Original Research Article

Soil compaction and soil amendments on the growth and biomass yield of maize (*Zea mays* L.) and soybean (*Glycine max* L.)

ABSTRACT

Two factorial pot experiments arranged in a Completely Randomised Design (CRD) with three replications were carried out to assess the impact of different levels of soil compaction and fertilizer amendments on root growth and biomass yield of maize (*Zea mays* L.) and soybean (*Glycine max* L.) plants. The treatments were different rates of bulk densities – 1.3, 1.5 and 1.7 Mg m^{-3} and fertilizer amendments of 100% poultry manure (applied at 15 g/plant), 100% 15:15:15 NPK fertilizer (applied at 2.89 g/plant) and 50% rate each of poultry manure and NPK fertilizer (applied at 7.5 g poultry manure + 1.45 g NPK/plant), and control (no fertilizer amendments). Soil compaction reduced plant heights of maize and soybean plants. Increasing soil compaction resulted in the accumulation of most of the root biomass in the uncompacted soil above the compacted layer. Addition of soil amendments increased the relative root biomass of maize plants in the uncompacted soil, while that in the compacted soil was reduced. In the case of soybean plants, although the relative root biomass in the uncompacted soil was relatively greater than that of maize plants, application of soil amendments tended to slightly decrease the relative root biomass over that of 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 plants over the control. The magnitude response of the crops to the soil amendments was greater in soybean than in maize plants. Soil compaction and amendments significantly influenced root/shoot ratio of both crops. At the bulk density 1.3 to 1.5 Mg m^{-3}, the root/shoot ratio decreased with increasing compaction. Beyond the bulk density of 1.5 to 1.7 Mg m^{-3}, the root/shoot ratio increased with increasing soil compaction. The fertilizer amendments applied significantly influenced the root/shoot ratio of maize but not soybean plants. The fertilizer amendments increased the biomass of both root and shoot but more so in the former than the later. The fertilizer amendments x compaction interactions showed that the root/shoot ratio was influenced by the type of crop, and the confounding effects of factor interactions on the relative increases/decreases in shoot and root growth. Overall, soil compaction accounted for 52 to 100% of the variations in the magnitude of the measured parameters of maize plants, and 62 to 98% for soybean plants. The ideal bulk density for shoot biomass production of both crops should, therefore, be within the range of 1.3 – 1.5 Mg m^{-3}. At soil bulk density of 1.5 Mg m^{-3} and above, soil amendment should be added to ameliorate the negative impact of soil compaction.

Keywords: Fodder, maize, poultry manure, root/shoot biomass ratio, soil compaction, soybean

1. INTRODUCTION

The urgent need to feed the increasingly growing populations worldwide calls for farmer motivation, especially in Sub-Saharan Africa. In Ghana, for instance, farmers are provided with inputs such as machinery (mainly tractors), fertilizers and improved seeds. This is to ensure a paradigm shift from the use of simple farming tools such as the hoes and cutlasses to mechanized farming. This invariably shortens the time needed to cultivate the soil and subsequently solves the problems associated with inadequate farm labour. Although tractor mounted implements ensure efficiency on farms, indiscriminate use may cause physical degradation of the land with soil compaction being a major problem. Soil compaction caused by heavy machinery with high inflation pressure of the tires on wet soils happens mostly during soil tillage [1]. It results in reduced soil porosity, high soil bulk density and root penetration resistance [2 – 4]. These impede germination, seedling emergence, root and shoot growth and crop yield as a result of reduced soil fertility, aeration, hydraulic properties and, water and nutrient uptake [5 – 8]. It must, however, be emphasized that soil compaction in agricultural fields are not only attributed to tractor mounted implements. Grazing animals and anthropogenic activities are also contributing factors. Texture, moisture, structure and initial bulk density are soil factors which affect plants' response to compaction [9].

Currently, considerable attention is being paid to soil physical properties which may possibly inhibit the growth and development of roots and seedlings of crops in the field. This is due to the fact that problems associated with soil compaction are becoming more severe as the use of bigger and heavier farm machinery is promoted. According to Oldeman *et al*. [10], about 18 million hectares of lands in Africa has been degraded by compaction resulting in sealing and crusting of soil. Increasing the productivity of these lands will require the amelioration of soil compaction for prolific crop growth and yield. The study of root tolerance to soil compaction particularly under different soil amendments in the field where environmental conditions cannot be controlled is difficult, expensive and time consuming. Therefore, studies have been carried out in fairly controlled environments to facilitate the choice of interventions to adopt in order to deal with the problem of soil compaction. In the field, this approach is time consuming and very expensive. Controlled experiments in the laboratory, however, offer a good opportunity in the screening of crop genotypes for tolerance to soil compaction [11]. While much is known about the negative effects of soil compaction on the growth and yield of many crops, the impact of combined soil amendments and compaction caused by conventional tillage has not been extensively researched [12]. Furthermore, the use of soil amendments to reduce the adverse impact of soil compaction on root growth has received less research attention. It is in the light of these research gaps that this study was carried out to contribute to the much needed information and knowledge on the impact of soil amendments in enhancing root growth and tolerance to soil compaction for sustained crop growth and yield.

2. MATERIALS AND METHODS

2.1 Experimental set up and design

Two pot experiments were conducted at the Department of Horticulture, Kwame Nkrumah University of Science and Technology (KNUST), Kumasi. Soil samples, classified as Orthi-Ferric Acrisol [13] were collected from a depth of 0 – 40 cm from the Plantations Section of the Department of Crop and Soil Sciences, KNUST. A total of 72 12 L volume plastic buckets were used for the experiment; 36 buckets each for maize and soybean plants. Each bucket was graduated at 2 L interval and had a surface area of 0.07 m^2. Each bucket assembly consisted of a top 2 L space for watering, followed by a 2 L soil core (1.3 Mg m^{-3}), and a bottom 8 L core for the 3 levels of compaction (1.3, 1.5 and 1.7 Mg m^{-3}). The buckets had three drainage holes at the bottom, and were arranged on raised wooden platforms.

2.2 Soil compaction

In order to obtain and replicate the desired bulk densities, it was necessary to standardize the method of packing of the soil into the bucket. The volume of the bucket was obtained from the litre graduations (2 L intervals) of the buckets. The soil cores were packed to the various bulk densities by dropping a 2 kg metal block from a height of 30 cm onto the soil surface which was completely shielded by a wooden board. For the bulk densities of 1.3, 1.5 and 1.7 Mg m^{-3}, half of the requisite air-dried soil was packed into the bottom 8 L volume of the bucket covered with a wooden shield and the metal mass dropped 5, 7 and 9 times respectively. The shield was then removed and the rest of the soil packed onto the first half using the wooden shelve and the metal mass and drops of 8, 10 and 12 times for the 1.3, 1.5 and 1.7 Mg m^{-3}, respectively (Figure 1). The 2 L soil core with a bulk density of 1.3 Mg m^{-3} was imposed over each of the bottom 8 L core using the shield and two drops of the metal block. The mass of soil to attain the 1.3, 1.5 and 1.7 Mg m^{-3} bulk densities was 10.4, 12.0 and 13.6 kg, respectively.

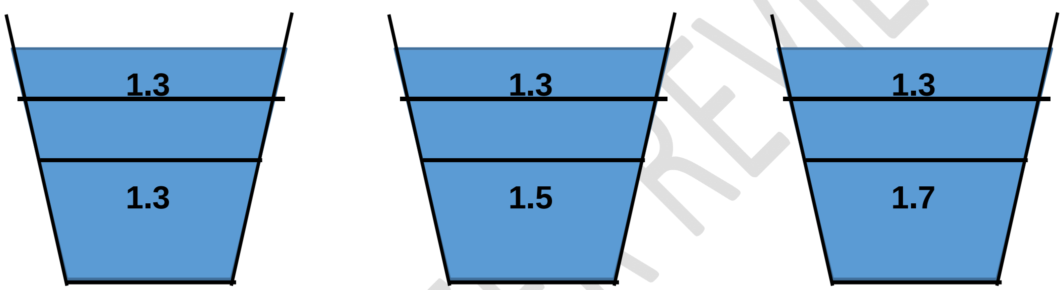

Figure 1. Preparation of buckets for the experiment

2.3 Preparation of pots for plants and planting

Each layered pot comprised a top 2 L space for watering, a middle 2 L soil of 1.3 Mg m^{-3}, and a bottom 8 L soil for the different compaction levels (i.e., 1.3, 1.5, and 1.7 Mg m^{-3}) (Figure 1). Three seeds were sown per pot. This was thinned to two seedlings per pot after 7 days. Early on, germination test was conducted on the maize and the soybean to determine viability. After sowing; water loss was estimated and compensated for by weighing every 2 days, and plants were watered using a watering can. The buckets had three drainage holes at the bottom and arranged on raised wooden platforms (Plates 1 and 2).

Plate 1. Maize plants at 4 weeks after planting under different compaction levels

Plate 2. Soybean plants at 4 weeks after planting under different compaction levels

The maize (*Zea mays* L.) and soybean (*Glycine max* L.) varieties used as test crops were "Obaatanpa" (an open pollinated variety) and "Anidaso", respectively. Each experiment was a 3×4 factorial arranged in a Completely Randomized Design (CRD) with three replications. The treatments were soil at three compaction levels (i.e., bulk densities of 1.3, 1.5 and 1.7 Mg m^{-3}), and four levels of fertilizer amendments: control (no fertilizer), 100% or sole poultry manure (applied at 15 g/plant), 100% or sole 15:15:15 NPK fertilizer (applied at 2.89 g/plant) and 50% each of poultry manure and 15:15:15 NPK fertilizer (applied at 7.5 g poultry manure/plant + 1.45 g 15:15:15 NPK/plant). A summarized description of the physicochemical properties of the soil and manure is presented in Table 1.

Table 1. Physicochemical properties of soil and poultry manure

Property	Soil	Poultry manure
Organic carbon (%)	1.20	33.92
Total N (%)	0.06	2.79
*P	10.25	0.95
K (%)	1.10	3.46
C/N ratio	20.00	12.16
pH (1:1 H_2O)	4.02	8.50
Ca (cmol/kg)	10.40	8.74
Mg (cmol/kg)	2.60	1.46
Na (cmol/kg)	0.80	2.03
Sand (%)	61.23	0.33
Silt (%)	27.64	-
Clay (%)	11.13	-
Texture	Sandy loam	-

*P = Available P in soil (mg/kg) and total P in manure (%)

2.4 Data collection and analyses

2.4.1 Shoot and root growth

A tape measure was used to measure plant heights at 2 weeks' interval until harvesting at 60 days after planting. Plant shoot samples were cut at the soil surface level, and the samples were oven-dried at 105°C for 30 minutes to destroy the tissues. They were later dried at 80°C until the weight was constant, and were weighed for the dry shoot mass. The fresh root mass was obtained after cutting the soil core into two, comprising a top layer of 1.3 Mg m^{-3} and the bottom layer of the compacted treatments. The total fresh root mass comprised the roots in the top soil core (designated non compacted 1.3 Mg m^{-3}), the bottom core of the compacted treatments (1.3, 1.5. and 1.7 Mg m^{-3}) and the roots that passed between the soil core and the bucket (i.e. roots along the soil core). The latter was obtained by scrapping the roots along the soil core with a knife. The roots in the soil cores were retrieved after washing off the soil over a nest sieves and weighing the cleaned roots. The dry mass was recorded by weighing after oven drying the sample at 60°C for 48 hours.

2.4.2 Nutrient uptake

Plant shoot root samples were cut at the soil surface level, while fresh roots were obtained by cutting the soil cores into two (i.e., a top layer of 1.3 Mg m^{-3} and the bottom compacted layers). Thus, the total fresh roots comprised the roots in the top soil core (i.e., uncompacted 1.3 Mg m^{-3}), the bottom core of the compacted layers, and roots along the peripheries of the soil core. The roots were retrieved by washing off the soil over nested sieves, and weighing the washed roots. Both shoot and root samples were oven dried at 60°C for 48 hours, to constant weight. The samples were then weighed, shredded, sub-sampled and milled into fine powder in a stainless steel puck mill. Milled plant materials were analysed for N, P and K contents by standard procedures.

2.4.3 Statistical analysis

The data collected were subjected to analysis of variance using GenStat statistical package (12th Edition). The Least significant difference (Lsd) at 5% was used to compare treatment means.

3. RESULTS AND DISCUSSION

3.1 Plant height

The analysis of variance showed soil compaction and amendments to significantly (*P* = .05) influence the plant height of maize and soybean plants (Table 2). Plant height used as an indicator of growth of both crops, generally followed the normal growth curve of plants with time, increasing from 7 to 60 days after planting (DAP) at which time the study was terminated. The productivity of soil depends not only on its physical properties but chemical and biological properties. The application of mineral fertilizers and poultry manure significantly (*P* = *.05*) increased the height of both maize and soybean plants (Table 2). The interaction effect of soil compaction and fertilizer amendments (*P* = *.05*) was significant on the height of maize plants, but not soybean plants.

Table 2. Impacts of soil compaction and fertilizer amendments on the plant height of maize and soybean plants

Bulk density (Mg m^{-3})	**Plant height (cm)**	
	Maize	**Soybean**
1.3	124.92	45.50
1.5	99.58	38.67
1.7	76.83	31.83
Lsd (5%)	4.05	1.74
Soil amendment (g/plant)		
Control	97.00	33.11
Sole PM	100.67	42.00
Sole NPK	105.33	38.11
50% PM + 50% NPK	98.78	41.44
Lsd (5%)	4.68	2.01
[†]Interaction		
Control x 1.3	123.67	
Control x 1.5	90.33	
Control x 1.7	77.00	
Sole NPK x 1.3	132.00	
Sole NPK x 1.5	110.67	
Sole NPK x 1.7	73.33	
Sole PM x 1.3	122.67	
Sole PM x 1.5	100.67	
Sole PM x 1.7	78.67	
50% PM + 50% NPK x 1.3	121.33	
50% PM + 50% NPK x 1.5	96.67	
50% PM + 50% NPK x 1.7	78.33	
Lsd (5%)	8.10	

Lsd = Least significant difference; PM = Sole poultry manure; [†]Soil amendment x Bulk density interaction

The mean height at harvest ranged from 76.83 – 124.92 cm under bulk density of 1.7 and 1.3 Mg m^{-3}, respectively. The corresponding values for soybean plants were 31.83 and 45.50 cm. In all cases the differences among the 3 levels of bulk density were significant (*P* = *.05*). A comparison of plant height at 1.3 Mg m^{-3} as base value, showed a progressive reduction of 20 and 38% for maize plants and 15 and 30% for soybean plants at 1.5 and 1.7 Mg m^{-3}, respectively. Between the latter two bulk densities, plant height reduction was 23 and 18% for maize and soybean plants, respectively. Muhammad et al. [14] observed that plant height is a genetic characteristic which is modified by environmental factors at the active growth stages. The results have indicated that increasing soil compaction significantly (*P* = *.05*) reduced the height of maize and soybean plants, with the former being more sensitive than the latter to compaction. The reduction in plant height could be due to factors that limited cell elongation which include impedance to root growth, poor soil aeration and low water and nutrient uptake as similarly reported by several authors [11, 15].

The plant height of maize plants (Table 2) followed the trend of sole NPK > sole PM > 50% PM + 50% NPK > control with a range of 97 to 105 cm under control, and sole NPK, respectively. The differences between sole NPK, and both the control, and 50% PM + 50% NPK were significant, as well as, that between the control and poultry manure. However, the height difference between poultry manure and both half rates (integrated application) and NPK were not significant. In the latter, the sole NPK produced the tallest plant in contrast to sole PM in the former. Plant height of soybean plants was thus in the order of PM > 50% PM + 50% NPK > sole NPK > control with a range of 33.11 – 42.00 cm for the control and sole PM respectively. Significant differences (*P* = *.05*) were observed between the control and all the soil amendments; and between sole PM and both sole NPK and the half rates. The results as presented showed that soil fertility improvement through mineral fertilizer and poultry manure application is essential for the growth of the test crops and a better expression of their potential genetic height. Under these conditions, more nutrients are made available for uptake and for the needed metabolic activities for cell elongation and growth. Application of soil amendments at all levels of soil compaction tended to enhance plant height relative to compacted soil without amendments. The plant height of both crops at soil bulk density of 1.3 and 1.5 Mg m^{-3} was ameliorated more under sole NPK than sole PM and 50% PM + 50% NPK. However, at 1.7 Mg m^{-3}, the latter treatments were more effective than sole NPK. The beneficial effects of organic matter on soil physical properties, such as bulk density and porosity may be implicated in these observations.

3.2 Dry shoot biomass yield

Soil compaction significantly (*P* = *.05*) influenced the shoot biomass of maize and soybean plants (Table 3). In the case of maize plants, shoot biomass ranked as 1.3 > 1.5 > 1.7 Mg m^{-3} with a range of 69.95 – 115 g/plant for the 1.7 and 1.3 Mg m^{-3}, respectively. The difference among the treatments were significant (*P* = *.05*). All the soil amendments significantly increased the shoot biomass of maize and soybean plants over the control. Shoot biomass of maize plants ranged from 78.43 and 109.05 g/plant for the control and sole NPK, respectively with a trend of sole NPK > 50% PM+ 50% NPK > sole PM > control. In all cases, the differences among the treatments were significant (*P* < .05). The increase of shoot biomass over the control were 28, 18 and 10% under sole NPK, 50% PM+ 50% NPK, and sole PM, respectively. The shoot biomass of soybean plants followed the same trend as maize plants with yield ranging between 35.56 and 67.91 g/plant. Yield increments over the control were 48, 41 and 28% under sole NPK, 50% PM+ 50% NPK, and PM, respectively. The magnitude of response to soil amendments was greater in soybean plants than in maize plants. The soil compaction x amendments interaction significantly influenced shoot biomass yield of maize and soybean plants. It revealed the magnitude of the soil amendments in increasing the biomass yield at each level of soil compaction. The depressive effect of soil compaction on shoot yield was therefore ameliorated by soil amendments.

Table 3. Impacts of soil compaction and fertilizer amendments on shoot biomass of maize and soybean plants

Bulk density (Mg m^{-3})	**Shoot biomass (g/plant)**	
	Maize	Soybean
1.3	115.72	69.84
1.5	92.62	57.70
1.7	69.95	32.66
Lsd (5%)	4.42	1.63
Soil amendment (g/plant)		
Control	78.43	35.56
Sole PM	109.05	67.91
Sole NPK	87.39	49.64
50% PM + 50% NPK	96.17	60.50
Lsd (5%)	5.11	1.89
†Interaction		
Control x 1.3	111.02	48.90
Control x 1.5	91.55	41.67
Control x 1.7	59.60	16.10
Sole NPK x 1.3	133.23	87.65
Sole NPK x 1.5	104.48	68.12
Sole NPK x 1.7	89.43	47.97
Sole PM x 1.3	92.87	64.42
Sole PM x 1.5	77.42	57.90
Sole PM x 1.7	65.00	26.59
50% PM + 50% NPK x 1.3	125.75	78.39
50% PM + 50% NPK x 1.5	97.02	63.13
50% PM + 50% NPK x 1.7	65.76	39.98
Lsd (5%)	8.85	3.27

Lsd = Least significant difference; PM = Sole poultry manure; †Soil amendment x Bulk density interactions

Shoot biomass therefore decreased with increasing soil bulk density as similarly reported in several studies [e.g. 15 – 17]. The reduction in shoot biomass of maize plants as bulk density increased from 1.3 – 1.5 Mg m^{-3}, and 1.7 Mg m^{-3} was 20 and 40%, respectively. Shoot biomass of soybean plants (Table 3) varied from 32.66 – 69.84 g/plant for the 1.7 and 1.3 Mg m^{-3}, respectively with significant differences (P = *.05*) among the treatments. The reduction in shoot biomass, using that of 1.3 Mg m^{-3} as a base gave 17 and 57 % at the 1.5 and 1.7 Mg m^{-3}, respectively. The adverse impact of soil compaction on shoot biomass in both soybean and maize plants was greater at 1.7 Mg m^{-3} with the former being more. The response of shoot biomass of maize and soybean plants to increasing bulk density appears to suggest optimum bulk density for shoot biomass production to be 1.3 Mg m^{-3} with a range between 1.3 and 1.5 Mg m^{-3}. The magnitude of response, however seem to be influenced by the stage of growth as well as the fertility level of the soil. In this context, Ocloo [18] found the ideal range of bulk density for the growth of maize and soybean seedlings to be 1.1 – 1.5 Mg m^{-3} with 1.3 Mg m^{-3} as the most preferable in terms of shoot biomass yield and root penetration ratio. Beutler and Centurion [19], on the other hand, reported that soybean growth and yield started to decline beyond a bulk density of 1.36 Mg m^{-3} on soil with no fertilizer and 1.48 Mg m^{-3} on soils that received fertilizer treatment.

The reduction in shoot yield with increasing soil compaction may be attributed to one or a combination of the adverse conditions that were created in the soil environment. In this study, increasing soil compaction increased soil bulk density, reduced both total and aeration porosity with the later below the artificial critical level of 10% for favourable gaseous exchange at the 1.7 Mg m^{-3}. The implication of these conditions include increased impedance to root growth, which in turn, reduces the requisite water and nutrient uptake for satisfactory root and shoot growth. The reduced aeration porosity and its negative impact on gaseous exchange resulting in reduced oxygen supply accumulation of carbon dioxide could adversely affect root growth and indirectly affect shoot growth. Similar observations have been reported in numerous studies [e.g. 5, 11, 14, 18, 20]. Efforts to increase and sustain crop growth and yield on compacted soils include breaking compacted layers through ripping by tines and subsoiling [21 – 23], biological drilling [12], and ameliorating the negative impact of compaction through the application of mineral and organic sources of nutrients to enhance vigorous root growth [19, 24, 25].

The percentage increment by soil amendment in shoot yield at each level of soil compaction, using the yield from the control as standard is presented (Table 4). In both crops, the impact was greatest under sole NPK and at the highest level of soil compaction. The magnitude of impact was greater on soybean than on maize plants as indicated earlier by the main effect of soil amendments. The effect of poultry manure was also greater at the 1.7 Mg m^{-3} than the remaining bulk densities.

Table 4. Percentage increment in shoot biomass yield by soil amendments at each level of soil compaction

Soil amendment (g/plant)	**1.3 Mg m^{-3}**		**1.5 Mg m^{-3}**		**1.7 Mg m^{-3}**	
	Maize (%)	Soybean (%)	Maize (%)	Soybean (%)	Maize (%)	Soybean (%)
Control	-	-	-	-	-	-
Sole NPK	17	44	12	39	33	66
Sole PM	-	24	1	28	23	39
50% PM + 50% NPK	18	38	6	34	9	60

PM = Sole poultry manure

The results have shown the need for soil amendments in enhancing shoot biomass yield but more so on compacted soils and for soybean cultivation. The need for mineral fertilizer in enhancing crop growth on soils low in nitrogen and soil organic matter has also been demonstrated, even in the case of soybean plants contrary to the general notion that nitrogen-fixing legumes do not need fertilizers, especially, N. On such soils, as was used in this experiment, N would be needed. In this context, integrated plant nutrition, using combined mineral and organic sources of nutrients could be an advantage considering the near addictive effects of the 50% NPK+ 50% PM on shoot biomass yield observed in this study. In soybean plants, the calculated sum of half biomass yield of sole NPK and sole PM was 78.2, 62.95 and 36.3 g/plant at the 1.3, 1.5 and 1.7 Mg m^{-3}, respectively. The corresponding yields of the 50% NPK+ 50% PM were 78.39, 63.13 and 39.98 g/plant. In maize plants, the sum of the sole NPK and sole PM were 113.06, 90.95 and 77.22 g/plant at the 1.3, 1.5 and 1.7 Mg m^{-3}. The corresponding yields of the 50% PM+ 50% NPK were 125.75, 97.02 and 65.76 g/plant.

3.3 Root biomass

The results of this study (Table 5) showed that soil compaction and amendments and their interactions significantly (*P = .05*) affected root biomass, distribution and penetration ratio. In this study, total effective root biomass refers to the sum of the mass of roots retrieved from the uncompacted and compacted soil cores excluding those between the inner walls of the buckets and soil cores (i.e., roots along the periphery of the soil cores). Total effective dry root biomass of maize plants ranged from 27.64 and 67.87 g/plant for the 1.7 and 1.3 Mg m^{-3}, respectively. The differences in root biomass among the 3 levels of compaction were significant (P = .05). The reduction in root biomass as bulk density increased from 1.3 – 1.5 and 1.7 Mg m^{-3} was 50 and 59%, respectively. With regard to soybean plants, total dry root biomass ranged between 8.17 and 10.49 g/plant for the 1.5 and 1.3 Mg m^{-3}, respectively following a trend of 1.3 > 1.7 > 1.5 Mg m^{-3}. Root biomass at 1.3 Mg m^{-3} was significantly (P = .05) greater than those of 1.5 and 1.7 Mg m^{-3} which did not significantly differ from each other. The reduction in total root biomass relative to that of the 1.3 Mg m^{-3} was 22 and 14 % for the 1.5 and 1.7 Mg m^{-3}, respectively.

Table 5. Impacts of soil compaction and fertilizer amendments on effective root biomass of maize and soybean plants

Bulk density (Mg m^{-3})	**Effective root biomass (g/plant)**	
	Maize	Soybean
1.3	67.87	10.49
1.5	33.98	8.17
1.7	27.64	9.05
Lsd (5%)	2.34	1.73
Soil amendment (g/plant)		
Control	24.34	5.83
Sole PM	49.10	13.82
Sole NPK	63.99	14.79
50% PM + 50% NPK	59.15	13.88
Lsd (5%)	2.41	1.68
†Interaction		
Control x 1.3	27.97	5.58
Control x 1.5	25.23	3.46
Control x 1.7	19.81	8.46
Sole NPK x 1.3	105.55	13.72
Sole NPK x 1.5	50.13	11.61
Sole NPK x 1.7	36.29	11.93
Sole PM x 1.3	74.73	11.25
Sole PM x 1.5	27.31	7.25
Sole PM x 1.7	23.67	9.40
50% PM + 50% NPK x 1.3	63.23	11.42
50% PM + 50% NPK x 1.5	33.24	10.35
50% PM + 50% NPK x 1.7	30.80	6.43
Lsd (5%)	5.88	3.47

Lsd = Least significant difference; PM = Sole poultry manure; †Soil amendment x Bulk density interaction

The results of this study showed the application of soil amendments to significantly influence the total root biomass of both maize and soybean plants. Total dry root biomass of maize plants was in the order of sole NPK > 50% PM + 50% NPK > sole PM > control with a range of 24.34 – 63.99 g/plant for the control and NPK, respectively. All the soil amendments significantly (P = .05) out yielded the control. Root biomass of the NPK was significantly greater than those of sole PM and 50% PM + 50% NPK which did not differ significantly. Considering the control as base value, the percentage increase in root biomass of maize plants was 42, 43 and 62% under sole PM, 50% PM + 50% NPK and sole NPK, respectively. In the case of soybean plants, total biomass ranged from 5.83 to 12.42 g/plant with a similar trend as that of maize plants. From a base value of 5.83 g/plant, sole NPK, 50% PM + 50% NPK and sole PM increased root biomass by 53, 38 and 37%, respectively. The impact of the application of soil amendments in ameliorating soil compaction for root biomass yield was therefore greater for maize than soybean plants. The development of extensive root system enhances the ability of plants to abstract nutrients and water from the soil. The constraining impact of soil compaction on root growth therefore tends to limit the availability of water and nutrients for satisfactory plant growth and yield [21, 27]. The results of the study have clearly demonstrated the ameliorative impact of soil amendments in reducing the adverse effects of soil compaction on root biomass yield. The provision of readily available nutrients favoured root development and vigour for effective nutrient and water uptake from the soil. The subsequent translocation of the nutrients and water to the shoot may underscore significant increases in shoot biomass.

The ameliorative impact of soil amendments on soil compaction effects on root growth became more evident when the soil amendment and compaction interactions were examined. The results as presented in Table 5 showed that at each level of soil compaction, all the soil amendments significantly increased total root biomass over the control with no amendment. The increases in root biomass were greater in maize than soybean plants. The magnitude of reduction in total root biomass indicated that the negative impact of soil compaction was greater on maize (a monocot) than soybean (a dicot) roots. A similar observation was reported by Materechera et al. [26]. Chen and Weil [27] also found that rye toots decreased more rapidly than rapeseed roots as bulk density increased. In order to sustain crop growth and yield in compacted soils, ameliorative strategies to address the adverse impacts of soil compaction on root growth and biomass production need to be developed. In this context, the application of adequate amounts of soil amendments has been found to offset the negative effects of soil compaction on root growth [24, 25, 28].

3.4 Root/shoot biomass ratio

The results (Table 6) showed soil compaction and amendments to significantly influence root/shoot ratio. The impact of soil compaction showed root/shoot ratio to range from 0.37 – 0.59 for maize plants and 0.14 – 0.27 for soybean plants. In maize plants, the significantly greater ratio at 1.3 Mg m^{-3} was reduced by 37% at the 1.5 Mg m^{-3}. In soybean plants, the reduction was 7%. The implication is that, at the lower range of bulk density, 1.3 – 1.5 Mg m^{-3}, the reduction in root biomass resulting from increasing compaction is greater than that in the shoot biomass. The tendency was for root/shoot ratio to decrease. This is evidenced in this study by a reduction in shoot and root biomass yield of maize plants by 20 and 50%, respectively when bulk density increased from 1.3 – 1.5 Mg m^{-3}. The corresponding decrease in soybean plants was 17 and 22%. However, beyond 1.5 Mg m^{-3}, the tendency was for root/shoot ratio to increase with increasing soil compaction.

Table 6. Impact of soil compaction on root/shoot ratio of maize and soybean plants

Bulk density (Mg m^{-3})	**Maize (per plant)**	**Soybean (per plant)**
1.3	0.59	0.15
1.5	0.37	0.14
1.7	0.40	0.27
Lsd (5%)	0.04	0.08
Soil amendments (g/plant)		
Control	0.29	0.50
Sole PM	0.56	0.25
Sole NPK	0.51	0.27
50% PM + 50% NPK	0.44	0.23
Lsd (5%)	0.05	0.20
†Interaction		
Control x 1.3	0.25	0.11
Control x 1.5	0.28	0.08
Control x 1.7	0.33	0.54
Sole NPK x 1.3	0.79	0.16
Sole NPK x 1.5	0.48	0.17
Sole NPK x 1.7	0.41	0.25
Sole PM x 1.3	0.80	0.18
Sole PM x 1.5	0.35	0.13
Sole PM x 1.7	0.37	0.36
50% PM + 50% NPK x 1.3	0.50	0.15
50% PM + 50% NPK x 1.5	0.34	0.16
50% PM + 50% NPK x 1.7	0.47	0.16
Lsd (5%)	0.08	0.19

Lsd = Least significant difference; PM = Sole poultry manure; †Soil amendment x Bulk density interaction

Increasing soil compaction from 1.5 – 1.7 Mg m^{-3} increased root/shoot ratio by 7 and 48 % in maize and soybean plants, respectively. The underlying reason in this case was that the reduction in shoot biomass, 24 and 43% in maize and soybean plants, was greater than the decreases in their corresponding root biomass of 19 and 10% at the 1.7 Mg m^{-3}. According to Marschner [20], the root cap, as a sensor of stress due to the restriction of root growth in the compacted soil, is implicit in this process. It triggers the accumulation of Abscicic Acid (ABA) in the roots which is transported to the shoot; this subsequently results in depression of shoot growth by inhibiting cell extension in shoot tissue and inducing stomatal closure. This area of research has received very limited research attention. Yet, studies on the interdependence of shoots and roots in many ways and the role of phytohormones in their response to various stress conditions in the rooting zone are required to inform the development of strategies for sustainable plant growth and yield. Such stresses include moisture, nutrients, drought and compaction. It is however worthy to note the main findings of the impact of soil compaction on root/shoot ratio. The magnitude and direction of change in root/shoot ratio due to increasing soil compaction depend on the level of compaction and the type of crop. At the lower range of soil compaction, 1.3 – 1.5 Mg m^{-3} in this work and 1.1 – 1.5 Mg m^{-3} in Ocloo [18], root/shoot ratio decreased with increasing compaction. Beyond these ranges (i.e., 1.5 – 1.7 Mg m^{-3}) in this study, and 1.5 – 1.9 Mg m^{-3} [18], root/shoot ratio increased with increasing soil compaction.

The soil amendments applied significantly (*P* = *.05*) influenced the root/shoot ratio of maize plants, but not soybean plants (Table 6). All the soil amendments increased root/shoot ratio in both maize and soybean plants over the control. In the maize plants, the root/shoot ratio was in a decreasing order of sole NPK > sole PM > 50% PM+ 50% NPK > control with a range of 0.31 to 0.59 for the control and sole NPK, respectively. In the soybean plants, the range was 0.16 to 0.19 for the control and sole PM with a trend of sole PM > sole NPK > 50% PM+ 50% NPK = control. The increments in the root/shoot ratio indicated that the application of soil amendments increased biomass of both root and shoot, especially in the roots. The increment in root biomass of maize plants were 62, 43 and 42% under sole NPK, 50% PM+ 50% NPK, and sole PM, respectively. The corresponding increases in shoot biomass were 28, 18 and 10%. In soybean plants, the increments in the root and shoot biomass were 53 and 48% under sole NPK, 37 and 28% under sole PM, and 38 and 41% under 50% PM+ 50% NPK.

A similar trend was observed under the amendment x compaction interaction (Table 6). In all cases, soil amendment significantly (*P* = *.05*) increased the root/shoot ratio at each level of soil compaction. However, under each amendment x compaction level, root/shoot ratio tended to decrease with increasing bulk density in maize plants contrary to the observed increases in root/shoot ratio with increasing bulk density under the main effect of soil compaction. The latter scenario was observed in the case of soybean plants. The direction of change in the magnitude of root/shoot ratio is therefore not as simple. It seems to be influenced by the type of crop (cereal or legume) and the confounding effects of factor interactions on the relative increases/reduction in shoot and root growth. This can be viewed in the simple general observation that under abundant supply of essential nutrients, particularly N and P, root growth is stimulated but more so in shoot in fertile than infertile soil [20, 29, 30]. The present study has amply shown soil amendments to ameliorate the adverse impact of soil compaction on root and biomass yield. This, obviously, has implications for the magnitude of the root/shoot ratio, which is the dry matter (photosynthate) portioned into the root as a proportion of that in the shoot. The beneficial effects of the manure (other than nutrients) such as soil moisture storage and availability could account for the greater soybean plants height recorded under all treatments that incorporated PM than NPK. This is indicative of the benefits of integrated plant nutrition [31, 32] involving the combination of mineral fertilizer and poultry manures.

The data on plant parameters were examined for correlations with bulk density to ascertain the direction of change (positive or negative) in the measured parameters with changes in bulk density (Table 7). This will facilitate the acquisition of relevant information regarding the response of the measured parameters of maize and soybean plants to changes in bulk density.

Table 7. Pearson correlation matrix of soil compaction and crop parameters (*P* = .05)

Maize	Coefficient of correlation				
	BD	PH	SB	ERB	RSR
BD		-1.00	-1.00	-0.93	-0.80
PH			0.99	0.89	0.66
SB				0.87	0.64
ERB					0.93
RSR					
Soybean					
BD		-1.00	-0.98	-0.62	0.83
PH			0.96	ns	-0.69
SB				ns	-0.85
ERB					ns
RSR					

BD = Bulk density; PH = Plant height; SB = Shoot biomass; ERB = Effective root biomass; RSR = Root/Shoot ratio

The results depicted the negative impact of increasing soil compaction on shoot biomass, effective root biomass, and the root/shoot ratio of maize and soybean plants. In the soybean plants, the root/shoot ratio increased with bulk density. The coefficient of correlation (*r*) for maize plants were -1.0, -0.93, and -0.80 for shoot biomass, effective root biomass, and root/shoot ratio, respectively. Increasing soil compaction therefore decreases the magnitude of these measured parameters. The negative *r* for root/shoot ratio indicates that root biomass is depressed more than shoot biomass as soil compaction increases. An examination of the data revealed that root/shoot ratio of maize plants decreased as bulk density increased from 1.3 – 1.5 Mg m^{-3} and increased from 1.5 – 1.7 Mg m^{-3}. However, the magnitude of the rise could not offset that of the fall, resulting in a general trend of decreasing root/shoot ratio. With regard to soybean plants, the *r* values -0.98, -0.62, and 0.83 for shoot biomass, effective root biomass, and root/shoot ratio, respectively. All the measured parameters except root/shoot ratio decreased in magnitude with increasing soil compaction. The positive correlation between bulk density and root/shoot ratio accords with the generally observed trend of the shoot being more depressed than the root with increasing soil compaction, which is the general response of plants to stresses, such as soil compaction, drought/moisture stress and nutrient deficiency [20].

3.5 Nutrient uptake

The results on nutrient uptake as presented in Table 8 showed that uptake of N, P and K by maize and soybean plants decreased with increasing bulk density (i.e., uptake was highest in the order of 1.3 > 1.5 > 1.7 Mg m^{-3}). Thus, uptake of N, P and K at the 1.3 Mg m^{-3} was significantly (*P* = .05) higher than either 1.5 or 1.7 Mg m^{-3} under both maize and soybean plants. Overall, nutrient uptake in maize plants ranged from 0.84 – 2.44 g N/plant, 0.87 – 2.50 g P/plant, and 0.47 – 2.46 g K/plant. The percentage reductions in N, P and K relative to 1.3 Mg m^{-3} were 50, 51 and 50% at 1.5 Mg m^{-3} and 66, 64 and 81 Mg m^{-3} at 1.7 Mg m^{-3}, respectively. In soybean plants, nutrient uptake in g/plant for sole NPK ranged between 0.41 and 1.50, 0.46 and 1.57 and, 0.22 and 1.40, respectively, wherein the highest and lowest uptakes were recorded under the 1.3 and 1.7 Mg m^{-3} treatments, respectively. Relative to bulk density at 1.3 Mg m^{-3}, the percentage reductions in the uptake of N, P and K were 49, 50 and 49, and 73, 71 and 84% at 1.5 and 1.7 Mg m^{-3}, respectively. The adverse soil conditions created by high soil compaction as observed in this study are highly evidenced by the reductions in nutrient uptake by both maize and soybean plants, as reported in several studies [e.g. 15, 20, 21].

Table 8. Impact of different soil compaction levels and soil amendments on the uptake of nutrients by maize and soybean plants

Bulk density (Mg m^{-3})	**Maize (g/plant)**			**Soybean (g/plant)**		
	N	P	K	N	P	K
1.3	2.44	2.50	2.46	1.50	1.57	1.40
1.5	1.21	1.22	1.23	0.76	0.78	0.71
1.7	0.84	0.87	0.47	0.41	0.46	0.22
Lsd (5%)	0.43	0.44	0.70	0.25	0.25	0.34
Soil amendment (g/plant)						
Control	1.12	0.66	2.13	0.48	0.29	0.93
Sole PM	1.08	0.72	0.41	0.69	0.49	0.28
Sole NPK	2.03	3.44	1.24	1.29	2.16	0.78
50% PM + 50% NPK	1.76	1.30	1.78	1.10	0.82	1.12
Lsd (5%)	0.50	0.51	1.39	0.29	0.29	0.40
†Interaction						
Control x 1.3	1.79	1.31	3.74	0.80	0.59	1.66
Control x 1.5	1.10	0.53	2.12	0.50	0.25	0.98
Control x 1.7	0.48	0.13	0.53	0.13	0.04	0.14
Sole NPK x 1.3	3.66	5.21	1.91	2.41	3.43	1.26
Sole NPK x 1.5	1.45	2.70	0.99	0.94	1.76	0.64
Sole NPK x 1.7	0.97	2.42	0.81	0.52	1.30	0.44
Sole PM x 1.3	1.32	1.21	0.69	0.92	0.84	0.48
Sole PM x 1.5	1.05	0.72	0.41	0.78	0.53	0.30
Sole PM x 1.7	0.88	0.23	0.13	0.36	0.10	0.05
50% PM + 50% NPK x 1.3	2.98	2.27	3.52	1.87	1.43	2.21
50% PM + 50% NPK x 1.5	1.27	0.91	1.41	0.82	0.59	0.92
50% PM + 50% NPK x 1.7	1.02	0.71	0.42	0.62	0.43	0.23
Lsd (5%)	0.86	0.89	1.39	0.50	0.50	0.69

Lsd = Least significant difference; PM = Sole poultry manure; †Soil amendment x Bulk density interaction

The stimulation of root growth, evidenced by the increases in root biomass (Table 5) coupled with the availability of nutrients from soil amendments increased the uptake of N, P and K over that of the control (i.e., no applied amendment) as presented in Table 8. In maize plants, N uptake was highest (P = .05) under sole NPK and lowest under sole PM and control, with a range of 1.08 – 2.03 g/plant. The uptake of P varied between 0.66 and 3.44 g/plant and followed a similar trend as observed for N. With regard to K, uptake ranged between 0.41 and 2.13 g/plant, highest under the control and lowest under the application of PM. In the case of soybean plants, N, P and K uptake ranged between 0.48 and 1.29, 0.29 and 2.16, and 0.28 and 1.12 g/plant, respectively. Similar to maize plants, the trends in the magnitudes of uptake differed with the soil amendments for both N and P, wherein uptake was highest under NPK fertilizer and lowest under the control. Contrary to maize plants, uptake of K was highest under 50% PM + 50% NPK and lowest under sole PM application. Overall, sole NPK and combined application of PM and NPK resulted in higher (P = .05) N and P uptake relative to the control and sole PM treatments by both maize and soybean plants. It is thus, evident that application of NPK fertilizer enhanced N and P uptake by maize and soybean plants, possibly because of the readily availability of the minerals for uptake relative to the other amendments. Similar observation was made by Hakansson and Lipiec [28] and Onwonga et al. [33]. The ameliorative impact of soil amendments in reducing the adverse effect of soil compaction in nutrient uptake is also evidenced by the results on soil amendment x compaction interactions (Table 8). In both maize and soybean plants, this was more evident with the direct incorporation of N, P and K, (i.e., applications of 50% PM + 50% NPK and sole NPK fertilizer), especially for N and P uptake. Application of soil amendments, however, tended to depress the uptake of K by both plants under the different soil compaction levels.

4. CONCLUSIONS

The study has clearly shown the impact of different levels of soil compaction, amendments and their interactions on some the growth, biomass yield and nutrient uptake by maize and soybean plants. Soil compaction reduced crop growth, shoot and root biomass and root penetration ratio of maize and soybean plants. The magnitude of reduction increased as bulk density increased. Soil compaction beyond 1.5 M gm^{-3}, adversely affected root and shoot biomass yield of maize and soybean. Thus, the ideal bulk density for shoot biomass production of both crops should be 1.3 Mg m^{-3} or with a range of 1.3 ≤ 1.5 Mg m^{-3}. The main effects of soil amendments manifested in the enhancement of the growth of maize and soybean plants over that of the control. Soil amendments enhanced plant height at each level of soil compaction. A similar impact was observed in root and shoot biomass yield and root penetration ratio of both crops. Increasing soil compaction resulted in the accumulation of most of the root biomass in the uncompacted soil above the compacted layer. The addition of soil amendments increased the relative root biomass of maize plants in the uncompacted soil while that in the compacted soil where reduced. In the case of soybean plants, although the relative root biomass accumulated in the uncompacted soil was relatively greater than that of maize plants, the application of soil amendments tended to slightly decrease the relative root biomass over that of the control. The shoot biomass of both crops decreased with increasing soil bulk density. The soil amendments significantly increased the shoot biomass of maize and soybean plants over the control. The magnitude of the responses of the crops to the soil amendments was greater in soybean plants than in maize plants. Soil compaction and amendments significantly influenced root/shoot ratio of both crops. At the bulk density 1.3 – 1.5 Mg m^{-3}, the root/shoot ratio decreased with increasing compaction. Beyond the bulk density of 1.5 – 1.7 Mg m^{-3}, the root/shoot ratio increased with increasing soil compaction. The magnitude of the increase (1.5 – 1.7 Mg m^{-3}) could not offset that of the decrease (1.3 – 1.5 Mg m^{-3}), resulting in a general trend of decreasing root/shoot ratio. The soil amendments increased the biomass of both root and shoot but more so in the former than the latter. A more enhanced uptake of N and P by both maize and soybean plants was observed with the application of sole NPK and combined PM and NPK due to their readily availability for uptake by a greater percentage of the root biomass. Uptake of N and P increased with decreasing compaction level (low bulk density) by both maize and soybean plants. Overall, nutrient uptake, with the exception of K was highly enhanced upon the application of the soil amendments. There is the need for mineral fertilizer in enhancing crop growth on compacted soils, and soils low in N and organic matter, even for the production of soybean. Soil amendments, especially, NPK fertilizer should therefore be applied to enhance crop growth and development on compacted soils. Soil testing should be done to know the right amount of fertilizers to apply. Further studies should be conducted to simulate the growth parameters measured in the buckets to conditions in the field and the parameters correlated to yield.

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COMPETING INTERESTS

Authors have declared that no competing interests exist.