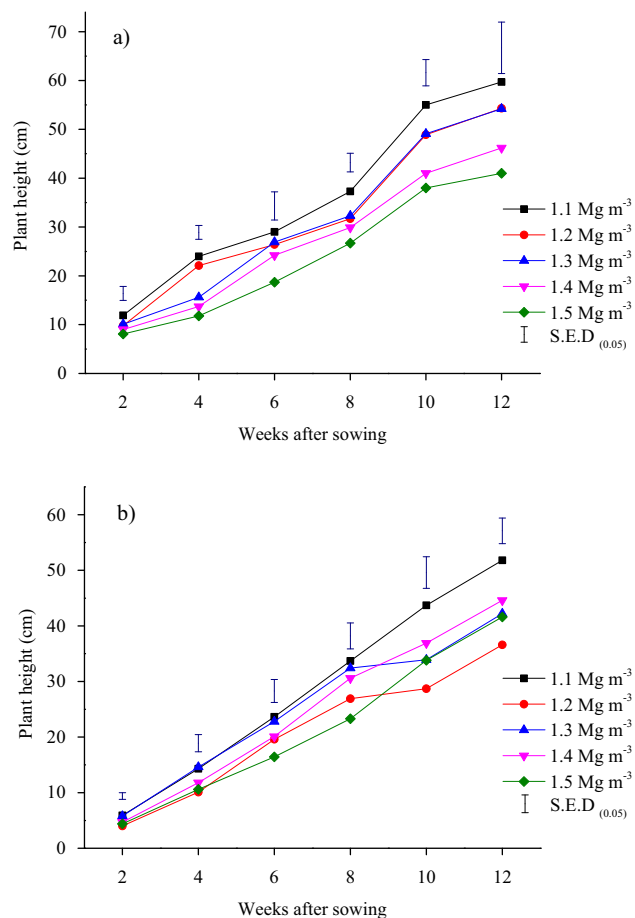
The alteration in soil saturated hydraulic conductivity ( $K_{\text{sat}}$ ) following soil compaction is presented in Table 2. Significant ( $p < 0.05$ ) differences were observed in the  $K_{\text{sat}}$  values. Soil  $K_{\text{sat}}$  was higher by 4.4–23.8% in  $1.1 \text{ Mg m}^{-3}$  than the other treatments in year 1. Furthermore, soil  $K_{\text{sat}}$  in  $1.2 \text{ Mg m}^{-3}$  was similar to that in  $1.1 \text{ Mg m}^{-3}$ , while the lowest value was observed in  $1.5 \text{ Mg m}^{-3}$ . The available moisture at field capacity as influenced by soil compaction is presented in Table 2. Soil moisture at field capacity differed significantly ( $p < 0.05$ ) among soil compaction levels. The highest soil moisture was in  $1.1 \text{ Mg m}^{-3}$ . In comparison, it was statistically at par with moisture content at  $1.2 \text{ Mg m}^{-3}$  (30.8%). Lower moisture contents by 11.7, 20.0, and 31.1% were recorded in 1.3, 1.4, and  $1.5 \text{ Mg m}^{-3}$  relative to  $1.1 \text{ Mg m}^{-3}$ , respectively.

### 3.3 Growth attributes

The results of the growth attributes of groundnut as influenced by soil compaction in year 1 and year 2 are presented as follows:

#### 3.3.1 Plant height

The height of groundnut plants as influenced by soil compaction is illustrated in Figure 2. Groundnut plant height was significantly ( $p < 0.05$ ) influenced by soil compaction in both years of the study. In year 1, superior plant height was recorded in  $1.1 \text{ Mg m}^{-3}$  (59.7 cm). Lower values in the range of 9.0–31.3% were recorded in 1.2, 1.3, 1.4, and



**Figure 2:** Effect of soil compaction on groundnut plant height in: (a) year 1 and (b) year 2.

$1.5 \text{ Mg m}^{-3}$ , respectively. Values of plant height in 1.2 and  $1.3 \text{ Mg m}^{-3}$  were lower but comparable with that in  $1.1 \text{ Mg m}^{-3}$ . Similarly, superior plant height was observed in  $1.1 \text{ Mg m}^{-3}$ , while lower values in the range of 13.9–29.3% were recorded in higher levels of soil compaction ( $1.2 - 1.5 \text{ Mg m}^{-3}$ ) in year 2.

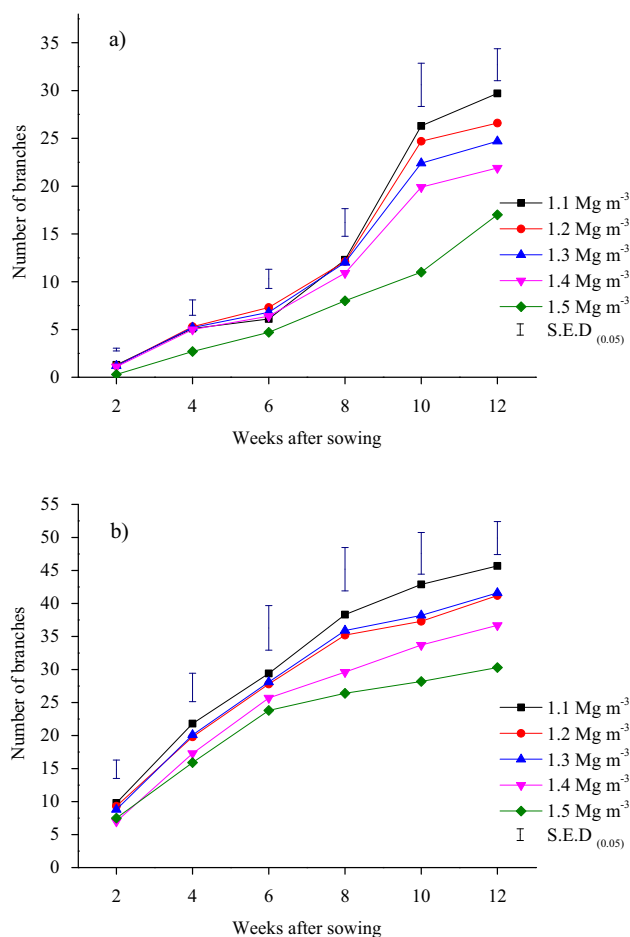
**Table 2:** Saturated hydraulic conductivity and field capacity as influenced by soil compaction

Soil compaction ( $\text{Mg m}^{-3}$ )	$K_{\text{sat}}$ ( $\text{cm h}^{-1}$ )	$\theta_{\text{FC}}$ (%)
1.1	$49.4 \pm 2.88^a$	$31.5 \pm 3.09^a$
1.2	$47.3 \pm 5.64^{ab}$	$30.8 \pm 6.05^a$
1.3	$43.7 \pm 5.74^{bc}$	$27.8 \pm 3.00^{ab}$
1.4	$41.9 \pm 5.17^c$	$25.2 \pm 3.40^{bc}$
1.5	$39.9 \pm 6.15^c$	$21.7 \pm 4.02^c$
S.E.D. (0.05)	1.993	1.834

Values are mean values  $\pm$  standard deviation; mean values with the same letter(s) in the same column are not significantly different at  $p < 0.05$ ;  $K_{\text{sat}}$ : saturated hydraulic conductivity;  $\theta_{\text{FC}}$ : moisture content at field capacity; S.E.D: standard error of differences of mean values.

#### 3.3.2 Number of branches

Figure 3 presents the number of branches of groundnut as influenced by soil compaction. Number of branches of groundnut was highest at 12 WAS and differed significantly in years 1 and 2. Increase in soil compaction resulted in corresponding decrease in number of branches. Further, the highest number of branches was recorded in  $1.1 \text{ Mg m}^{-3}$  and was higher by 11.7, 20.2, and 35.6% than that in 1.2, 1.3, and  $1.4 \text{ Mg m}^{-3}$ , respectively in year 1. The lowest number of branches was recorded in  $1.5 \text{ Mg m}^{-3}$ . In year 2, the highest number of branches was observed in  $1.1 \text{ Mg m}^{-3}$  (45.7 branches), while lower values in the

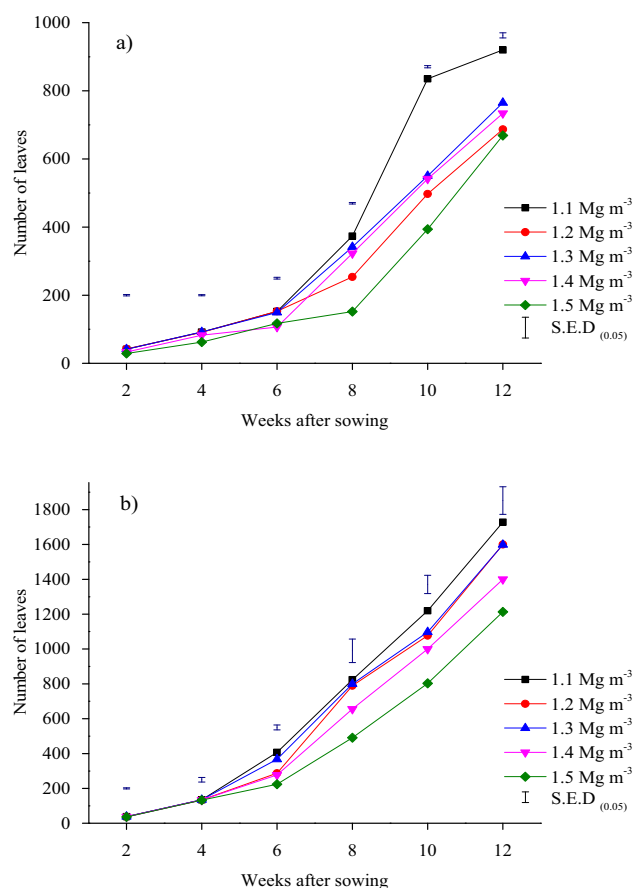


**Figure 3:** Number of branches of groundnut as influenced by soil compaction in: (a) year 1 and (b) year 2.

range of 3.3–33.7% was recorded in higher levels of soil compaction.

### 3.3.3 Number of leaves

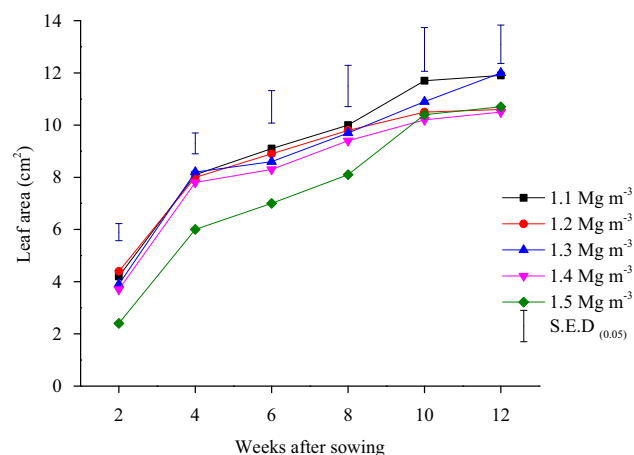
The result of the number of leaves of groundnut as influenced by soil compaction across 12 WAS is illustrated in Figure 4. In year 1, number of leaves differed significantly ( $p < 0.05$ ) and was highest in 1.1  $\text{Mg m}^{-3}$ . Lower values in the range of 16.8–25.3% was recorded in 1.2, 1.3, and 1.4  $\text{Mg m}^{-3}$ , respectively. The lowest number of leaves was recorded in 1.5  $\text{Mg m}^{-3}$  at 12 WAS. Similarly, the highest number of leaves in groundnut plants was recorded at 12 WAS in year 2, in 1.1  $\text{Mg m}^{-3}$  having the highest number of leaves. Lower values by 7.4, 7.5, and 19.0% were recorded in 1.2, 1.3, and 1.4  $\text{Mg m}^{-3}$  compared with 1.1  $\text{Mg m}^{-3}$ , respectively, while plants in 1.5  $\text{Mg m}^{-3}$  had the lowest number of leaves.



**Figure 4:** Effect of soil compaction on number of leaves of groundnut in: (a) year 1 and (b) year 2.

### 3.3.4 Leaf area

Figure 5 depicts the leaf area of groundnut plants as affected by soil compaction. Leaf area was observed only in year 1 and was higher in 1.3  $\text{Mg m}^{-3}$  by 4.3 and



**Figure 5:** Leaf area of groundnut plant as influenced by soil compaction in year 1.

10.1% relative to 1.1 and 1.5 Mg m<sup>-3</sup>, respectively. Lower values of leaf area were recorded in 1.2 and 1.4 Mg m<sup>-3</sup>. Leaf area between 1.2 and 1.5 Mg m<sup>-3</sup> was similar. In addition, the difference in leaf area was significant among the levels of soil compaction.

### 3.4 Fresh mass of growth attributes

The results of the fresh mass of growth attributes of groundnut as affected by soil compaction in years 1 and 2 are presented as follows:

#### 3.4.1 Fresh leaf mass

The result of fresh leaf mass of groundnut as influenced by soil compaction in year 2 is presented in Table 3. The highest fresh leaf mass was recorded in 1.1 Mg m<sup>-3</sup>. This was, however, similar to fresh leaf mass values obtained for groundnut plants in 1.2, 1.4, and 1.5 Mg m<sup>-3</sup>. In comparison, the lowest fresh leaf mass was obtained in 1.3 Mg m<sup>-3</sup>.

#### 3.4.2 Fresh mass of above-ground biomass

The result of fresh mass of above-ground biomass of groundnut produced under different levels of soil compaction

in year 2 is presented in Table 3. The highest fresh mass of above-ground biomass was recorded in 1.1 Mg m<sup>-3</sup>. This was higher by 21.0–25.0% than that in 1.4, 1.5, and 1.3 Mg m<sup>-3</sup>, respectively, while the lowest fresh mass (545.0 g plant<sup>-1</sup>) was recorded in 1.2 Mg m<sup>-3</sup>.

#### 3.4.3 Fresh root mass

The fresh root mass of groundnut as influenced by soil compaction is presented in Table 3. In year 1, significant ( $p < 0.05$ ) differences were observed in the fresh root mass of groundnut under the soil compaction treatments. The highest value was recorded in 1.1 Mg m<sup>-3</sup>. Lower values by 4.8, 39.6, and 41.9% were recorded in 1.2, 1.4, and 1.5 Mg m<sup>-3</sup>, respectively, while 1.3 Mg m<sup>-3</sup> resulted in the lowest groundnut fresh root mass. The differences in fresh root mass were significant among the treatments. In year 2, the highest fresh root mass was also recorded in 1.1 Mg m<sup>-3</sup>. Lower values in the range of 6.3–41.3% were recorded among higher levels of soil compaction, with 1.3 Mg m<sup>-3</sup> having the lowest value. Statistically, the difference in fresh root mass of groundnut was significant among the soil compaction levels.

#### 3.4.4 Fresh stem mass

Table 3 presents the result of fresh stem mass of groundnut produced under different levels of soil compaction in

**Table 3:** Effect of soil compaction on fresh mass of groundnut growth parameters

Soil compaction (Mg m <sup>-3</sup> )	Fresh leaf mass	Fresh stem mass	Fresh root mass (kg ha <sup>-1</sup> )	Above ground biomass	Total biomass
<b>Year 1</b>					
1.1	nd	nd	750.0 ± 166.67 <sup>a</sup>	nd	19444.4 ± 4241.67 <sup>a</sup>
1.2	nd	nd	713.9 ± 105.56 <sup>a</sup>	nd	12833.3 ± 1736.11 <sup>b</sup>
1.3	nd	nd	380.6 ± 80.56 <sup>b</sup>	nd	12777.8 ± 3700.00 <sup>b</sup>
1.4	nd	nd	452.8 ± 122.22 <sup>b</sup>	nd	18222.2 ± 950.00 <sup>a</sup>
1.5	nd	nd	436.1 ± 189.56 <sup>b</sup>	nd	4638.9 ± 616.67 <sup>c</sup>
S.E.D <sub>(0.05)</sub>	nd	nd	99.74	nd	2190.24
<b>Year 2</b>					
1.1	6527.8 ± 141.67 <sup>a</sup>	10166.7 ± 202.78 <sup>a</sup>	577.8 ± 94.44 <sup>a</sup>	19555.6 ± 180.56 <sup>a</sup>	28083.3 ± 297.22 <sup>a</sup>
1.2	6388.9 ± 286.11 <sup>ab</sup>	8944.4 ± 66.67 <sup>b</sup>	541.7 ± 100.00 <sup>ab</sup>	15138.9 ± 150.00 <sup>d</sup>	19944.4 ± 180.56 <sup>b</sup>
1.3	5888.9 ± 205.56 <sup>c</sup>	8666.7 ± 322.22 <sup>bc</sup>	338.9 ± 58.33 <sup>c</sup>	15638.9 ± 133.3 <sup>c</sup>	20000 ± 227.78 <sup>b</sup>
1.4	6111.1 ± 61.11 <sup>b</sup>	9000.0 ± 61.11 <sup>b</sup>	458.3 ± 72.22 <sup>abc</sup>	16166.7 ± 125.0 <sup>b</sup>	19444.4 ± 391.67 <sup>b</sup>
1.5	6305.6 ± 261.11 <sup>ab</sup>	8500.0 ± 191.67 <sup>c</sup>	416.7 ± 63.89 <sup>b</sup>	15666.7 ± 302.78 <sup>c</sup>	18611.1 ± 450.00 <sup>c</sup>
S.E.D <sub>(0.05)</sub>	169.74	159.11	64.93	154.99	265.51

Values are mean values ± standard deviation; mean values with the same letter(s) in the same category in a column are not significantly different at  $p < 0.05$ ; nd: not determined; S.E.D: standard error of differences of mean values.

year 2. The highest fresh stem mass of groundnut was produced in  $1.1 \text{ Mg m}^{-3}$ . Lower values in the range of 11.5–14.8% were recorded in 1.4, 1.2, and  $1.3 \text{ Mg m}^{-3}$ , while plants in  $1.5 \text{ Mg m}^{-3}$  had the lowest fresh stem mass. In addition, the fresh stem mass of groundnut differed significantly among the treatments.

### 3.4.5 Fresh total biomass of groundnut

The effect of soil compaction on the total mass of fresh biomass of groundnut is presented in Table 3. Though there was no significant ( $p < 0.05$ ) difference in the fresh mass of total biomass of groundnut among the treatments in year 1, plants in  $1.1 \text{ Mg m}^{-3}$  had the highest total biomass. This was followed by 1.4, 1.2, and  $1.3 \text{ Mg m}^{-3}$  which were lower by 6.3–34.3%, while groundnut plants in  $1.5 \text{ Mg m}^{-3}$  had the lowest fresh total biomass. However, the fresh total biomass of groundnut differed significantly among the treatments in year 2. Plants in  $1.1 \text{ Mg m}^{-3}$  had the highest fresh total biomass, while those in 1.3, 1.2, and  $1.4 \text{ Mg m}^{-3}$  were lower by 28.8, 29.0, and 30.8%, respectively, and the lowest fresh total biomass was obtained in  $1.5 \text{ Mg m}^{-3}$ .

## 3.5 Dry mass of growth attributes

The results of the dry mass of growth attributes of groundnut observed under soil compaction levels in years 1 and 2 are presented as follows:

### 3.5.1 Dry root mass

Table 4 presents the result of the dry root mass of groundnut grown under different levels of soil compaction. In year 1, groundnut plants in 1.2 and  $1.3 \text{ Mg m}^{-3}$  had the highest dry root mass ( $17.3 \text{ g plant}^{-1}$ ). Lower values (by 40.5, 43.9, and 52.0%) were obtained in 1.5, 1.4, and  $1.1 \text{ Mg m}^{-3}$ , respectively. In year 2, however, groundnut plants in  $1.1 \text{ Mg m}^{-3}$  had the highest dry root mass. This was followed closely by plants in  $1.2 \text{ Mg m}^{-3}$  which were lower by 19.1%. Dry root mass of ground was similar for plants in 1.3, 1.4, and  $1.5 \text{ Mg m}^{-3}$ . The difference in dry root mass of groundnut among soil compaction levels was not significant at  $p < 0.05$ .

### 3.5.2 Dry leaf mass

The result of the effect of soil compaction on the dry leaf mass of groundnut in year 2 is presented in Table 4. The dry leaf mass of groundnut was significantly ( $p < 0.05$ ) influenced by soil compaction, with plants grown in  $1.1 \text{ Mg m}^{-3}$  having the highest dry leaf mass. This was closely followed by plants in  $1.3 \text{ Mg m}^{-3}$ , while those in 1.2 and  $1.4 \text{ Mg m}^{-3}$  were lower by 17.6 and 23.3%, respectively. The lowest dry leaf mass was obtained in  $1.5 \text{ Mg m}^{-3}$ .

### 3.5.3 Dry stem mass

There was no significant ( $p < 0.05$ ) difference in the dry stem mass of groundnut among soil compaction levels in

**Table 4:** Effect of soil compaction on dry mass of groundnut growth parameters

Soil compaction ( $\text{Mg m}^{-3}$ )	Dry root mass	Dry leaf mass ( $\text{kg ha}^{-1}$ )	Dry stem mass	Tap root length (cm)
<b>Year 1</b>				
1.1	$230.6 \pm 19.44^c$	nd	nd	$26.6 \pm 0.90^b$
1.2	$480.6 \pm 25.00^a$	nd	nd	$29.2 \pm 0.50^a$
1.3	$480.6 \pm 11.11^a$	nd	nd	$30.2 \pm 0.40^a$
1.4	$269.4 \pm 25.00^b$	nd	nd	$20.0 \pm 1.70^c$
1.5	$286.1 \pm 19.44^b$	nd	nd	$12.7 \pm 0.60^d$
S.E.D <sub>(0.05)</sub>	16.85	nd	nd	0.77
<b>Year 2</b>				
1.1	$188.9 \pm 16.67^a$	$1827.8 \pm 52.78^a$	$2450.0 \pm 41.67^b$	nd
1.2	$152.8 \pm 11.11^b$	$1505.6 \pm 58.33^c$	$1930.6 \pm 44.44^{cd}$	nd
1.3	$133.3 \pm 11.11^b$	$1716.7 \pm 52.78^b$	$2777.8 \pm 19.44^a$	nd
1.4	$133.3 \pm 5.56^b$	$1402.8 \pm 22.22^d$	$1977.8 \pm 41.67^c$	nd
1.5	$133.3 \pm 19.44^b$	$1388.9 \pm 38.89^d$	$1888.9 \pm 30.56^d$	nd
S.E.D <sub>(0.05)</sub>	11.16	38.26	30.02	nd

Values are mean values  $\pm$  standard deviation; mean values with the same letter(s) in the same category in a column are not significantly different at  $p < 0.05$ ; nd: not determined; S.E.D: standard error of differences of mean values.



year 2 (Table 4). However, the highest dry stem mass was obtained in  $1.3 \text{ Mg m}^{-3}$ . This was higher than those in 1.1, 1.4, and  $1.2 \text{ Mg m}^{-3}$  by 13.4–43.9%, while  $1.5 \text{ Mg m}^{-3}$  resulted in the lowest dry stem mass of groundnut.

### 3.6 Tap root length

The influence of soil compaction on the tap root length of groundnut in year 1 is presented in Table 4. Significant ( $p < 0.05$ ) differences were observed in the tap root length of groundnut grown under the different levels of soil compaction. The longest tap root was obtained in  $1.3 \text{ Mg m}^{-3}$ . This was higher by 3.4–51.0% than those in 1.2, 1.1, and  $1.4 \text{ Mg m}^{-3}$ , while  $1.5 \text{ Mg m}^{-3}$  led to the shortest tap root.

### 3.7 Fresh yield attributes

The results of the yield attributes of groundnut as influenced by soil compaction in years 1 and 2 are presented as follows:

#### 3.7.1 Number of pods

Table 5 shows the results of the number of pods of groundnut plants under the influence of soil compaction. In year 1, number of pods differed significantly ( $p < 0.05$ ) and was highest in  $1.1 \text{ Mg m}^{-3}$ . This was followed by plants in 1.2 and  $1.3 \text{ Mg m}^{-3}$  which were lower by 18.7 and 30.3%, respectively. Soil compaction at 1.4 and  $1.5 \text{ Mg m}^{-3}$  substantially reduced the number of groundnut pods produced relative to  $1.1 \text{ Mg m}^{-3}$ . Differences in number of pods were also significant among soil compaction levels in year 2. The highest number of pods was obtained in  $1.1 \text{ Mg m}^{-3}$  and was followed by 1.3, 1.2, and  $1.4 \text{ Mg m}^{-3}$ , while  $1.5 \text{ Mg m}^{-3}$  gave the lowest number of pods.

#### 3.7.2 Fresh pod mass

Table 5 presents the result of groundnut fresh pod mass produced under the influence of soil compaction. In year 1, the fresh pod mass of groundnut differed significantly ( $p < 0.05$ ) among the treatments and was highest in  $1.1 \text{ Mg m}^{-3}$ . Lower fresh pod mass (by 12.0, 42.3, and 65.4%) were obtained in 1.3, 1.2, and  $1.4 \text{ Mg m}^{-3}$ , respectively, while the lowest fresh pod mass was obtained in

$1.5 \text{ Mg m}^{-3}$ . In year 2,  $1.1 \text{ Mg m}^{-3}$  also gave the highest fresh pod mass. This was higher than those obtained in 1.3, 1.2, and  $1.4 \text{ Mg m}^{-3}$  by 93.1, 96.1, and 129.8%, respectively, while the lowest fresh pod mass was obtained in  $1.5 \text{ Mg m}^{-3}$ .

#### 3.7.3 Number of seeds

Table 5 presents the number of seeds of groundnut produced under the effect of varying soil compaction levels. In year 1, the number of groundnut seeds produced was highest in  $1.3 \text{ Mg m}^{-3}$ . This was followed by those of  $1.2 \text{ Mg m}^{-3}$  which were lower by 39.9%, while plants grown in  $1.5 \text{ Mg m}^{-3}$  produced the lowest number of seeds. The difference in number of seeds among the treatments was significant. Furthermore, in year 2, plants grown in  $1.1 \text{ Mg m}^{-3}$  produced the highest number of seeds, while those in 1.3, 1.4, and  $1.2 \text{ Mg m}^{-3}$  were lower by 34.9–51.7%. Soil compaction at  $1.5 \text{ Mg m}^{-3}$  resulted in the lowest number of seeds produced.

#### 3.7.4 Fresh seed mass

The effects of soil compaction on the mass of fresh groundnut seeds produced in year 1 are shown in Table 5. Groundnut plants cultivated in  $1.3 \text{ Mg m}^{-3}$  had the highest fresh seed mass. This was higher than the fresh seed mass of 1.1 and  $1.2 \text{ Mg m}^{-3}$  by 35.3 and 64.1%, respectively, while plants cultivated in 1.4 and  $1.5 \text{ Mg m}^{-3}$  had substantially low fresh seed mass relative to other treatments. The difference in fresh seed mass of groundnut among soil compaction levels was significant at  $p < 0.05$ .

### 3.8 Dry mass of yield attributes

The results of the dry mass of groundnut yield attributes as influenced by soil compaction in year 1 and year 2 are presented as follows:

#### 3.8.1 Dry pod mass

Table 5 shows the result of the dry mass of groundnut pods produced under different levels of soil compaction in year 2. Soil compaction at  $1.1 \text{ Mg m}^{-3}$  led to the highest dry pod mass. Lower values in the range of 44.0–56.5% were obtained in 1.3, 1.4, and  $1.2 \text{ Mg m}^{-3}$ , while  $1.5 \text{ Mg m}^{-3}$

Table 5: Groundnut yield parameters as affected by soil compaction

Soil compaction ( $\text{Mg m}^{-3}$ )	No. of pods	No. of seeds ( $\text{ha}^{-1}$ )	Fresh pod mass	Fresh seed mass	Dry pod mass ( $\text{kg ha}^{-1}$ )	Dry seed mass	Dry shell mass
<b>Year 1</b>							
1.1	510.3 $\pm$ 5.00 <sup>a</sup>	270.3 $\pm$ 2.50 <sup>c</sup>	3527.8 $\pm$ 33.33 <sup>a</sup>	1944.4 $\pm$ 69.44 <sup>b</sup>	nd	1352.8 $\pm$ 72.22 <sup>b</sup>	nd
1.2	414.7 $\pm$ 5.56 <sup>b</sup>	286.94 $\pm$ 5.00 <sup>b</sup>	2036.1 $\pm$ 38.89 <sup>c</sup>	1602.8 $\pm$ 69.44 <sup>c</sup>	nd	1119.4 $\pm$ 58.33 <sup>c</sup>	nd
1.3	355.56 $\pm$ 3.61 <sup>c</sup>	477.8 $\pm$ 6.94 <sup>a</sup>	3102.8 $\pm$ 52.78 <sup>b</sup>	2630.6 $\pm$ 133.3 <sup>a</sup>	nd	1583.3 $\pm$ 61.11 <sup>a</sup>	nd
1.4	154.7 $\pm$ 2.50 <sup>d</sup>	188.1 $\pm$ 6.39 <sup>d</sup>	1222.2 $\pm$ 61.11 <sup>d</sup>	1333.3 $\pm$ 91.67 <sup>d</sup>	nd	991.7 $\pm$ 50.00 <sup>d</sup>	nd
1.5	132.5 $\pm$ 5.00 <sup>e</sup>	138.1 $\pm$ 4.17 <sup>e</sup>	713.9 $\pm$ 105.56 <sup>e</sup>	1036.1 $\pm$ 55.56 <sup>e</sup>	nd	797.2 $\pm$ 97.22 <sup>e</sup>	nd
S.E.D (0.05)	3.65	4.28	52.01	72.03	nd	56.93	nd
<b>Year 2</b>							
1.1	4088.9 $\pm$ 72.22 <sup>a</sup>	4644.4 $\pm$ 122.22 <sup>a</sup>	7736.1 $\pm$ 194.44 <sup>a</sup>	nd	3500.0 $\pm$ 116.67 <sup>a</sup>	2561.1 $\pm$ 58.33 <sup>a</sup>	972.2 $\pm$ 88.89 <sup>a</sup>
1.2	2444.4 $\pm$ 77.78 <sup>c</sup>	2244.4 $\pm$ 94.44 <sup>c</sup>	3944.4 $\pm$ 116.67 <sup>c</sup>	nd	1522.2 $\pm$ 94.44 <sup>c</sup>	1055.6 $\pm$ 91.67 <sup>c</sup>	494.4 $\pm$ 94.44 <sup>bc</sup>
1.3	3125.0 $\pm$ 322.22 <sup>b</sup>	3022.2 $\pm$ 147.22 <sup>b</sup>	4005.6 $\pm$ 77.78 <sup>b</sup>	nd	1958.3 $\pm$ 213.89 <sup>b</sup>	1244.4 $\pm$ 88.89 <sup>b</sup>	633.3 $\pm$ 75.00 <sup>b</sup>
1.4	2438.9 $\pm$ 75.00 <sup>c</sup>	2347.2 $\pm$ 108.33 <sup>c</sup>	3366.7 $\pm$ 52.78 <sup>c</sup>	nd	1577.8 $\pm$ 91.67 <sup>c</sup>	1022.2 $\pm$ 86.11 <sup>c</sup>	500.0 $\pm$ 75.00 <sup>bc</sup>
1.5	2111.1 $\pm$ 80.56 <sup>d</sup>	1144.4 $\pm$ 108.33 <sup>d</sup>	2527.8 $\pm$ 113.89 <sup>d</sup>	nd	944.4 $\pm$ 75.00 <sup>d</sup>	458.3 $\pm$ 47.22 <sup>d</sup>	416.7 $\pm$ 50.00 <sup>c</sup>
S.E.D (0.05)	130.23	95.92	98.81	nd	104.76	62.56	63.84

Values are mean values  $\pm$  standard deviation; mean values with the same letter(s) in the same category in a column are not significantly different at  $p < 0.05$ ; nd: not determined; S.E.D: standard error of differences of mean values.

resulted in the lowest dry pod mass. The differences in dry pod mass among soil compaction levels were significant ( $p < 0.05$ ).

### 3.8.2 Dry seed mass

The result of the effect of soil compaction on the dry mass of groundnut seeds produced is presented in Table 5. Though the trend in result was similar to that of fresh seed mass, there was no significant ( $p < 0.05$ ) difference in the dry seed mass of groundnut in year 1. Groundnut plants in 1.3  $\text{Mg m}^{-3}$  had the highest dry seed mass and were superior by 17.0–59.7% than those in 1.1, 1.2, and 1.4  $\text{Mg m}^{-3}$  respectively, while 1.5  $\text{Mg m}^{-3}$  resulted in the lowest dry seed mass of groundnut. In year 2, significant ( $p < 0.05$ ) differences were observed in dry seed mass of groundnut. Plants grown in 1.1  $\text{Mg m}^{-3}$  were highest in dry seed mass, followed by those in 1.3  $\text{Mg m}^{-3}$  which were lower by 51.4%. The lowest dry seed mass was obtained in 1.5  $\text{Mg m}^{-3}$ .

### 3.8.3 Dry shell mass

The effect of soil compaction levels on the dry shell mass of groundnut produced in year 2 is presented in Table 5. The dry shell mass of groundnut differed significantly ( $p < 0.05$ ) with soil compaction levels. Groundnut plants in 1.1  $\text{Mg m}^{-3}$  were highest in dry shell mass, while those in 1.3, 1.4, and 1.2  $\text{Mg m}^{-3}$  were lower by 34.9, 48.6, and 49.1%, respectively. Groundnut plants grown in the highest soil compaction level (1.5  $\text{Mg m}^{-3}$ ) had the lowest dry shell mass.

## 4 Discussion

The soil used for the study had high sand content relative to its silt and clay fractions (sandy loam). This presupposes the preponderance of macropores relative to micropores. Hence, it can be inferred that prior to compaction, the soil used for this study had low water holding capacity. This supports studies that have reported the lack of adsorption capacity for basic plant nutrients and low water holding capacity in coarse texture soils [44,45]. The soil pH which was slightly acidic, was within the optimum pH range of 6.0 and 7.0 reported for most agricultural crops [46]. The soil pH (6.4) was close to the zone (about 6.5) where nutrients are reported to be readily

available [46]. Total nitrogen was also slightly lower than the critical value of  $1.5 \text{ g kg}^{-1}$  reported for tropical soils in ref. [47]. The low level of nitrogen may be due to nutrient mining resulting from intensive farming in the area where the soil was collected. Ref. [47] reported that low levels of nitrogen in soils may be related to intense leaching and erosion due to rainfall. The organic carbon of the soil was below the threshold ( $20 \text{ g kg}^{-1}$ ) reported in ref. [48]. Ref. [45] reported that values of org. C below  $15.00 \text{ g kg}^{-1}$  are rated low and may not sustain intensive cropping system. Refs. [47,49] reported that low soil organic matter in the surface soils in the tropics could be due to continuous cropping in this area. Though the available phosphorus was below the value ( $15 \text{ mg kg}^{-1}$ ) regarded as productive zone for soils [50], it was within the critical range ( $8\text{--}12 \text{ mg kg}^{-1}$ ) for tropical soils [47]. The higher values for soil organic carbon, total nitrogen, and available phosphorus recorded in year 2 could be due to the 2-year fallow period observed between the termination of the first planting in year 1 and the commencement of the second planting in year 2. Decrease in saturated hydraulic conductivity and field capacity following the increase in soil compaction could be due to reduction in available pore space after compression. These results support the findings of ref. [10] in which it was noted that soil compaction exerts negative impacts on soil physical quality and promotes soil physical quality degradation.

Soil compaction significantly influenced groundnut growth parameters with number of leaves, plant height, and number of branches observed to decrease with the increase in soil compaction level. This could be due to its effects on soil moisture and nutrient uptake by the crop. Similar observations were reported by refs. [1,2,11] which reported that shorter main roots reduce water uptake and thus plant physiological performance. Though tap root length was highest in  $1.3 \text{ Mg m}^{-3}$ , tap root length decreased with further increase in compaction. This could be due to the increase in the presence of hard pan under compacted layers which restricts root growth. This is in line with the results from previous studies [2,5,51,52]. The superior tap root length obtained for  $1.1\text{--}1.3 \text{ Mg m}^{-3}$  could be due to the degree of looseness of the soils which enhances aeration under these conditions. This finding is corroborated by the observation of ref. [51], which explained that enhanced root growth in loose soils might be due to warm top layers relative to compacted soils. Besides, this depends on the presence and distribution pattern of pores having diameters greater than the plant's roots, and pore continuity [53]. Hence, the superior plant growth in  $1.1 \text{ Mg m}^{-3}$  could be ascribed to the number of available pore spaces for root exploration of

air and water for respiration and uptake of water and nutrients for tissue development. This is in line with the report in ref. [15], in which it was averred that soil compaction affects soil hydraulic and diffusive properties. Ref. [53] reported that alterations in root growth affect root functioning and shoot growth due to low root water uptake rate in compacted soils. Pore spaces have been reported to decrease with the increase in soil compaction and thus, vary under different soil compaction conditions [54,55]. Therefore, it can be inferred from this study that higher available pore spaces in  $1.1 \text{ Mg m}^{-3}$  resulted in better plant growth relative to groundnut plants grown in  $1.5 \text{ Mg m}^{-3}$  where stunted growth, lowest number of leaves, and branches could have been due to restricted water and nutrient uptake for plant use. This shows that when soil is compacted, both the infiltration capacity and water holding capacity of the soil are reduced, thus reducing the soil's potential to hold water for plant use [16,19]. Though, the highest leaf area was in  $1.3 \text{ Mg m}^{-3}$ , the result shows that the influence of soil compaction on groundnut leaf area did not follow a particular trend as observed in the plant height, number of leaves, and number of branches. This could be because leaf area might be more of a genetically influenced plant growth parameter that is not significantly influenced by environmental factors such as soil compaction. In another study [56] on sweet potato, it was reported that differences in the growth of some crop parameters was due to the influence of genetic variations other than the surrounding environment. Also, studies have shown moderate compaction to enhance crop growth and yield [9,53].

The significant differences observed in yield and biomass under the different soil compaction levels can be attributed to differences in alteration of soil physical conditions in the rhizosphere. This could indirectly influence physiological processes such as photosynthesis and respiration through its influence on soil hydrological properties which affect nutrient mobilization, thereby resulting in variations in the number of pods, mass of pods, and total biomass of groundnut. This is in line with the report in ref. [57], which attributed low yield production of crops to low conversion rate of photosynthetic products into carbohydrates, while refs. [58,59] reported that plants with large number of leaves have the potentials for absorbing higher amount of sunlight for photosynthesis, which could be translated to higher yield than those with fewer number of leaves. As a result of its short tap root and low number of leaves, it can be inferred that  $1.5 \text{ Mg m}^{-3}$  reduced the potentials of groundnut plants to convert sufficient photosynthetic products into pods and high biomass. Similar results

were reported in previous studies [1,5,10]. Ref. [60] also reported high yield in low soil compaction and low yield in high soil compaction, while ref. [53] explained that compacted soil reduces crop yield by adversely impacting leaf stomatal resistance via reduced root growth and development. Conversely, ref. [9] reported that barley yield was not affected by compaction. The high fresh root mass, dry root mass, fresh mass of total biomass, number of pods, number of seeds, and fresh seed mass recorded in 1.2 and 1.3 Mg m<sup>-3</sup> in year 1 is in line with the findings of ref. [53], which suggested that moderate soil compaction could provide suitable conditions for a restricted system to absorb more water and to increase water use efficiency due to better root–soil contact area.

## 5 Conclusion

The nitrogen, phosphorus, and potassium contents in the soil were in appreciable quantities to support growth and yield of groundnut in both years of the study. Groundnut growth and yield were substantially influenced by soil compaction. Our results showed that superior growth and yield of groundnut can be obtained in soil compaction of 1.1 Mg m<sup>-3</sup>. Though no trend was observed between 1.2 Mg m<sup>-3</sup> and 1.3 Mg m<sup>-3</sup>, soil compaction at 1.3 Mg m<sup>-3</sup> consistently favored high seed production across the 2 years of study. This could be good for cultivating groundnut for its biological yield, while 1.1 Mg m<sup>-3</sup> could be best suited for growing groundnut for its economic yield. Increase in soil compaction at 1.4 Mg m<sup>-3</sup> and 1.5 Mg m<sup>-3</sup> were associated with consistent low growth and yield of groundnut. High soil compaction (1.5 Mg m<sup>-3</sup>) adversely affected soil saturated hydraulic conductivity and moisture content at field capacity and, thus, resulted in stunted growth and low yield. It is therefore necessary to reduce the use of heavy machinery and practices associated with the occurrence of high compaction (1.5 Mg m<sup>-3</sup>) and adopt management practices that would keep soil compaction within the range of 1.1–1.3 Mg m<sup>-3</sup>.

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**Data availability statement:** The data that support the findings of this study are available from the University of Ibadan but restrictions apply to the availability of these data, which were used under license for the current study, and so are not publicly available. Data are however available from the authors upon reasonable request and with permission of the University of Ibadan.

## References

- [1] Hargreaves PR, Baker KL, Graceson A, Bonnett S, Ball BC, Cloy JM. Soil compaction effects on grassland silage yields and soil structure under different levels of compaction over three years. *Eur J Agron.* 2019;109:125916.
- [2] Moraes MT, Debiasi H, Franchini JC, Mastroberti AA, Levien R, Leitner D, et al. Soil compaction impacts soybean root growth in an Oxisol from subtropical Brazil. *Soil Tillage Res.* 2020;200:104611.
- [3] Soane BD. Processes of soil compaction under vehicular traffic. In: Lal R, Sanchez PA, Cummings Jr RW, editors. *Land clearing and development in the tropics*; 1986. Rotterdam, Boston: Balkema Publishers; p. 265–83.
- [4] Raper R. Site specific management of soil compaction. *Conservation tillage of cotton and rice proceedings. Conservation Tillage Conference*; 2001. p. 247.
- [5] Ghosh U, Daigh ALM. Soil compaction problems and subsoiling effects on potato crop: a review. *Crop, Forage Turfgrass Manag.* 2020;121:800. doi: 10.1002/cft2.20030.
- [6] McCoy EL. Energy requirement for root penetration of compacted soil. In: Boersma LL, editor. *Future developments in soil science research*. Madison, Wisconsin, USA: SSSA. Inc.; 1987. p. 367–78.
- [7] Alblas J, Wamink F, Van dan Akker J, Van dan Werf HMG. Impact of traffic induced compaction of sandy soils on the yield of silage maize in the Netherlands. *Soil Tillage Res.* 1994;29:157–65.
- [8] Carman K. Compaction characteristics of towed wheels on clay loam in a soil bin. *Soil Tillage Res.* 2002;65:37–43.
- [9] Hu W, Beare M, Tregurtha C, Gillespie R, Lehto K, Tregurtha R, et al. Effects of tillage, compaction and nitrogen inputs on crop production and nitrogen losses following simulated forage crop grazing. *Agric Ecosys Env.* 2019;289:289. doi: 10.1016/j.agee.2019.106733.
- [10] Ferreira CJB, Tormena CA, Severiano EDC, Zotarelli L, Edner BJ. Soil compaction influences soil physical quality and soybean yield under long-term no-tillage. *Arch Agron Soil Sci.* 2020;67:383–96. doi: 10.1080/03650340.2020.1733535.
- [11] Mariotti B, Hoshika Y, Cambi M, Marra E, Feng Z, Paoletti E, et al. Vehicle-induced compaction of forest soil affects plant



- morphological and physiological attributes: a meta-analysis. *For Eco Mgt.* 2020;462:118004. doi: 10.1016/j.foreco.2020.118004.
- [12] Adediran KA. Erosion and Infiltration response of a hapistalf soil to tillage induced surface roughness. PhD thesis. Ibadan, Nigeria: University of Ibadan; 1998.
- [13] McBride RA, Martin H, Kennedy B. Soil compaction. University of Guelph/Ontario Ministry of Agriculture, Food and Rural Affairs. Factsheet. 1997;88-082:5.
- [14] Lal R. Compaction, erosion and soil mechanical problems on tropical arable lands. Proceedings of the International Workshop on Soil Research to Solve Selected Problems on Soils in the Tropics. Townsville, Queensland, Australia: ACIAR; 12-16 September 1983. p. 160–1.
- [15] Lipiec J, Stepniewski W. Effects of soil compaction and tillage systems on uptake and losses of nutrients. *Soil Tillage Res.* 1995;35:37–52.
- [16] Adebayo AN, Braide FG, Kaul RN. The effects of machine traffic on the growth pattern of maize in irrigated soils. In: Solube RA, Udo EJ, editors. Soil fertility, soil tilth and post clearing land degradation in the humid tropics. Proceedings of International Society of Soil Science (Commissions iv and vi) organized by the Soil Science Society of Nigeria. Ibadan, Nigeria: 21st–26th July, 1985. p. 368–85.
- [17] Boone FR, Vander Werf HMG, Kroesberggen B, Ten Hag BA, Boers A. The effects of compaction of the arable layer in sandy soils on the growth of maize for silage. *Netherland J Agric Sci.* 1986;34:155–70.
- [18] University of Minnesota Extension Service. Soil compaction causes, effects and control. <http://www.Extension.Umn.edu/dist>. 2001; Assessed: 6 June, 2016.
- [19] Daum RD, Shipp RF. Agricultural soil compaction – causes, effects and cures. <http://www.abe.psu.edu/extension/factsheets/b/B79>. 2003; Assesses on 6 July, 2014.
- [20] Carley DH, Fletcher SM. An overview of world groundnut markets. In: Pattee H, Stalker H, editors. Advances in peanut science. Oklahoma: American Peanut Research Education Society, Inc.; 1995. p. 554–77.
- [21] FAO. Advances in Arachis genomics for peanut improvement. FAO, Food and Agricultural Organisation of the United Nation, FAO Statistical Database. 2009; p. 287.
- [22] Taru VB, Kyagya IZ, Mshelia SI, Adebayo EF. Economic efficiency of resource use in groundnut production in Adamawa State of Nigeria. *World J Agric Sci.* 2008;4(S):896–900.
- [23] Enwezor WO, Ohiri AC, Opuwaribo EE. A review of fertilizer uses on crops in South eastern zone of Nigeria. Department of fertilizer Procurement and Distribution. Fed Min Agric LRes Rural Dev. 1988;1:53–100.
- [24] Woodroof JG. Peanut production, processing and products. 3rd edn. Westport, Connecticut: Avi Publishing Company Inc.; 1983. p. 307–10.
- [25] Arslan M. Effects of haulm cutting time on haulm and pod yield of peanut. *J Agron.* 2005;4:39–43.
- [26] Ahmad N, Rahim M, Khan U. Evaluation of different varieties, seed rates and row spacing of groundnut, planted under agro-ecological conditions of Malakand division. *J Agron.* 2007;6:385–7.
- [27] Naab JB, Prasad PVV, Boote KJ, Jones JW. Response of peanut to fungicide and phosphorous in on-station and on-farm tests in Ghana. *Peanut Sci.* 2009;36:157–64.
- [28] Purseglove JW. Tropical crops: Dicotyledons. Essex, UK: Longman; 1968. p. 224–36.
- [29] Ntare BR, Waliyar F, Ramouch M, Ndjeunga J. Market prospects for groundnut in West Africa. Common funds for commodities; CFC Technical paper no. 39; 2004. p. 118.
- [30] Idinoba ME, Idinoba PA, Gbadegesin A, Jagtap SS. Growth and evapotranspiration of groundnut (*Arachis hypogaea*) in a transitional humid zone of Nigeria. *Afr J Agric Res.* 2008;3(5):384–8.
- [31] Filipovic D, Husnjak S, Kosutic S, Gospodaric Z. Effects of tillage systems on compaction and crop yield of Albic Luvisol in Croatia. *J Terramechanics.* 2006;43(2):177–89.
- [32] Emielu AJ. An evaluation of food crops farming inside old Cocoa Grooves. *Nigerian Agric J.* 1987;14(1):25–40.
- [33] Ojo AD, Sadiq I. Effect of climate change on cocoa yield: a case of Cocoa Research Institute Nigeria (CRIN) Farm, Oluoyole Local Government, Ibadan, Oyo State. *J Sustain Dev Afr.* 2010;12(1):350–8.
- [34] Smyth AJ, Montgomery DN. Soils and land use of Central Western Nigeria. 1st edn. Ibadan, Nigeria: Government Western Nigerian Press; 1962. p. 276.
- [35] McLean EO. Soil pH and lime requirement. In: Page et al., editors., Agronomy monogram 9. Methods of soil analysis. Part 2. Chemical and microbial properties. 2nd edn. Madison, WI: ASA and SSSA; 1982. p. 199–224.
- [36] Nelson DW, Sommers LE. Total carbon, organic carbon and organic matter. In: Page et al., editors., Agronomy monogram 9. Methods of Soil Analysis. Part 2. 2nd edn. Madison, WI: ASA and SSSA; 1982. p. 539–79.
- [37] Bremner JM, Mulvaney CS. Total nitrogen. In: Page et al., editors., Agronomy monogram 9. Methods of Soil Analysis. Part 2. 2nd edn. Madison, WI: ASA and SSSA; 1982. p. 895–926.
- [38] Olson SR, Sommers LE Phosphorus. In: Page et al., editors., Agronomy monogram 9. Methods of Soil Analysis. Part 2. 2nd edn. Madison, WI: ASA and SSSA; 1982. p. 403–34.
- [39] Rhodes JD. In: Page AL, editor., Cation exchange capacity methods of soil analysis, Part 2: chemical microbiological properties. 2nd edn. Madison, Wisconsin: American Society of Agronomy; 1982. p. 149–57.
- [40] Jackson ML. Soil chemical analysis. New York: Advance Course Prentice-Hall; 1970. p. 127–57.
- [41] Bouyoucos GJ. Hydrometer method improved for making particle size analysis of soils. *Agron J.* 1962;54:464–5.
- [42] Reynolds WD, Elrick DE, Young EG, Amoozegar A, Booltink HWG, Bouma J. Saturated and field-saturated water flow parameters. In: Dane JH, Topp GC, editors. Methods of soil analysis. Part 4. Physical methods. Madison, Wisconsin: Soil Science Society of America, Inc; 2002. p. 797–878.
- [43] Topp GC, Zebchuk W. The determination of soil water desorption curves for soil cores. *Can J Soil Sci.* 1979;59:155–62.
- [44] Oguike PC, Mbagwu JSC. Variations in some physical properties and organic matter content of soils of coastal plain sand under different land use types. *World J Agric Sci.* 2009;5:63–9.
- [45] Akpan-Idiok AU. Physicochemical properties, degradation rate and vulnerability potential of soils formed on coastal plain sands in Southeast, Nigeria. *Int J Agric Res.* 2012;7:358–66.
- [46] Lal R. Methods and guidelines for assessing sustainability use of soil and water resources in the tropics. *Soil Manag Support Serv Technical Monogr.* 1994;No. 21:1–78.

- [47] Enwezor WO, Ohiri AC, Opuwaribo EE, Udo EJ. Review of fertilizer use on crops in Southeastern Nigeria. Fertilizer Procure Distribution, Lagos, Niger. 1989;420.
- [48] Federal Ministry of Agriculture, Water Resources and Rural Development. Fertilizer use and Management Practices for Crops in Nigeria. Technical Bulletin Series. No. 2; 2011.
- [49] Juo ASR, Caldwell J, Kang BT. Place of alley cropping in sustainable agriculture in the tropics. Trans 15th Int Soil Sci Congr. 1994;7a:98–109.
- [50] FPDD. Literature review on soil fertility investigation in Nigeria. Lagos, Nigeria: Fertilizer Procurement and Distribution Division, Federal Ministry of Agriculture and Natural Resources; 1990. p. 163.
- [51] Lipiec J, Håkansson I, Tarkiewicz S, Kossowski J. Soil physical properties and growth of spring barley related to the degree of compactness of two soils. Soil Tillage Res. 1991;19:307–17.
- [52] Medvedev VV, Lyndina TE, Laktionova TN. Effect of running systems agricultural engineering on soil and plants. Proc. 2nd Int. Conf. on Subsoil Compaction. Gödöllo, Hungary; 29–31 May, 2000. p. 91–8.
- [53] Lipiec J, Medvedev VV, Birkas M, Dumitru E, Lyndina TE, Rousseva S, et al. Effect of soil compaction on root growth and crop yield in Central and Eastern Europe. Int Agrophysics. 2003;17:61–9.
- [54] Cassel DK, Raczkowski CW, Denton HP. Tillage effects on corn production and soil physical properties. Soil Sci Soc Am J. 1995;59:1436–43.
- [55] Griffith DR, Mannering JV, Box JE. Soil and moisture management with reduced tillage. In: Sprague MA, Triplett GB, editors. No tillage and surface tillage agriculture. New York, USA: Wiley; 1996. p. 19–57.
- [56] Anshebo T, Veerragavatham D, Kannan M. Genetic variability and correlation studies in sweet potato (*Ipomoea batatas* L. Lam.). Madras Agric J. 2004;91(7–12):420–4.
- [57] Kathabwalika DM, Chilembwe EHC, Mwale VM, Kambewa D, Njoloma JP. Plant growth and yield stability of orange fleshed sweet potato (*Ipomoea batatas*) genotypes in three agro-ecological zones of Malawi. Int Res J Agric Sci Soil Sci. 2013;3(11):383–92.
- [58] Ahmed M, Nigussie-Dechassa R, Abebie B. Effects of planting methods and vine harvesting on shoot and tuberous root yields of sweet potato (*Ipomoea batatas* (L.) Lam.) in the Afar region of Ethiopia. Afr J Agric Res. 2012;7(7):1129–41.
- [59] Kareem I. Effects of phosphorus fertilizer treatments on vegetative growth, tuberous yield and phosphorus uptake of sweet potato (*Ipomoea batatas*). Afr J Agric Res. 2013;8(22):2681–4.
- [60] Dauda A, Usman B. Effect of soil compaction and bulk density on the growth and yield of soybean (*Glycine max.*) on sandy clay loam soil of the semi-arid region of Northern Nigeria as influenced by tractor wheel traffic. J Agric Eco Res Int. 2019;18(1):1–6.