The Impact of Different Levels of Soil Compaction on Soil Physical Properties and Root Growth of Maize and Soybean Seedlings

C. Y. Ocloo[1], C. Quansah[2], V. Logah[2]* and B. K. Amegashie[2]
[1] *Ministry of Food and Agriculture, P.O. Box 86, Sunyani, Ghana*
[2] *Department of Crop and Soil Sciences, Faculty of Agriculture, Kwame Nkrumah University of Science and Technology, Kumasi, Ghana*
*Corresponding author; E-mail: *vlogah.canr@knust.edu.gh* or *vlogah@yahoo.co.uk*

Abstract

Two factorial glasshouse experiments were carried out at the Soil Research Institute, Kwadaso, Kumasi, to examine the effect of soil compaction on soil physical properties and root growth of commonly cultivated maize and soybean varieties in Ghana. There were five levels of soil compaction, using bulk density as an index of compaction, and three varieties each of soybean (*Glycine max* L.) and maize (*Zea mays* L.) in a completely randomized design (CRD) with three replications. The soybean and maize were grown in a stack of three polyvinyl (PVC) cylinders each of diameter 8.54 cm and height 15.5 cm filled with the test soil, and consisted of top, middle and bottom sections with a height of 2.5 cm, 5 cm and 8 cm, respectively. The test soil, Asuansi series (Ferric Acrisol) was equilibrated to a constant gravimetric moisture content of 18%, and uniformly compacted in the cylinders to the desired bulk densities of 1.1, 1.3, 1.5, 1.7 and 1.9 Mg m^{-3}. The middle sections, to which the five compaction treatments were applied, were sandwiched between the top and bottom sections each of which had a bulk density of 1.1 Mg m^{-3}. Saturated hydraulic conductivity varied between 25.6 and 44.2 mm h^{-1} under bulk densities of 1.9 and 1.1 Mg m^{-3}, respectively. The hydraulic conductivity decreased by 6.6%, 12.9%, 32.6% and 42.1% as bulk density increased from 1.1 to 1.3, 1.5, 1.7 and 1.9 Mg m^{-3}. The distribution of roots in the three soil sections was assessed as the ratio of root length in each section to the total root length in the sections, expressed as percentage relative root length. The respective relative root lengths of the 1.1 and 1.9 Mg m^{-3} for soybean were 12.15% and 76.98% on the top section, 47.05% and 19.64 % in the middle section, and 40.97% and 3.38% in the bottom section. Significant ($P < 0.05$) varietal differences were recorded in root penetration ratio among the soybean varieties. Soybean roots were more sensitive to increasing soil compaction than maize. The ideal bulk density for the growth of soybean and maize was 1.1–1.5 Mg m^{-3} with 1.3 Mg m^{-3} being the most preferable based on the performance of measured plant parameters. The study has indicated that Anidaso, Nangbaar and Ahoto soybean varieties could generally show similar tolerance to varying levels of soil compaction. The three varieties of maize (Obatanpa, Enibi and Mamaba) studied also showed similar responses to soil compaction. The results could provide a firsthand information to breeders and crop growers on crop selection in compacted soils.

Introduction

Soil compaction by machinery traffic in agriculture is a well recognized problem in many parts of the world (Soane & Van Ouwerkerk, 1994; Hamza & Anderson, 2005). Compaction induced by vehicular traffic has adverse effects on a number of key soil properties such as bulk density, mechanical impedance, porosity, hydraulic conductivity (Radford *et al.*, 2000; Hamza & Anderson, 2005), mineralization and microbial activity (Sérgio *et al.*, 2011). All these factors can potentially reduce root penetration, water extraction and plant growth (Kirkegaard *et al.*, 1992; Passioura, 2002). The overall effect causes increased

West African Journal of Applied Ecology, vol. **22**(2), 2014: 17–30.

erosion and reduced plant growth and yield. It is, however, recognized that root penetration and exploration of the soil horizons are essential for the optimization of crop growth and yield (Petersen *et al.,* 2006).

McGarry (2001) reported that soil compaction is regarded as most serious environmental problem caused by conventional agriculture but the most difficult type of degradation to locate on arable lands since it may show no clear marks on the soil surface. Much of the potential yield of crops indicated by breeders could be realized if different types of crops were adapted to the physico-chemical environment in which they are grown. The problem of soil compaction is becoming more severe as big and heavier machines continue to be used in all parts of the world.

According to Oldeman *et al.* (1991), 18 million hectares of Africa's land have been degraded by compaction, sealing and crusting. Globally, soil compaction induced degradation affects several million hectares of croplands. Since the amelioration of soil compaction is very expensive, a more practical approach may be to adapt compacted soils to tolerant genotypes. The work of plant breeders indicates that different crops and even different cultivars of the same crop may have varying levels of tolerance to soil compaction. Jorge *et al.* (2013) evaluated five different cotton cultivars against varying levels of soil compaction and found varietal differences in their response. A crop that is better able to tolerate soil compaction and still maintains high yields would be preferred in modern mechanized agriculture.

The study of root tolerance to soil compaction on the field where environmental factors cannot be controlled is difficult, expensive and time consuming. Most studies on soil compaction are, therefore, carried out in the laboratory where factors are easy to control. The use of simple laboratory methods, such as the rapid and non-destructive soil section seedling test of Asady *et al.* (1985), for the establishment of preliminary quantitative values of tolerances is necessary to inform the selection and matching of crops with compacted soils. Even, in this, not much work has been done especially on local crop varieties cultivated in sub-Saharan Africa. The objective of this study was, therefore, to examine soil properties and root growth of different varieties of maize and soybean seedlings under different levels of soil compaction using bulk density as index of compaction.

Materials and methods

Experimental site

The study was carried out at the Soil Research Institute, Kwadaso, Kumasi. According to Taylor (1952), the area lies between latitudes 06^0.39' and 06^0.43' N and longitudes 1^0.39' and 1^0.42' W of the Greenwich meridian. The soil used for the study was taken from the Institute's experimental field, which has been under cultivation for over 20 years, and belongs to Asuansi series classified by Adu (1992) as Ferric Acrisol according to FAO (1990) and Typic Haplustult according to USDA (1998). The soil was taken from a 0-20 cm depth. The soil has been under cultivation with annual crops such as maize and cowpea.

Soil chemical analysis

Initial soil analysis was carried out to determine the fertility status of the test soil. Soil *p*H was determined in a soil:water ratio of 1:2.5 using a glass electrode (H19017 Microprocessor). Soil texture was determined by the hydrometer method (Boyoucos, 1962). Organic carbon, total N, and available P were determined by the Walkley – Black method as described by Nelson & Sommers (1982), Kjeldahl digestion and distillation procedure as described in Soils Laboratory Staff (1984) and Bray's I procedure (Bray & Kurtz, 1945), respectively. Exchangeable bases (calcium, magnesium, potassium and sodium) in the soil were determined in 1.0 *M* ammonium acetate (NH_4OAc) extract (Black, 1986), and the exchangeable acidity (hydrogen and aluminium) was determined in 1.0 *M* KCl extract as described by Page *et al.* (1982).

Soil physical analysis

Bulk density. Bulk density in the field at 0–20 cm depth was determined by the core method described by Blake & Hartge (1986). A cylindrical metal sampler of diameter 5 cm and height 15 cm was used to sample undisturbed soil. The core was driven to the desired depth (0–20 cm) and the soil sample was carefully removed to preserve the known soil volume as existed *in situ*. The soil was then weighed, dried at 105 ^{0}C for 2 days and reweighed, and bulk density computed.

Gravimetric water content. The gravimetric method was used to determine the water content of the soil before compacting to the various bulk densities. Ten grams of the soil was oven dried at 105 ^{0}C for 24 h. After drying, the dry mass of the soil was taken and this was subtracted from the initial mass to give the percentage moisture content.

Preparation of pots for the plants. Three cylinders with a height of 2.5 cm, 5.0 cm and 8.0 cm were cut from a PVC tube (8.54 cm diameter) and stacked together. The corresponding volume of each section was 15.71 cm^2, 31.42 cm^2 and 50.27 cm^2, respectively. The bottom of the cylinders were shielded with a flat wooden plate and holes perforated on the wooden plates to allow drainage.

Standardization of bulk density. The bulk densities used were 1.1 Mg m^{-3} for the top and bottom sections and 1.3 Mg m^{-3}, 1.5 Mg m^{-3}, 1.7 Mg m^{-3} and 1.9 Mg m^{-3} for the middle section to depict the compacted layers in the field (Kirkgaard *et al.*, 1992). In order to obtain and replicate the desired bulk density, it was necessary to standardize the method of packing of the soil into the containers. The mass of soil to be packed into the cylinders to give the desired bulk density was calculated from the Hillel's (1998) equation.

Packing of the soil in the sections was carried out using the Proctor test. This was carried out by dropping 2.10 kg mass from a height of 30 cm onto the soil surface which was completely shielded by a flat wooden plate (Vickers, 1983). For bulk densities of 1.3, 1.5, 1.7 and 1.9 Mg m^{-3}, about half of the soil was packed into the container, covered with the shield and the mass dropped 5, 7, 9 and 11 times, respectively. The shield was then removed and the rest of the soil packed on to the first half. The shield was put back in place and the mass dropped again. It was dropped 8, 10, 12 and 14 times, respectively. For the bulk density of 1.1 Mg m^{-3} the whole soil was packed into the container, covered with the shield and the mass dropped once.

After compaction, section samples were taken using a metal cylinder and dried in an oven at 105 ^{o}C. Bulk density was then calculated. The mean values (1.08, 1.30, 1.51, 1.73 and 1.86 Mg m^{-3}) for the middle and 1.12 Mg m^{-3} for the top and bottom sections from two replicates were very close to the respective desired bulk densities of (1.3, 1.5, 1.7 and 1.9 Mg m^{-3}) and 1.1 Mg m^{-3}, respectively.

Determination of field moisture capacity. Net water requirement is the quantity of water necessary to restore soil moisture to field capacity. Sample container assemblies were prepared by sandwiching the compacted middle sections of 1.3, 1.5, 1.7 and 1.9 Mg m^{-3} between the top and bottom 1.1 Mg m^{-3}. The three sections were sealed together into one air-tight and water-tight soil container with cellotape. The soil container assemblies with the surface of the soil covered with polythene sheets were saturated with water from below and drained for 48 h. The containers were then weighed to obtain their mass at field capacity.

Infiltration rate. The infiltration rate of the set up was also determined by using the mini-disk infiltrometer which has a radius of 2.25 cm and infiltrates water at 2.0 cm suction. This was done to determine the infiltration rate for the various bulk densities and the soil hydraulic conductivity calculated.

Porosity, effective porosity and air – filled porosity. These were calculated using standard equations.

Experimental Design/Treatments

Two experiments, using maize (*Zea mays* L.) and soybean (*Glycine max* L.) as test crops were conducted. Each experiment was a 5 × 3 factorial arranged in a Completely Randomized Design (CRD) with three replications. The treatments were soils with five different compaction levels or bulk densities (1.1 (Bd1), 1.3 (Bd2), 1.5 (Bd3), 1.7 (Bd4) and 1.9 (Bd5) Mg m^{-3}) and three varieties each of maize and soybean.

Test crops

The maize varieties were Enibi (V1), Mamaba (V2) both hybrids and Obatampa (V3), an open pollinated variety whilst the soybean varieties were Ahoto (V1), Anidaso (V2) and Nangbaar (V3).

Planting

The set up was carried out at the plant house at the Soil Research Institute, Kwadaso, Kumasi. Three seeds were then sown per soil section assembly. The seedlings were thinned to two per pot 7 days after sowing. After sowing; water loss was estimated and compensated by weighing every 2 days and plants were watered using watering can.

Plant parameters measured

The soybean was harvested 15 days after planting whilst maize was harvested at soil level 21 days after planting.

Root mass

Fresh root mass was obtained after cutting the section cylinder into its three parts, ie. the top layer, middle layer and bottom layers. The roots were stained with three drops of 0.01% methylene blue (from a graduated pipette) for easy identification and selection. This was done after the soil was washed off the roots. The root mass was then taken for both the soybean and the maize. After the fresh mass determination, the roots were put in an oven at 70 ^{0}C for 48 h and the dry mass of the roots taken.

Root length

After washing the soil from the roots using a 2-mm sieve, the length of the collected roots were determined using the line intersection method (Newman, 1966) expressed as;

$$RL = \frac{\pi NA}{2H}$$

where RL = Total root length, A = Area of grid sheet, N = Number of intersections between the roots and random straight lines of the grid sheet, and H = total length of straight lines.

Root penetration ratio (RPR)

Root penetration ratio (RPR) is defined as the number of roots that entered the compacted middle section divided by the number of roots that exited the same section. Root penetration ratio was obtained by counting the number of roots that entered the top of the bottom section divided by the number of roots that exited the middle layer. For accuracy, the roots that passed between the compacted soil and the plastic cylinder were discarded. Only roots that were found inside the soil were counted and used for the calculation.

Relative root length

Relative root length (RRL) was calculated as the percent of root length in each section relative to the total root length in the whole section.

Data analysis

The data obtained in the study were subjected to Analysis of Variance (ANOVA) using SAS 9.1 Software to determine the variability in bulk density and measured plant parameters. Least Significant Difference (LSD) at 5% was used to compare treatment means.

Results

Characteristics of Ferric Acrisol (Asuansi series)

The results of the physico-chemical properties of the soil used for the experiment are presented in Table 1. Landon's (1991) guidelines were used to interpret the results. The analyses indicated that the soil is sandy loam which was moderately acidic, with very low organic carbon content, low nitrogen and medium level of phosphorus and potassium. The bulk density accords with the normal range (1.0–1.3 g/cm^3) for non –compacted mineral soils.

TABLE 1

Physico – chemical properties of Asuansi Series (Ferric Acrisol) at Kwadaso before commencement of study

Parameter	*Description*
*p*H (H_20)	5.50
Org. carbon (%)	1.26
Soil total N (%)	0.21
Available P (mg/kg soil)	22.90
Exchangeable cations (cmol(+)/kg soil) Calcium	0.21
Magnesium	2.27
Sodium	0.07
Potassium	0.33
Acidity (Al +H)	0.10
CEC (cmol(+)/kg)	8.41
Particle size distribution	
Sand (%)	60.50
Silt (%)	29.46
Clay (%)	10.04
Texture	Sandy loam
Bulk density	1.42 Mg m^{-3}

The effect of compaction on porosity, field capacity and saturated hydraulic conductivity

Total porosity ranged from 28.3%–58.5% for the bulk density of 1.9 and 1.1 Mg m^{-3}, respectively (Table 2). The respective air-filled porosities were 4.46% and 27.09%. Both total and air-filled porosity generally decreased as bulk density increased. The total porosity of 58.5% at 1.1 Mg m^{-3} decreased by 13%, 26%, 39% and 52% as bulk density increased to 1.3, 1.5, 1.7 and 1.9 Mg m^{-3}, respectively. The corresponding decreases in air-filled porosity of 27.09% at 1.1 Mg m^{-3} were 28.72%, 38.05%, 80.25% and 116%. Air-filled porosity decreased with increasing bulk density, and so also did saturated hydraulic conductivity which varied between 25.6 and 44.2 mm h^{-1} at 1.9 and 1.1 Mg m^{-3}. The hydraulic conductivity decreased as bulk density increased. Moisture content at field capacity was 17.24% at 1.9 Mg m^{-3} and 28.55% at 1.1 Mg m^{-3}. The percentage reduction in the field capacity moisture content as bulk density increased from 1.1 Mg m^{-3} to 1.3, 1.5, 1.7 and 1.9 Mg m^{-3} was 14.5, 36.7, 37.1 and 39.6.

TABLE 2

Effect of bulk density on porosity, field capacity and saturated hydraulic conductivity of the soil samples used

P_b (Mgm^{-3})	*Porosity (f) (%)*	*Percent moisture at field capacity*	*Effective porosity (%)*	*Air filled porosity (fa) (%)*	*Saturated hydraulic conductivity (mmh^{-1})*	*Water Content (èv) (%)*
1.1	58.5	28.55	29.95	27.09	44.2	31.41
1.3	50.9	24.4	26.5	19.31	41.3	31.72
1.5	43.9	18.08	25.82	16.78	38.5	27.12
1.7	35.9	17.97	17.93	5.35	29.78	30.55
1.9	28.3	17.24	11.06	4.46	25.6	32.76

The effect of compaction, soybean variety and their interactions on root mass

The analysis of variance showed that soybean root mass was significantly influenced by soil compaction (Table 3). The three varieties studied produced equal root mass. The dry root mass (Table 3) as influenced by bulk density ranked as 1.9 = 1.7 < 1.5 < 1.1 = 1.3 Mg m-3 with a range of 0.03–0.05 g. The increase of bulk density from 1.3 to 1.9 Mg m^{-3} caused a decrease in dry root mass by 40%.

Soybean root length as affected by soil compaction

Results indicated that root length was significantly ($P < 0.05$) influenced by soil compaction. With a range of 22.79–83.20 cm the effect of bulk density on root length was in the order of 1.3 > 1.1 > 1.5 > 1.7 > 1.9 Mg m^{-3} (Table 4a). Relative to 1.3 Mg m^{-3}, which recorded the highest root length of 83.20 cm, soil compaction reduced root length as bulk density increased to 1.5, 1.7 and 1.9 Mg m^{-3} by 20%, 59% and 73%, respectively. Relative root length was used to assess root distribution in the three soil sections. Relative root length was calculated as the ratio of the root length in each section to the total length in the three soil sections expressed as percentage. The results (Table 5) showed that as bulk density in the middle section increases, roots

TABLE 3

Effect of soil compaction on dry root mass of soybean and maize at 15 DAP and 21 DAP respectively

Bulk density) (Mg m^{-3})	*Maize root mass/plant (g)*	*Soybean root mass/plant (g)*
1.1	0.16	0.05
1.3	0.16	0.05
1.5	0.12	0.04
1.7	0.10	0.03
1.9	0.08	0.03
LSD (0.05)	0.02	0.05
Soybean variety		
Anidaso	0.12	0.04
Nangbaar	0.13	0.04
Ahoto	0.13	0.04
LSD (0.05)	0.02	0.01
CV (%)	15.24	15.94

TABLE 4a

Effect of soil compaction and soybean variety on root length and root penetration ratio at 15 DAP

Treatment (Bulk density) (Mg m^{-3})	*Root Length Root (cm)*	*Penetration Ratio (g)*
1.1	78.74	0.88
1.3	83.20	0.88
1.5	66.27	0.62
1.7	33.88	0.25
1.9	22.79	0.02
LSD (P < 0.05)	12.52	0.11
Soybean Variety		
Anidaso	58.67	0.57
Nangbaar	57.67	0.54
Ahoto	54.58	0.47
LSD (0.05)	19.40	0.08
CV (%)	22.82	21.04

tend to accumulate in the topsoil section. Thus, the mean relative root lengths of the top section were 11.97%, 13.22%, 19.78%, 52.59% and 76.98% for densities of 1.1, 1.3, 1.5, 1.7 and 1.9 Mg m-3, respectively. The respective mean values of the latter bulk densities for the middle section were 47.05%, 46.72%, 46.96%, 37.95% and 19.64% (Table 5).

The roots reaching the bottom section, however, decreased significantly as the density of the middle section increased.

TABLE 4b

Interaction of bulk density and soybean variety on root length and root penetration ratio

Treatment	*Root length (cm)*	*Root Penetration Ratio (g)*
Bd1V1	77.79	0.87
Bd1V2	79.61	0.89
Bd1V3	78.83	0.87
Bd2V1	83.81	0.88
Bd2V2	84.07	0.89
Bd2V3	81.72	0.87
Bd3V1	59.98	0.61
Bd3V2	70.19	0.65
Bd3V3	68.62	0.59
Bd4V1	30.65	0.00
Bd4V2	36.93	0.44
Bd4V3	34.05	0.29
Bd5V1	18.60	0.00
Bd5V2	25.15	0.00
Bd5V3	24.62	0.05
LSD (P<0.05)	10.6	0.11
CV (%)	22.82	21.04

Bd1, Bd2, Bd3, Bd4, Bd5; bulk densities at 1.1, 1.3, 1.5, 1.7, 1.9 g/cm3 respectively. V1, V2 and V3; Anidaso, Nangbaar and Ahoto.

Soil compaction and soybean varietal interactions on root length

The analysis of variance showed the bulk density × soybean interaction to cause differences in root length (Table 4b). The difference in the root length of the soybean varieties at bulk densities 1.1 and 1.3 Mg m^{-3} were not significant. However, root length at these bulk densities for each variety differed significantly ($P < 0.05$) from those of 1.5,

TABLE 5
Effect of soil compaction (bulk density) and soybean variety on root length distribution

Bulk density (Mg m^{-3})	Variety	Relative root length (%) Top	Middle	Bottom
1.1	Ahoto	11.49	46.56	41.95
1.1	Anidaso	11.70	48.14	40.69
1.1	Nangbaar	13.26	6.46	40.28
Mean		**12.15**	**47.05**	**40.97**
1.3	Ahoto	14.97	45.88	39.15
1.3	Anidaso	12.41	46.72	40.87
1.3	Nangbaar	12.27	47.57	40.16
Mean		**13.22**	**46.72**	**40.06**
1.5	Ahoto	24.04	45.55	30.41
1.5	Anidaso	17.35	48.1	34.55
1.5	Nangbaar	17.95	47.23	34.82
Mean		**19.78**	**46.96**	**33.26**
1.7	Ahoto	56.67	43.33	0
1.7	Anidaso	51.06	33.26	15.68
1.7	Nangbaar	50.03	37.25	12.72
Mean		**52.59**	**37.95**	**9.47**
1.9	Ahoto	90.12	9.88	0
1.9	Anidaso	71.32	22.05	6.63
1.9	Nangbaar	69.51	26.98	3.51
Mean		**76.98**	**19.64**	**3.38**

1.7 and 1.9 Mg m-3. Root length of each variety at the latter three bulk densities also differed significantly ($P < 0.05$). The results further showed Anidaso to record the greatest root length at each level of compaction.

Soil compaction, maize variety and their interactions on root penetration ratio

The mean root penetration ratio (Table 4b) decreased as bulk density increased with values varying from 0.25 to 0.89. The 1.1 and 1.3 Mg m^{-3} bulk densities recorded similar ratios which were significantly ($P < 0.05$) greater that than those of the 1.5, 1.7 and 1.9 Mg m^{-3}. The differences in the ratio of the latter three bulk densities were significant ($P < 0.05$). For a percentage increase of 27, 35 and 42 at 1.5, 1.7 and 1.9 Mg m^{-3} relative to the 1.1 Mg m^{-3}, root penetration ratio, respectively, decreased by 17%, 45% and 72%. At high bulk densities, a relatively small increase in density caused larger decreases in root penetration ratio. Root penetration ratio did not differ significantly among the varieties. It was, however, significantly affected by the bulk density × maize variety interaction (Table 4b).

Effect of soil compaction, maize variety on root length

Root length was significantly influenced by bulk density. The mean root length as influenced by bulk density (Table 6a) ranged from 44.44 to 133.75 cm. The differences in root length, apart from that of 1.7 and 1.9 Mg m^{-3}, were significant ($P < 0.05$). For a percentage change of 13, 24 and 32 as 1.3 Mg m^{-3} increased to 1.5, 1.7 and 1.9 Mg m^{-3} respectively, root length of maize decreased by 30%, 59% and 67%.

At the base values at the 1.3 Mg m^{-3} bulk density, root dry mass was reduced by 27%, 25% and 18% for Enibi, Mamaba and Obatanpa, respectively, at the 1.5 Mg m^{-3}. The corresponding percentage reduction values at the 1.7 and 1.9 Mg m^{-3} were 33, 31 and 35; and 53, 50, 53. The base values of root penetration ratio of the varieties at 1.3 Mg m^{-3} were reduced by 28%, 21% and 13% for Enibi, Mamaba and Obatanpa, respectively, at the 1.5 Mg m^{-3} bulk density. At the base values of root length of the varieties at 1.3 Mg m^{-3} bulk density root length of Enibi, Mamaba and Obatanpa was, respectively, reduced by 26%, 35% and 30% at 1.5 Mg m^{-3}; 60%, 96% and 57% at 1.7 Mg m^{-3}; and 67%, 67% and 66% at 1.9 Mg m^{-3}.

TABLE 6a
Root length and root penetration ratio as affected by soil compaction and maize variety

(Bulk density) (Mg m^{-3})	*Root length (cm)*	*Root penetration ratio*
1.1	119.52	0.89
1.3	133.75	0.89
1.5	93.33	0.74
1.7	54.81	0.49
1.9	44.44	0.25
LSD ($P < 0.05$)	12.11	0.09
Maize variety		
Enibi	87.26	0.63
Mamaba	85.54	0.65
Obatanpa	94.71	0.67
LSD ($P < 0.05$)	15.64	0.07
CV (%)	18.21	14.95

The effect of soil compaction and maize varietal interactions on root length

Generally, bulk density × maize varietal interactions caused significant differences in root length (Table 6b). The difference in the mean root length of V1 (Enibi) and V2 (Mamaba) at bulk densities 1.1, 1.3 and 1.5 Mg m^{-3} were not significant. Similarly the interactions of the three varieties at bulk densities 1.7 and 1.9 Mg m^{-3} were not significant. Most of the remaining interaction means were significant ($P < 0.05$).

The distribution of roots in the three soil sections as assessed by the percentage relative root length is presented in Table 7. As observed in the case of soybean, maize roots tended to accumulate in the top soil section as the bulk density of the middle section increased. The mean relative root length (Table 7) of the top section was 6.45%, 10.56%, 23.77%, 52.86% and 75.29% for densities of 1.1, 1.3, 1.5, 1.7 and 1.9 Mg m^{-3}, respectively. On the other hand, the roots reaching the bottom section decreased significantly as the density of the middle section increased.

Discussion

The impact of soil compaction on soil physical properties

The magnitude of bulk density was used as the indicator of the level of soil compaction. This forms the basis for using bulk density and soil compaction interchangeably in the discussion to express the impacts of the latter on the variables measured. As total porosity and air-filled porosity decreased under increasing compaction of the soil, so also did hydraulic conductivity. The implication of the reduced hydraulic conductivity is a decreased water flow in the soil as bulk density increases. This could adversely affect the rate

TABLE 6b
Interaction effect of bulk density and maize variety on Root Penetration Ratio (RPR) and Root Length

Treatment	*RPR*	*Root Length (cm)*
Bd1V1	0.88	117.07
Bd1V2	0.86	114.98
Bd1V3	0.92	126.50
Bd2V1	0.85	129.50
Bd2V2	0.92	129.38
Bd2V3	0.90	131.74
Bd3V1	0.71	140.13
Bd3V2	0.73	95.60
Bd3V3	0.78	85.91
Bd4V1	0.52	98.48
Bd4V2	0.50	51.81
Bd4V3	0.44	60.76
Bd5V1	0.19	42.43
Bd5V2	0.26	43.22
Bd5V3	0.29	47.67
LSD ($P<0.05$)	0.10	29.15
CV (%)	14.95	18.22

Bd1, Bd2, Bd3, Bd4, Bd5; bulk densities at 1.1, 1.3, 1.5, 1.7, 1.9 g/cm^3, respectively. V1, V2 and V3; Enibi, Mamaba and Obatanpa.

of water uptake from the soil by plant roots since, according to Hillel (1998), the rate of water uptake depends not only on rooting density (the effective length of roots per unit volume) and the difference between average soil water suction and root suction but also on hydraulic conductivity. Reduced water uptake and, hence, water availability to a crop impair shoot and root growth leading to reduction in the final yield.

Effect of soil compaction, crop genotype and their interactions on root growth

The results of the study have clearly shown that soil compaction has adverse effects on all the plant parameters studied. The root masses of both soybean and maize decreased as the dry bulk density of the soil increased. The reduction in root dry matter yield due to soil compaction has been reported (Asady *et al.*, 1985; Lipiec & Håkannsson, 2000). The reduction in the root growth was due to the adverse impacts of compaction on soil properties. These include increased mechanical impedance, reduction in infiltration and hydraulic conductivity (Table 2) resulting from a decrease in volume and continuity of the large soil pores which are most conducive to water.

Under the condition of increased bulk density and reduced volume of large pores in the soil, the forces of the root necessary for deformation and displacement of the soil particles become limiting, root elongation rates decrease and the growth of the roots is impaired (Marschner, 1995). According to Bengough & Mullins (1990) and Cook *et al.* (1996), such conditions increase mechanical impedance, reduced oxygen, water and nutrient availability and create unfavourable conditions for root growth. The prevalence of these unfavourable conditions at the higher bulk densities (1.7 and 1.9 Mg m^{-3}) in this study, coupled with increased mechanical impedance as bulk density increased, possibly accounted for the recorded reductions in the root dry matter yield, root length and root penetration ratios.

Root length is very important in the exploitation of soil water and nutrients from the soil by roots for plant growth (Marschner, 1995). The results under both soybean and maize showed a decreased root length alongside the reduced root dry mass yield due to increasing soil compaction. By recording the highest root length of 83.20 cm and 133.75 cm under soybean and maize, respectively, the bulk density of 1.3 Mg m^{-3} though not significantly different from the

TABLE 7

Effect of soil compaction (bulk density) and maize variety on root length distribution

Bulk density(Mg m⁻³)	*Variety*	*Relative root length (%)*		
		Top	*Middle*	*Bottom*
1.1	Enibi	6.54	50.26	43.20
1.1	Mamaba	6.71	47.93	45.36
1.1	Obatanpa	6.10	51.39	42.51
Mean		**6.45**	**49.86**	**43.69**
1.3	Enibi	11.22	50.96	37.82
1.3	Mamaba	12.45	47.00	40.55
1.3	Obatanpa	8.0	53.47	38.53
Mean		**10.56**	**50.48**	**38.97**
1.5	Enibi	22.51	50.35	27.14
1.5	Mamaba	25.37	43.34	31.29
1.5	Obatanpa	23.44	49.55	27.01
Mean		**23.77**	**47.75**	**28.28**
1.7	Enibi	53.96	34.34	11.70
1.7	Mamaba	49.32	33.75	16.93
1.7	Obatanpa	55.30	32.21	12.49
Mean		**52.86**	**33.43**	**13.71**
1.9	Enibi	75.5	19.96	4.54
1.9	Mamaba	74.45	21.32	4.23
1.9	Obatanpa	75.92	18.18	5.90
Mean		**75.29**	**19.82**	**4.89**

1.1 Mg m^{-3}, appear to be the most ideal for root and seedling growth of soybean and maize. On the other hand, the bulk densities of 1.7 Mg m^{-3} and 1.9 Mg m^{-3} were very restrictive to root growth and dry matter yield in both soybean and maize. Apart from the adverse soil conditions due to compaction alluded to earlier for the reduction in root length, Glinski & Lipiec (1990) pointed out that the growth of roots in compacted soil requires much greater energy to form and sustain a unit root length.

The percentage relative root length, which was used to assess root distribution in the three soil sections, showed concentration of roots in the uncompacted topsoil section as the bulk density of the middle section increased. Kirkgaard *et al*. (1992) also observed that when only one compacted layer occurs in the soil (e.g. from tillage operations) as occurred in the middle of the three soil section assemblies in the study, a reduction in root growth in the compacted zone of high soil strength is often compensated for by higher growth rates in loose soil above or below the compacted zone. This occurs unless gas exchange (O_2 or CO_2) becomes a limiting factor for root growth and activity because of a high rooting density in the loose soil zone (Asady & Smucker, 1989).

In the study, excessive soil compaction drastically reduced the percentage of roots exiting the compacted zone. Small increases in bulk density caused significant reductions in root penetration ratio. Soybean was generally more sensitive to soil compaction than maize. In a similar soil section experiment, Asady *et al.* (1985) found that as bulk density of the middle section increased, root penetration ratio decreased. The reduction was attributed among other factors to reduced air-filled porosity, as recorded in this study (Table 2), which, in turn, created an oxygen stressed environment for root growth.

The main effect of the soybean varieties, which is the average over the five levels of bulk density, showed no significant differences in the dry root mass, root length and root penetration ratio. While the main effect of bulk density showed a general reduction in the above listed root parameters for both soybean and maize with increasing bulk density, it reveals nothing about the magnitude of response of the individual crop varieties at the levels of bulk density studied. Yet, such information is needed to facilitate the choice of tolerable varieties for different levels of soil compaction. This gap is filled by the results of the bulk density × crop variety interaction. As observed under soybean, a preferable bulk density range of 1.1–1.3 Mg m^{-3} and perhaps up to 1.5 Mg m^{-3} is more favourable for maize root growth with 1.7 and 1.9 Mg m^{-3} considered limiting.

Conclusion

The study has amply shown the impact of soil compaction, crop variety and their interactions on some soil and plant parameters. Soil compaction reduced dry root mass, root length and root penetration ratio of maize and soybean seedlings. Subsoil compaction induced accumulation of maize and soybean roots in the upper uncompacted soil. The magnitude of root accumulation in the uncompacted layer increases with increasing bulk density. The study has shown that soybean roots are more sensitive to soil compaction than maize roots and has indicated the ideal bulk density for maize and soybean seedling growth to be in the range of 1.1–1.5 Mg m^{-3} with 1.3 Mg m^{-3} being the most preferable. The three maize varieties showed similar tolerance to soil compaction as was the case with soybean. Though the study was a pot experiment and may not fully depict soil compaction on the field, the results could provide a firsthand information for breeders and growers on relative tolerance of crops to soil compaction.

References

Adu S. V. (1992). Soils of the Kumasi region, Ashanti Region, *Ghana Soil Research Institute (CSIR) Memoir* No **8**.

Asady G. W., and **Smucker J. M.** (1989). Compaction and root modifications of soil aeration. *American Journal of Soil Science Society* **53***:*251–254.

Asandy G. H., Smucker A. J. M. and **Adam M. W.** (1985). Quantitative measurements of root tolerance to compacted soil. *Crop Science* 25: 802–806.

Barraclough P. B. and **Weir A. H.** (1988). Effects of a compacted subsoil layer on root and shoot growth, water use and nutrient uptake of winter wheat. *Journal of Agricultural Science* **110**: 207–216.

Bray R. H. and **Kurtz L. T.** (1945) Determination of total organic and available forms of phosphorus in soil. *Soil Science* 599: 39–45.

Bengough A. G. and **Mullins C. E.** (1990). Mechanical impedance to root growth: a review of experimental techniques and root growth responses. *J. Soil Sci.* **41:** 314–358.

Blake G. R. and **Hartage K. H.** (1986). Bulk density. In *Methods of soil Analysis. Part I. Physical and mineralogical methods*. (A. Klute, ed.) Monograph No. 9 Amer. Soc. Agronomy of Soil Science Soc. America Madison Wisconsin.

Black C. A. (1986). *Methods of soil analysis, I. Physical and mineralogical properties, including statistics of measurement and sampling. II. Chemical and microbiological properties*. Agronomy Series, ASA, Madison. Wis.

USA.

Boyoucos G. J. (1962). Hydrometer methods improved for making particle size analysis of soils. *Soil Sci. Soc. Am. Proc.* **26**: 464–465.

Cook A., Marriot C. A., Seel W. and **Mullins E. C.** (1996). Effects of soil mechanical impedance on root and shoot growth of *Lolium perenne* L., *Agrostis capilaris* and *Trifolium repens* L. *J. Exp. Bot.* **47**: 1075–1084.

FAO (1990). Soil Map of the World. Revised Legend. World Soil Research report No 60. FAO, Rome.

Glab T. (2007). Effect of soil compaction on root system development and yield of tall fescue. *Int. Agro-Physias* **21**: 233–239.

Glinski J. and Lipiec J. (1990). *Soil physical conditions and plant roots*. CRC Press, Boca Raton, Fl., 250.

Gupta S. C. and **Allmaras R. R.** (1987). Models to assess the susceptibility of soils to excessive compaction. *Advances in Soil Science* **6**: 65–100.

Hamza M. A. and **Anderson W. K.** (2003). Responses of soil properties and grain yields to deep ripping and gypsum application in a compacted layer loamy sand soil contrasted with sandy clay loam soil in Western Australia. *Australian Journal of Agricultural Research* **54**: 273–282.

Hillel D. (1998). *Environmental Soil Physics*. Academic Press. San Diego, CA. 771 pp.

Jorge F. F., Itaynara B. and **Ciro A. R.** (2013). Sensitivity of cotton cultivars to soil compaction. *Ciências Agrárias, Londrina* **34**(6): 3645–3654.

Kirkegaard J. A., SO H. B. and **Troedson R. J.** (1992a). The effect of soil strength on the growth of pigeon pea radicles and seedlings. *Plant Soil* **140**: 74–75.

Kirkegaard J. A., SO H. B., Troedson R. J. and **Kushwaha B. L.** (1992b). The effect of compaction on the growth of pigeon pea on clay soils. II. Mechanisms of crop response and season effects on an Oxisol in a humid Coastal Environment. *Soil Tillage Research.* **24**:129–147.

Kramer P. J. (1969). *Plant and Soil Water Relationships. A Modern Synthesis*. McGraw-Hill, New York. 482 pp.

Landon J. R. (1991). *Booker Tropical Soil Manual. A handbook for Soil Survey and Agricultural Land Evaluation in the Tropics and Subtropics.*

Lipiec J., Hakansson I., Tarkiewicz S. and **Kossowski J.** (1991) Soil physical-properties and growth of spring barley as related to the degree of compactness of two soils. *Soil and Tillage Research* **19***:* 307–317.

Lipiec J. and **Hakansson I.** (2000). A review of the usefulness of relative bulk density values in studies of soil structure and compaction. *Soil Tillage Research* **53**:71–85.

Marschner H. (1995). *Mineral nutrition of higher plants,* 2nd edn. Academic Press. London. 889 pp.

McGarry D. (2001). Tillage and soil compaction. In *First World Congress on Conservation Agriculture*. (L. Garcia-Torres, J. Benites and A. Martinez-Vilela, eds.), pp. 281–291. Madrid, Spain, Natural Resouce Sciences.

Nelson D. W. and **Sommers L. W.** (1982). Total carbon, organic carbon, and organic matter. In *Methods of soil Analysis. 2. Chemical and Microbiological Properties*. (A. L. Page, R. H. Miller, and D. R. Keeney, eds.). *Agronomy* **9**: 301–312.

Newman E. I. (1966). A method of estimating the total length of root in sample. *J. Appl. Ecol.* **11**: 135–145.

Oldeman I. R., Hakkeling R. T. A. and **Sombroek W. G.** (1991). *World map of the status of human induced soil degradation, an explanatory note.* ISIRC. Wageningen, Netherlands/UNEP, Nairobi, Kenya. 34.

Page A. L., R. H. Miller and **Keeney D. R.** (eds) (1982). *Methods of soil analysis. Part 2. Chemical and microbiological properties*. 2nd edn. Agronomy series 9, ASA, SSSA, Madison, Wis. USA.

Passioura J. B. (2002). Soil compactions and plant growth. *Pl. Cell Envir.* **25**: 311–318.

Petersen M., Ayers P. and **Westfall D.** (2006). *Managing soil compaction. www.ext.colostate.edu/pubs/CROPS/00519.html*

Radford B. J., Bridge B. J., Davis R. J., McGarry D., Pillai U. P., Rickman J. F., Walsh P.A. and **Yule D. F.** (2000). Changes in the properties of a Vertisol and responses of wheat after compaction with harvester traffic. *Soil Tillage Research* **54**: 155–170.

Sadras V. O., O'Leary G. J. and Roget D. K. (2005). Crop responses to compacted soil capture and efficiency in the use of water and radiation. *Field Crop Research* **91**: 313–148.

Sands R., Greaten E. L. and **Gerard C. J.** (1979).

Compaction of sandy soils in radiata pine forests. In a penetrometer study. *Aust. J. Soil Res.* **17**:101–l 13.

Sérgio R. S., Ivo R. S., Nairam F. B. and **Eduardo S. M.** (2011). Effect of compaction on microbial activity and carbon and nitrogen transformations in two oxisols with different mineralogy. *Rev. Bras. Ciênc. Solo*: **35** (4).

Slowinska-Jurkiewicz A. and **Domzal H.** (1991). The structure of the cultivated horizon of soil compacted by wheels of agricultural tractors. *Soil Till Res.* **19** (2–3) 215–226.

Soane B. D. and **Van Ouwerkerk C.** (1994). Soil compaction problems in World agriculture, In *Soil compaction in crop production developments in agricultural engineering.* (B. D. Soane and C. Van Ouwerkerk, eds), pp. 1–26. Elsevier, Amsterdam.

Soils Laboratory Staff. Royal Tropical Institute. (1984). *Analytical methods of the service laboratory for soil, plant and water analysis. 1. Methods for soil analysis*. Royal Tropical Institute, Amsterdam.

Taylor C. J. (1952). *The vegetation zones of the Gold Coast*. Govt. Printer. Forestry Dept. Bull. No. 4, Accra.

USDA (1998). *Year Book of Agriculture*. Washington.

Vickers B. (1983). *Laboratory work in soil mechanics,* 2nd edn. Granada, London, U.K. 170 pp.