

**Root growth responses of maize (*Zea mays* L.)  
and soybean (*Glycine max* L.) to soil  
compaction and fertilization in a Ferric Acrisol**

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**ABSTRACT**

Mechanical impedance to root growth is one of the most important factors determining root elongation and proliferation within a soil profile. Two pot experiments were made at the Department of Horticulture, KNUST, Kumasi, Ghana, to determine the impact of subsurface compaction and different fertilizer amendments on the root growth of maize (*Zea mays* L.) and soybean (*Glycine max* L.). The experiments were arranged in a factorial Completely Randomized Design (CRD) with three replications. Maize and soybean were sown in 72 plastic buckets (36 for each crop) of 12 L volume filled with a Ferric Acrisol. The treatments were different levels of compaction, using bulk density as proxy – 1.3, 1.5 and 1.7 Mg m<sup>-3</sup>, and fertilizer amendments of 100% poultry manure (15 g/pot), 100% NPK fertilizer (2.89 g/pot) and 50% rate each of poultry manure (7.5 g/pot) and NPK fertilizer (1.45 g/pot). High soil compaction induced more root growth in the uncompacted soil and periphery of the soil core than the compacted zone. The applied soil amendments significantly increased the root penetration ratio (RPR) of both crops in relation to the control. The shoot biomass of both crops decreased with increasing soil bulk density. All the applied soil amendments significantly increased the shoot biomass of maize and soybean over the control. The magnitude response of the crops to the soil amendments was greater in soybean than in maize.

*Keywords: Maize, NPK fertilizer, Poultry manure, Soil compaction, Soybean*

**1. INTRODUCTION**

Soil compaction results from the physical consolidation of soil by an applied force. This consequently destroys the structure, reduces porosity, limits water and air infiltration, increases resistance to root penetration, and often results in reduced crop yield [1]. The processes of tillage induced soil compaction as outlined by [1 – 3] are as follows: (i) when soils are cultivated repeatedly at the same depth. The weight of the tillage equipment (discs, wheels or cultivator shovels) causes compression of the soil and smearing at the base of contact between the soil and tillage implement (ii) As soil particles are compressed, the pore space is reduced, thereby reducing the space available in the soil for air and water (iii) If the applied force is great enough, soil aggregates are destroyed (iv) The result is a dense soil with few large pores that has poor internal drainage and limited aeration.

The sensitivity of a given soil to compaction depends on the soil properties, mostly on texture, structure [4], moisture content and clay mineralogy. Accordingly, Défossez et al. [5] reported that the most important factor in making decisions about cultural operations is soil water due to its influence on soil compaction. Soil compaction may result from natural, as well as, human and animal induced processes. For instance, treading of wet soils by animals causes soil compaction [2, 6]; Human activities such as the use of agricultural machinery also induce compaction [7, 8]. The most yield limiting soil compaction is caused

32 by wheels from heavy equipment, particularly on wet soils [1]. Tillage induced compaction  
33 layer is mostly referred to as hardpan or plough pan and occurs just below the plough  
34 depth [3]. Soil compaction, especially in the subsoil layers may restrict deep root growth  
35 and plant access to subsoil water in the mid to late growing season when rainfall is usually  
36 sparse and evapotranspiration is high [3, 9]. Muhammad et al. [10] reported that the  
37 adverse effect of soil compaction on water flow and storage may be more serious than its  
38 direct effect on root growth. Root response to soil compaction depends on the presence  
39 and distribution patterns of pores having a diameter greater than the roots and on pore  
40 continuity; a soil matrix with larger pores are essential for optimal crop yields [11]. Soil  
41 compaction restricts root growth resulting in poor anchorage and susceptibility of plants to  
42 uprooting during grazing [12].

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44 Amelioration of soil compaction can be achieved through biological drilling in which root  
45 channels left by previous crops reduce the effects of subsoil compaction on subsequent crop  
46 root growth [9, 13, 14], no-tillage practice, [15], subsoiling [3, 12, 16, 17], cultivar  
47 improvement [18], and soil amendments [19]. These strategies have resulted in increased  
48 crop yields, although uncertainties regarding their application still remain. Addition of soil  
49 amendments increases the competitive advantage of the crop for nutrient uptake. This  
50 provides crops with the needed nutrients necessary for their growth and development, and  
51 reduces the limitations posed to root growth by compaction. The present study was thus,  
52 conducted to assess the effects of soil compaction and fertilization on the root growth and  
53 distribution of maize and soybean. The two crops were selected based on the fact that  
54 maize is the largest staple crop, while soybean is an emerging major crop in Ghana.  
55 Additionally, dicots (soybean) and monocots (maize) respond differently to the impact of soil  
56 compaction, hence the need and there is the need to investigate this phenomenon in  
57 Ghanaian soils.

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## 2. MATERIALS AND METHODS

### 60 2.1 Experimental set up and design

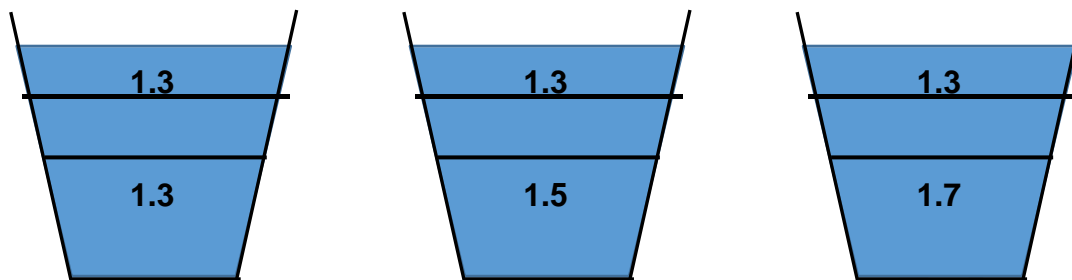
61 The study was conducted at the Department of Horticulture, Kwame Nkrumah University of  
62 Science and Technology (KNUST), Kumasi. The set up comprised two pot (12 L buckets)  
63 experiments with soil samples classified as Orthi-Ferric Acrisol [20] grown with maize and  
64 soybean. Each experiment was conducted with 36 buckets for maize and soybean. Each  
65 bucket was graduated at 2 L interval and had a surface area of 0.07 m<sup>2</sup>. Each bucket  
66 assembly consisted of a top 2 L space for watering, followed by a 2 L soil core (1.3 Mg m<sup>-3</sup>),  
67 and a bottom 8 L core for the 3 levels of compaction (1.3, 1.5 and 1.7 Mg m<sup>-3</sup>). The buckets  
68 had three drainage holes at the bottom, and were arranged on raised wooden platforms.  
69 Two different experiments were conducted with maize (*Zea mays* L.) and soybean (*Glycine*  
70 *max* L.) as test crops. Each experiment was a 3x4 factorial arranged in a Completely  
71 Randomized Design (CRD) with three replications. The treatments were soil at three  
72 compaction levels (i.e., bulk densities of 1.3, 1.5 and 1.7 Mg m<sup>-3</sup>), and four levels of fertilizer  
73 amendments: control (no fertilizer), 100% poultry manure (applied at 15 g/pot), 100%  
74 15:15:15 NPK fertilizer (applied at 2.89 g/pot) and ½ rate each of poultry manure and  
75 15:15:15 NPK fertilizer (applied at 7.5 g poultry manure + 1.45 g 15:15:15 NPK/pot).

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### 2.2 Soil compaction

78 The soil cores were packed at different bulk densities to give a two-layered core with the aid  
79 of a 2 kg metal block dropped from a height of 30 cm onto the soil surface overlaid with a  
80 wooden board. First, half of the required mass of air-dried soil was packed into the bottom 8  
81 L volume of the bucket. This was followed by overlaying the soil with a wooden board, and  
82 dropping a metal mass of 2 kg 5, 7 and 9 times to obtain the 1.3, 1.5 and 1.7 Mg m<sup>3</sup> bulk  
83 densities, respectively. The board was then removed and the rest of the soil was packed on  
84 top of the top half of the bucket. The soil was again covered with wooden board, the 2 kg

85 metal mass was dropped 8, 10 and 12 times for the 1.3, 1.5 and 1.7 Mg m<sup>-3</sup>, respectively. A  
86 2 L soil core with a bulk density of 1.3 Mg m<sup>-3</sup> was imposed over each of the bottom 8 L core  
87 using with two drops of the metal block. The mass of soil to attain the 1.3, 1.5 and 1.7 Mg m<sup>-3</sup>  
88 bulk densities were 10.4, 12.0 and 13.6 kg, respectively.  
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91 **Figure 1.** Preparation of buckets for the experiment

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### 93 **2.3 Planting**

94 Three seeds were sown per soil core assembly (i.e., pot). This was thinned to two seedlings  
95 per pot after 7 days. The maize and soybean varieties used were “Obaatampa” (an open  
96 pollinated variety) and “Anidaso”, respectively. Early on, germination test was conducted to  
97 determine seed viability of both crops. After sowing, water loss was estimated and  
98 compensated for by weighing every 2 days, and plants were watered using a watering can.  
99 Perforations were made at the bottom of each pot to facilitate drainage. The assemblies  
100 were then arranged on raised wooden platforms.  
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103 **Plate 1.** Experimental layout of maize under the different treatments

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107 **Plate 2.** Experimental layout of soybean under the different treatments

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109 **2.4 Application of soil amendments**

110 Mineral fertilizer N equivalent of 0.42 g was used as the basis for the amount of poultry  
 111 manure to apply. With an N content of 2.79 % in the poultry manure, this gave 15 g. The 15  
 112 g of poultry manure contained 2.79 % N, 0.95 % P and 3.46 % K, which supplied 0.42 g N,  
 113 0.32 g  $P_2O_5$  and 0.62 g  $K_2O$  per pot. Thus, the following quantities of soil amendments were  
 114 applied:

- 115 i. Control- no amendments
- 116 ii. 100 % NPK= 2.89 g 15:15:15 NPK fertilizer/pot
- 117 iii. 100 % NPK= 15 g Poultry manure/pot
- 118 iv.  $\frac{1}{2}$  Rate NPK +  $\frac{1}{2}$  Rate Poultry manure = 1.45 g 15:15:15 NPK + 7.5 g Poultry  
 119 manure/pot

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121 **2.5 Data collection and analyses**

122 **2.5.1 Root growth**

123 The roots in the soil cores were retrieved after washing off the soil over a nest sieves and  
 124 weighing the cleaned roots. The fresh root mass was obtained after cutting the soil core into  
 125 two, comprising a top layer of  $1.3 \text{ Mg m}^{-3}$  and the bottom layer of the compacted treatments.  
 126 The total fresh root mass comprised the roots in the top soil core (designated non  
 127 compacted  $1.3 \text{ Mg m}^{-3}$ ), the bottom core of the compacted treatments ( $1.3$ ,  $1.5$  and  $1.7 \text{ Mg}$   
 128  $\text{m}^{-3}$ ) and the roots that passed between the soil core and the bucket (i.e. roots along the soil  
 129 core). The latter was obtained by scrapping the roots along the soil core with a knife. The  
 130 dry mass was recorded by weighing after oven drying the sample at  $60^\circ\text{C}$  for 48 hours. The  
 131 relative root mass distribution (%) at the uncompacted zone, compacted zone and along the  
 132 soil column were determined by calculating the percentage in relation to the total root mass  
 133 (uncompacted layer + compacted layer + along the soil column). In relation to the effective  
 134 root biomass, only the roots at the uncompacted and compacted zones were considered.

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137 **Plate 3.** Inverted soil columns showing maize root growth at different soil bulk densities: A =  
138  $1.3 \text{ Mg m}^{-3}$ ; B =  $1.5 \text{ Mg m}^{-3}$ ; C =  $1.7 \text{ Mg m}^{-3}$

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#### 140 **2.5.2 Root penetration ratio**

141 Root penetration ratio (RPR) is defined as the number of roots that entered the compacted  
142 bottom core divided by the number of roots that exited the same core. The number of roots  
143 that entered the bottom core was obtained after using a sharp knife to separate the top layer  
144 of  $1.3 \text{ Mg m}^{-3}$  from the compacted bottom layer, staining the roots on top of the compacted  
145 layer with methylene blue and counting the roots with the aid of a hands lens. The  
146 compacted core was then turned upside down and the roots exiting the core counted after  
147 staining with methylene blue. For accuracy, the roots that passed between the compacted  
148 soil core from the top and the bucket were discarded. Only the roots that were found in the  
149 soil were counted and used for the calculation. The data collected were subjected to  
150 analysis of variance using GenStat statistical package (12th Edition). The Least significant  
151 difference (Lsd) at 5% was used to compare treatment means.

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### 153 **3. RESULTS AND DISCUSSION**

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#### **3.1 Root distribution**

155 The mean relative root biomass distribution of maize and soybean as affected by soil  
156 compaction are presented in Table 1. In maize, the relative root biomass distribution in the  
157 uncompacted soil layer ranged from 69.60 – 90.78% for the  $1.3$  and  $1.7 \text{ Mg m}^{-3}$ , respectively  
158 with a trend of  $1.7 > 1.5 > 1.3 \text{ Mg m}^{-3}$ . Increasing bulk density therefore resulted in more root  
159 biomass accumulation in the relatively loose top soil. The converse was true in the  
160 compacted soil cores with values between 9.22% for the  $1.7 \text{ Mg m}^{-3}$  and 30.40% for the  $1.3$   
161  $\text{Mg m}^{-3}$  in an order of  $1.3 > 1.5 > 1.7 \text{ Mg m}^{-3}$ . This implies less root accumulation in the  
162 compacted core as the bulk density of the compacted layer increased. These trends were  
163 similar for the soybean. The respective range of relative root biomass for the  $1.3$  and  $1.7 \text{ Mg}$   
164  $\text{m}^{-3}$  in the uncompacted and compacted soil was 69.59 – 90.77%, and 9.2 – 30.4%. The  
165 characteristic distribution of roots in compacted soil presented in this study has similarly  
166 been reported by [21, 22]. Chen and Weil [9] also observed greater root proliferation in the  
167 loose layer above the compacted layer for rapeseed and rye.

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170 **Table 1.** Relative root mass of maize and soybean in the uncompacted and compacted soil  
 171 layers

Bulk density (Mg m <sup>-3</sup> )	Maize		Soybean	
	Uncompacted layer	Compacted layer	Uncompacted layer	Compacted layer
1.3	69.60	30.40	69.59	30.41
1.5	72.36	2.71	72.40	27.60
1.7	90.78	9.22	90.77	9.22
<b>Amendment (g/pot)</b>				
Control	56.10	43.89	81.07	18.92
PM	58.57	41.42	74.25	25.74
NPK	68.17	31.82	78.88	21.11
½ PM + ½ NPK	62.75	37.24	76.81	23.18
<b>Lsd (%)</b>				
Bulk density	3.46	8.47	5.83	6.89
Amendment	3.21	1.76	1.88	1.32

172 Lsd = Least significant difference; PM = Poultry manure

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 174 This pattern of root biomass distribution is ascribed mainly to the magnitude of mechanical  
 175 impedance in the soil. When soils are compacted, the bulk density is increased and the  
 176 number of larger pores is reduced while smaller pores increase. In such situations, the  
 177 forces of roots necessary for deformation and displacement of soil particles for root  
 178 proliferation increase and readily become limiting with a consequent reduction in root  
 179 growth. There is also a tendency of roots to grow horizontally/laterally in the uncompacted  
 180 layer above the compacted soil core [1]. As shown in several studies [e.g. 1, 9, 21, 23], the  
 181 observed greater root biomass in the uncompacted than compacted soil in this study could  
 182 be the result of as a compensatory response to the increased mechanical impedance and  
 183 reduced total porosity and aeration porosity associated with compaction of the soil core. The  
 184 results further lend credence to the observation of Materechera et al. [24, 25] that monocot  
 185 and dicot species respond differently to changes in soil with dicots being better in  
 186 penetrating compacted soil than monocots. Thus, as indicated earlier, total effective root  
 187 biomass was more sensitive in maize than soybean to increases in soil compaction with the  
 188 reduction in the effective root biomass at 1.3 Mg m<sup>-3</sup> being 50 and 59% at 1.5 and 1.7 Mg m<sup>-3</sup>  
 189 <sup>3</sup>, respectively with the corresponding figures for soybean as 22 and 14%.

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 191 Effective root biomass of maize was also more responsive to soil amendments with the  
 192 percentage increases over the control (no amendment) being 42, 43 and 62 under PM, ½  
 193 PM + ½ NPK and NPK, respectively. The corresponding values for soybean were 37, 38 and  
 194 53%. Besides these observations, the results revealed variable impacts of soil amendments  
 195 on total effective root biomass (compacted + uncompacted root biomass) and their  
 196 distribution in the compacted and uncompacted layers. While all the soil amendments  
 197 increased effective root biomass at each level of soil compaction over the control (Table 2),  
 198 variable impacts were recorded in the case of relative root biomass distribution. In maize,  
 199 while relative root biomass in the uncompacted soil was increased over that of the control, it  
 200 was reduced in the compacted soil. The increases were 4, 11 and 18% under PM, ½ PM +  
 201 ½ NPK and NPK, respectively, with corresponding reductions of 6, 15 and 27%. Implicitly,  
 202 the decrease in the relative root biomass in the compacted soil core was compensated for  
 203 by the increased fibrous roots in the uncompacted layer. In the case of soybean, although  
 204 the relative root biomass accumulation in the uncompacted soil was relatively greater than  
 205 that of maize, the application of soil amendments tended to slightly decrease the relative  
 206 root biomass over that of the control. The percentage reduction was 3, 5 and 8% under

207 NPK,  $\frac{1}{2}$  PM +  $\frac{1}{2}$  NPK and PM respectively. The corresponding increases in the compacted  
208 core were 10, 18 and 27%. The variable characteristic distribution of different rooting  
209 systems (fibrous and tap root for maize and soybean) in the soil profile and their response to  
210 soil compaction, nutrient and water uptake could have accounted for the observed  
211 differences in the relative root biomass distribution in the compacted and uncompacted soil.  
212 In the presence of only one compacted layer, as may occur under conventional tillage and  
213 simulated in this study, a reduction in root growth in the compacted zone is often  
214 compensated for by higher growth rates in loose soil above or below the compacted zone  
215 [21]. Detailed examination of the relative root distribution (Table 1) under the various soil  
216 amendments showed that in the uncompacted top layer, roots were greater under NPK than  
217 poultry manure for Maize. Thus, potential nutrient and water uptake for metabolic activities  
218 and stem elongation would be expected to be greater under NPK than PM. Generally, the  
219 relative root distribution of soybean in the uncompacted top layer was greater than maize  
220 under all the treatments.

### 221 **3.2 Root restriction**

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223 The results of the impact of soil compaction on the peripheral root distribution along the soil  
224 core are presented in Table 2 for both maize and soybean. The peripheral relative root  
225 biomass for maize ranged from 27.70 – 39.22% in the order of  $1.7 < 1.3 < 1.5 \text{ Mg m}^{-3}$ . The  
226 same trend was observed in soybean with the values ranging between 40.40 and 43.56%.  
227 The peripheral root distribution increased as bulk density increased from  $1.3 \text{ Mg m}^{-3} - 1.5$   
228  $\text{Mg m}^{-3}$  and declined at  $1.7 \text{ Mg m}^{-3}$ . The peripheral root biomass was greater in soybean  
229 than in maize. The response of the soybean to soil compaction was to induce more root  
230 growth in the uncompacted soil and periphery of the soil core than the compacted zone. The  
231 same trend, nonetheless, was observed in maize, except that the magnitude was greater in  
232 soybean. With regard to the soil amendments, the peripheral relative root biomass for maize  
233 ranged from 28.96 to 42.72% in the increasing order of  $\frac{1}{2}$  PM +  $\frac{1}{2}$  NPK < NPK < PM <  
234 control and 34.24 to 49.60% in the NPK <  $\frac{1}{2}$  PM +  $\frac{1}{2}$  NPK < control < PM for both maize  
235 and soybean, respectively. In maize the highest peripheral relative root biomass was  
236 recorded by the control where no soil amendment was applied and the least value was  
237 recorded by  $\frac{1}{2}$  PMx  $\frac{1}{2}$  NPK (Table 2). This indicates the importance of soil amendments in  
238 enhancing the magnitude of effective roots. Also, the synergistic effect of both organic and  
239 inorganic amendment was evident as  $\frac{1}{2}$  PM +  $\frac{1}{2}$  NPK performed better than the sole  
240 amendments. In soybean, the sole NPK amendment recorded the least value of the  
241 peripheral relative root distribution, this also indicates that most of the effective roots  
242 produced under the sole NPK penetrated both the compacted and the uncompacted layer.

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**Table 2.** Relative root mass of maize and soybean as affected by soil compaction

Bulk density (Mg m <sup>-3</sup> )	Maize			Soybean		
	UL (%)	CL (%)	PSC. (%)	UL (%)	CL (%)	PSC (%)
1.3	43.94	24.21	31.84	39.46	17.24	43.33
1.5	37.84	22.94	39.22	40.89	15.59	43.56
1.7	42.91	29.32	27.70	54.08	5.50	40.40
<b>Amendments (g/pot)</b>						
Control	32.11	25.12	42.72	42.11	9.83	48.08
PM	38.34	27.12	34.52	56.22	19.49	49.60
NPK	47.36	22.11	30.52	35.93	9.62	34.24
½ PM + ½ NPK	44.57	26.45	28.96	45.10	13.61	41.32
<b>†Interactions</b>						
Control x 1.3	27.29	22.78	49.94	-	-	-
Control x 1.5	28.81	25.05	46.10	-	-	-
Control x 1.7	49.25	30.59	20.15	-	-	-
NPK x 1.3	50.69	20.69	28.60	-	-	-
NPK x 1.5	44.41	20.23	35.21	-	-	-
NPK x 1.7	41.97	29.82	28.92	-	-	-
PM x 1.3	42.77	26.57	30.64	-	-	-
PM x 1.5	28.86	24.29	47.23	-	-	-
PM x 1.7	39.28	33.47	27.23	-	-	-
½ PM + ½ NPK x 1.3	44.62	28.18	27.18	-	-	-
½ PM + ½ NPK x 1.5	45.92	23.77	30.29	-	-	-
½ PM + ½ NPK x 1.7	43.05	24.39	39.98	-	-	-
<b>Lsd (5%)</b>						
Bulk density	3.21	2.14	2.46	3.02	1.78	1.11
Amendments	2.37	2.22	2.53	3.41	4.35	2.41
†Interactions	3.11	2.71	2.65	ns	ns	ns

264 †Amendment x Bulk density interactions; BD = Bulk density; PM = Poultry manure; UL =  
265 Uncompacted layer; CL = Compacted layer; PSC. = periphery of soil core  
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267 The compaction x soil amendment interaction in maize (Table 2) revealed a tendency of the  
268 soil amendments (except ½ PM + ½ NPK fertilizer) to decrease peripheral root growth at 1.3  
269 and 1.5 Mg m<sup>-3</sup> and an increase at 1.7 Mg m<sup>-3</sup>. The ½ PM + ½ NPK fertilizer increased the  
270 peripheral root biomass of maize as soil compaction levels increased. Implicitly, the values  
271 of the peripheral root biomass represent the proportion of the total root mass presenting  
272 ineffective root surfaces for nutrient and water uptake which obviously would constrain shoot  
273 growth and biomass yield. These confounding impacts are often neglected in most pot  
274 experiments, yet they are important in the interpretation of results and potential extrapolation  
275 to field conditions. An additional observation in this study was the accumulation of loose  
276 roots at the base of the soil core, apparently originating from the peripheral root growth.  
277 These are indicative of root volume restriction (“bonsai” effect) which tends to inhibit shoot  
278 growth caused by limited nutrients and water supply to the shoots with the magnitude of  
279 reduction in root and shoot dry matter increasing with decreasing pot size. However, in pot  
280 experiments, as in this study, the growth is through the unrestrictive path encounter of roots  
281 with impeding soil compacted layers results not only in the restrictive root growth and  
282 oxygen supply, but induced counter root responses. Apart from growing and spreading  
283 horizontally in the loose soil above the compacted zone which deprives them of the full use



284 of moisture and nutrients in the deeper layer, roots tend to follow tortuous paths in search of  
 285 least resistant paths [11 ,26]. In the field, growth is through available larger interaggregate  
 286 and biopores greater than root diameter [14].

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### 3.3 Root penetration ratio

289 The results of the impact of soil compaction and soil amendments and their interactions are  
 290 presented in Table 3. The effect of soil compaction showed a general decrease in root  
 291 penetration ratio (RPR) with increasing bulk density. At a base of 0.33, RPR of maize was  
 292 reduced by 12% at 1.5 Mg m<sup>-3</sup> and 9% at 1.7 Mg m<sup>-3</sup>. With values ranging from 0.29 to 0.33,  
 293 the differences were not significant (*P* = .05). In the case of soybean RPR varied from 0.14  
 294 to 0.31 for the 1.7 and 1.3 Mg m<sup>-3</sup>, respectively. While there was no significant difference in  
 295 the values at 1.3 and 1.5 Mg m<sup>-3</sup>, values for the latter were significantly greater than those  
 296 for 1.7 Mg m<sup>-3</sup>. The percentage reduction in RPR at 1.7 Mg m<sup>-3</sup> was 13 and 55% compared  
 297 to those at 1.5 and 1.3 Mg m<sup>-3</sup>, respectively. These results indicated that the impact of soil  
 298 compaction on root proliferation was more severe on soybean than maize.

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**Table 3.** Root penetration ratio of maize and soybean in the different soil layers

Bulk density (Mg m <sup>-3</sup> )	Penetration ratio	
	Maize	Soybean
1.3	0.33	0.31
1.5	0.29	0.27
1.7	0.30	0.14
<b>Amendments (g/pot)</b>		
Control	0.22	0.14
Poultry manure	0.30	0.26
NPK fertilizer	0.39	0.28
½ Poultry Manure + ½ NPK Fertilizer	0.31	0.28
<b>†Interactions</b>		
Control x 1.3	0.27	-
Control x 1.5	0.23	-
Control x 1.7	0.15	-
NPK Fertilizer x 1.3	0.33	-
NPK Fertilizer x 1.5	0.42	-
NPK Fertilizer x 1.7	0.33	-
PM x 1.3	0.30	-
PM x 1.5	0.20	-
PM x 1.7	0.40	-
½ PM + ½ NPK fertilizer x 1.3	0.33	-
½ PM + ½ NPK fertilizer x 1.5	0.30	-
½ PM + ½ NPK fertilizer x 1.7	0.30	-
<b>Lsd (5%)</b>		
Bulk density	0.06	0.06
Amendments	0.07	0.07
†Interactions	0.13	ns

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 302  
 303  
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Lsd = Least significant difference; †Amendment x Bulk density interactions

One of the most important factors which affects roots penetration is soil bulk density [27]. High bulk densities adversely affects roots elongation and proliferation within a soil profile

305 [26]. At the higher bulk density,  $1.7 \text{ Mg m}^{-3}$ , the soil became so dense that root penetration  
306 through the compacted zone was impeded. Thus, fewer roots were able to exit the  
307 compacted soil core. This is not surprising since in sandy loams, as was used in this  
308 experiment, bulk densities in the range of 1.6 and  $1.8 \text{ Mg m}^{-3}$  restrict root penetration [28].  
309 According to NRC [29], when the bulk density of soil increase to a critical level, root  
310 penetration is restricted and root growth is reduced. Beyond the critical level, roots are  
311 unable to penetrate the soil and root growth is prevented. These changes affect the  
312 productivity of the plant and can lead to lower yield and/or higher cost of production. At the  
313 bulk density of  $1.7 \text{ Mg m}^{-3}$ , the maize and soybean were stunted and drought stressed.  
314 Limited root penetration on compacted soil have been found to aggravate the effects of  
315 drought in reducing soybean yield [30]. According to Marschner [21], for a given soil bulk  
316 density, the mechanical impedance increases as the soil dries. This is due to increased  
317 particle mobility indicating an increase in the forces required to displace and deform soil  
318 particles, and resultant suppression of root elongation. This, in turn, could restrict water and  
319 nutrient uptake and poor plant growth and yield.

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321 The impact of soil amendments was an increase in RPR over the control. The adverse  
322 impact of soil compaction was therefore ameliorated by the application of soil amendments.  
323 In the case of maize, RPR ranged from 0.22 to 0.39 with a decreasing trend of  $\text{NPK} > \frac{1}{2} \text{ PM}$   
324  $+ \frac{1}{2} \text{ NPK} > \text{ PM} > \text{ control}$ . NPK recorded significantly ( $P = .05$ ) greater RPR than all other  
325 amendments and the Control with a percentage increase over the latter being 46%. The  
326 RPR of the PM and  $\frac{1}{2} \text{ PM} + \frac{1}{2} \text{ NPK}$  were also significantly ( $P = .05$ ) greater than the control  
327 with increment in the range of 27-29%. In soybean, RPR varied between 0.14 and 0.28 in  
328 the order of  $\text{NPK} = \frac{1}{2} \text{ PM} + \frac{1}{2} \text{ NPK} > \text{ PM} > \text{ control}$ . However, the RPR of all the  
329 amendments did not differ significantly ( $P > .05$ ) from each other but were significantly  
330 greater than the Control with an increment of 46-50%. The compaction x amendments  
331 interaction significantly ( $P = .05$ ) influenced RPR of maize but not soybean. At each level of  
332 compaction, each of the soil amendments improved RPR but more so by NPK. The addition  
333 of soil amendments provided readily available nutrients to the roots thereby improving root  
334 growth and vigour for enhanced penetration of the compacted soil. Under such conditions,  
335 uptake of water and nutrients is also improved for the benefit of shoot growth and biomass  
336 yield.

#### 337 4. CONCLUSION

339 Increasing soil compaction resulted in the accumulation of most of the root biomass in the  
340 uncompacted soil above the compacted layer. The addition of soil amendments increased  
341 the relative root biomass of maize in the uncompacted soil while that in the compacted soil  
342 where reduced. In the case of soybean, although the relative root biomass accumulated in  
343 the uncompacted soil was relatively greater than that of maize, the application of soil  
344 amendments tended to slightly decrease the relative root biomass over that of the control.  
345 High soil compaction induced more root growth in the uncompacted soil and the periphery of  
346 the soil core than the compacted zone. The peripheral relative root biomass was greater in  
347 soybean than in maize according to the trend, with highest production in the  $1.3 \text{ Mg m}^{-3}$  soil  
348 layer. Application of soil amendments reduced the peripheral relative root biomass of both  
349 crops. In maize, the least peripheral relative root biomass was recorded by the  $\frac{1}{2} \text{ PM} \times \frac{1}{2}$   
350 NPK while the sole NPK amendment recorded the least peripheral relative root distribution  
351 in soybean. The results showed soil compaction and amendments, as well as their  
352 interaction, to distinctly influence the roots distribution of maize and soybean. The impact of  
353 increasing soil compaction on both crops was manifested in a greater accumulation of root  
354 biomass in the top uncompacted soil than the compacted soil cores.

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#### **COMPETING INTERESTS**

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Authors have declared that no competing interests exist.

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#### **AUTHORS' CONTRIBUTIONS**

439

This work was carried out in group effort by all authors. Authors CQ, SIB, AA, and HOT  
440 designed the study and wrote the protocol. Authors SIB, AA, HOT, CQ and CM conducted  
441 the study, generated and analyzed the data. Authors SIB, AA, HOT and CQ prepared the  
442 manuscript. Authors SIB, AAA, HOT and CM managed the literature searches. All authors  
443 reviewed the pre-submission draft, read and approved the final manuscript.