KWAME NKRUMAH UNIVERSITY OF SCIENCE AND TECHNOLOGY, KUMASI, GHANA

THE RESPONSE OF ROOTS AND BIOMASS YIELD OF SOYBEAN AND MAIZE SEEDLINGS TO DIFFERENT LEVELS OF SOIL COMPACTION

A THESIS SUBMITTED TO THE DEPARTMENT OF CROP AND SOIL SCIENCES, COLLEGE OF AGRICULTURE AND NATURAL RESOURCES, KWAME NKRUMAH UNIVERSITY OF SCIENCE AND TECHNOLOGY, KUMASI, GHANA, IN PARTIAL FULFILMENT OF THE REQUIREMENTS FOR THE AWARD OF MASTER OF SCIENCE DEGREE IN SOIL SCIENCE

BY

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DECLARATION

I, hereby, declare that this is the result of my one original research and that no part of it has been presented for another degree in this University or elsewhere.

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We hereby declare that the preparation and presentation of the thesis were supervised in accordance with the guidelines on supervision of thesis laid down by the University.

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DEDICATION

In all things give thanks and praises. It is on this note that I wish to dedicate this work to my mother Amitor Golomeke and Late Father, Francis Ocloo, because whatever I am today has been partly through their efforts. Sharing this dedication is Joyce Duah and the children.

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ABSTRACT

Two factorial experiments were carried out in a greenhouse at the Soil Research Institute, Kwadaso, Kumasi to investigate the response of roots and biomass yield of maize and soybean seedlings to different levels of soil compaction.

The treatments in each of the experiments comprised 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.). The experimental set up was a completely randomized design (CRD) with three replications.

The soybean and maize were grown in a stack of three polyvinyl (PVC) cylinders filled with the test soil and consisted of top, middle and bottom cores with a height of 2.5cm, 5cm and 8cm 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 cores, to which the five compaction treatments were applied, were sandwiched between the top and bottom cores each of which had a bulk density of 1.1 Mg m^{-3}. The three cores were sealed together into one air-tight and water-tight soil container by wrapping them with a plastic tape.

The soil parameters measured were bulk density, total and air-filled porosity, saturated hydraulic conductivity and field capacity. The plant parameters, measured 15 and 21

days after planting (DAP) of soybean and maize respectively, comprised plant height, root and shoot dry mass, root length, root penetration ratio and root:shoot ratio. The data were analyzed statistically for ANOVA using SAS software and regression analysis was used to establish the correlation between parameters and to produce predictive equations.

Total porosity and air-filled porosity generally decreased as bulk density increased with the former and latter ranging from 28.3 to 58.5% and -4.46 to 27.09% respectively at the bulk densities of 1.9 and 1.1 Mg m^{-3}. Air-filled porosity was more sensitive to soil compaction.

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 percent as bulk density increased from 1.1 to 1.3, 1.5, 1.7 and 1.9 Mg m^{-3}. Moisture content at field capacity (FC) decreased as bulk density increased with a value of 17.24 and 28.55 percent for the 1.9 and 1.1 Mg m^{-3} respectively.

Soil compaction, crop variety and their interactions significantly ($P<0.05$) influenced the measured plant parameters of soybean and maize. Increases in bulk density generally caused significant decreases in all the measured plant parameters except the root : shoot ratio which increased. The significant differences ($P<0.05$) were generally recorded between the lower (1.1 to 1.5 Mg m^{-3}) and higher (1.7 and 1.9 Mg m^{-3}) bulk densities.

The distribution of roots in the three soil cores, assessed as the ratio of root length in each core to the total root length in the three cores, expressed as percentage relative root length, showed a tendency of the roots to accumulate in the top core and a decrease in the bottom core as the bulk density of the middle core increased. The respective relative root lengths of the 1.1 and 1.9 Mg m^{-3} for soybean were 11.97 and 76.98 percent on the top core, 47.05 and 19.64 percent in the middle core, and 40.97 and 3.38 percent in the bottom core. The corresponding values for maize were 6.45 and 75.29 percent in the top core, 43.69 and 19.82 percent in the middle core and 49.86 and 4.89 percent in the bottom core.

Significant ($P<0.05$) varietal differences were recorded in soybean shoot dry mass and root penetration ratio. These parameters ranked as Anidaso>Nangbaar>Ahoto. In maize no significant ($P<0.05$) varietal differences were recorded in the measured plant parameters. However, the bulk density × maize variety interaction showed significant differences in these parameters. Such information may be confounded when only the main effects are examined.

The implication of the significant bulk density × crop variety interaction is that the magnitude of the effect of each factor depended on the level of the other factor.

Parameter relationships through regression analysis showed a highly negative correlation (r) between soil compaction and the measured plant parameters. The high coefficient of determination (R^2) of the regression equations make them satisfactory for predictive purposes. Correlations and predictive equations have also been established between soil porosity and measured plant parameters. The correlation in all cases was positive.

The intercept of the regression equations showed a unit increase in bulk density to reduce plant height of soybean by 12.9 cm, shoot and root dry masses by 0.43g and 0.03g respectively, root length by 80.16 cm and root penetration ratio by 1.18. The corresponding values for maize were 6.67 cm, 0.51 and 0.11 g, 114.55 cm and 0.84.

Soybean roots were more sensitive to increasing soil compaction than maize. Soil compaction reduced shoot dry matter more than root dry matter as bulk density increased. The root:shoot ratio, therefore increased with increasing soil compaction. The implication of abscicic acid (ABA) in this phenomenon is discussed. The ideal bulk density for the growth of soybean and maize was 1.1 to 1.5 Mg m^{-3} with 1.3 Mg m^{-3} being the most preferable based on the performance of measured plant parameters.

The limited study of the anatomical structures of the roots showed soil compaction to adversely impact on the epidermis, cortex, endodermis and the vascular bundles. The distortion and destructive impacts of soil compaction on the anatomical features were more severe at the 1.9 Mg m^{-3} and on soybean than maize. At the latter bulk density, the anatomical features were hardly discernible.

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CHAPTER ONE

1.0 INTRODUCTION

The overall suitability of a soil as a medium for plant growth depends not only upon the presence and quantity of chemical nutrients and the absence of toxicity, but also upon the state and mobility of water and air and the mechanical attributes of the soil. The soil must be loose and sufficiently friable to permit germination and root development without mechanical obstruction.

Generally, a good soil for crop production contains about 25 percent water and 25 percent air by volume. This 50 percent is referred to as pore space. The remaining 50 percent consists of solids made up of 45 percent mineral matter and 5 percent organic matter. Traditional agriculture has been compatible with ecological environment due to:

1) Low population pressure;
2) Improvement in soil structure by plant roots;
3) Erosion control through leaf litter, mulch and continuous canopy cover;
4) Nutrient contribution through ash and recycling by deep-rooted perennial.

However, the ever growing population of Ghana and elsewhere has resulted in the clearance of more land for crop production and farmers are encouraged through incentives by the government to shift from the use of simple tools such as the hoe and cutlass to increased use of tractor mounted implements.

Excessive and improper use of the latter cause soil compaction which is manifested in increased bulk density and reduced sizes and abundance of soil pores. These, in turn, impede root growth and adversely affect soil infiltrability and water storage and utilization, nutrient uptake and soil aeration. The overall effect causes increased 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).

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. Although genetic selection for adaptation to adverse environments may have contributed to greater crop production, studies on root tolerance to soil compaction, has not received much research attention. Meanwhile, the problem of soil compaction is becoming more severe as big and heavier machines continue to be used. According to Oldeman *et al*. (1991) 18 million hectares of Africa's land has been degraded by compaction, sealing and crusting. At the global level, compaction induced soil degradation affects about 68 million hectares of land. 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 indicate that different crops and even different cultivars of the same crop may have varying levels of tolerance to soil compaction. A crop that is better able to tolerate soil compaction and still maintain 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 core 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 regard, not much work has been done.

1.1 Research Objective

This study therefore seeks to investigate the responses of roots and dry matter yield of three varieties each of soybean (*Glycine max*) and maize (*Zea mays*) to soil compaction. The objective is based on the hypothesis that soil compaction has no significant effect on crop growth and yield.

CHAPTER TWO

2.0 LITERATURE REVIEW

2.1 What is Soil Compaction?

The Soil Science Society of America, (1996), defines soil compaction as the process by which the soil grains are re-arranged to decrease void space and bring them into closer contact with one another thereby increasing the bulk density.

Marshall and Holmes (1998), reported that soil and its layers may become compact naturally due to changes in their textural composition and moisture regime. Compaction can be influenced by internal and external factors (Bennie and Krynauw, 1985). The internal factors of importance are mineralogical composition, texture, organic matter and water content during the compaction process while the external factors are mainly the energy applied over the soil mass such as rain drop impact (Mckyes, 1985; Hodara and Slowinska-Jurkiewicz, 1993) and trampling by animals and humans (Tanner and Mamaril, 1959; Kozlowski, 1999). Human activity can compact the soil during agricultural activities such as the use of agricultural machinery (Hadas, 1994). Soil compaction due to animal trampling adversely affects soil properties and plant growth particularly under wet soil conditions. These properties include penetration resistance, water and nutrient movement over and through the soil (Di *et al*., 2001; Scholz and Hennings, 1995; Vahhabi *et al*., 2001).

According to Abu-Hamdeh and Al-jalil (1999), many compaction symptoms are related to changes in the soil's physical properties. Among these, soil bulk density and/or soil strength are most frequently used as a measure or indicator of soil compaction (Bennie, 1990; Kozlowski, 1999; USDA-NRCS, 1999).

2.2 Effect of Machinery Traffic and Animal Trampling on Soil Compaction

Soil compaction by machinery traffic in agriculture is a well recognized problem in many parts of the world (Raghavan *et al*., 1990; Soane and Van Ouwerkerk, 1994; Hamza and Anderson 2005). Compaction induced by vehicular traffic has adverse effects on a number of key soil properties such as bulk density, mechanical impedance, porosity and hydraulic conductivity (Radford *et al*. 2000; Hamza and Anderson 2005). All these factors can potentially reduce root penetration, water extraction and plant growth (Kirkegaard *et al.,* 1992a; Passioura, 2002). Evidence of reduction in crop yield as a result of soil compaction has been reported for dryland (rainfed) cropping systems (Ellington, 1986; Radford *et al.*, 2001; Hamza and Anderson 2003; Sadras *et al*., 2005). Any mechanical force, such as that exerted by tractor wheel traffic and/or animal and human trafficking on the soil reduces pore space with a resultant increased bulk desnity, poor internal drainage, reduced aeration and soil compaction. (Hamza and Anderson, 2003; Aliev, 2001; Ohtoma and Tan, 2001)

2.3 Soil Compaction and Hydraulic Conductivity

Many of the important functions of soils such as buffering, filtering, transport of chemicals (including nutrients and pollutants and transport of water to plant roots) occur in the unsaturated zone which lies between the water table and the soil surface (Dexter, 2004).

Zhang *et al.* (2005) reported that soil compaction affects hydraulic properties and thus can lead to soil degradation and other adverse effects on environmental quality. The detrimental effects of soil compaction caused by traffic include increased bulk density, decreased porosity and shifts in pore shapes and size distributions (Flowers and Lal, 1998; Radford *et al.*, 2000; Richard *et al*., 2001). Changes in these basic properties alter the soil's water retention and hydraulic conductivity which in turn affect soils infiltrability and its plant available water storage capacity.

According to Veen *et al*. (1992) both low saturated hydraulic conductivity and poor root to soil contact may negatively influence uptake of water and nutrients. Carpenter *et al.* (1985) in discussing the effect of wheel loads on subsoil stresses stated that although soil compaction affects many important soil physical properties, perhaps the most detrimental effect is the drastic reduction in hydraulic conductivity which ultimately results in soil erosion and reduced crop yields due to reduced infiltration, increased runoff and poor drainage.

Field management practices and tillage may introduce soil disturbances such as soil compaction and this, in turn, may affect hydraulic conductivity. Dorel *et al*. (2000) showed that soil hydraulic conductivity was drastically reduced in the compacted layers of a mechanised banana plantation. Studies by Marsili *et al.* (1998), Servadio *et al.* (2001) and Pagliai *et al.* (2003) have shown that the decrease in soil porosity in the compacted areas following the passage of agricultural machinery was strongly correlated with an increased soil penetration resistance and reduced hydraulic conductivity.

2.4 Soil Compaction effects on Aeration, Porosity and Root Growth

Soil compaction decreases soil porosity, particularly the volume of the large inter aggregate pores (Macropores). Macro porosity describes the volumetric percentage of pores greater than 30 µm diameter. Macropores are responsible for adequate soil aeration and rapid drainage of water and solutes through the soil (Mclaren and Cameron, 1996).

Rab (2004) reported that macropore volume less than 10% generally restricted root growth. Czyz *et al*. (2001) observed that aeration is one of the physical factors which may limit the development of plant root systems and growth and yield of crops on compacted soils. Boone and Veen (1994) noted that crop yield will be reduced only if compaction limits root development and function such that crops cannot obtain air, water and nutrients at adequate rate. According to Stepniewski *et al*. (1994) and Hakansson and Lipiec (2000), the transient nature of insufficient aeration makes it difficult to relate it to crop yield response due to soil compaction.

2.5 Types and Functions of Roots

The three universal functions of all roots are anchorage, absorption and translocation of water with dissolved nutrients. In many perennial and biennial species, roots are also sites for food storage.

There are two major types of root systems; fibrous and tap root systems. Fibrous roots are adventitious, arising from the lowest nodes of the stems. Species with fibrous system such as maize are more shallowly rooted than plants with persistent tap roots.

Most dicots such as soybean have a tap root system. The taproot originates from the primary root (radicle) of the seed. The taproot may have many branches originating from it. Roots of legumes may also have root nodules, which are sites for nitrogen fixation. A root can be divided into the zone of maturation, zone of cell elongation and the zone of cell division (apical meristem) protected by the root cap.

All the root cells originate from the divisions of the cells of the apical meristem. These cells are small, thin-walled, and contain large nuclei. Root meristem is protected by the root cap. The root cap is a dynamic, multifunctioning organ.

The primary root tissues are the epidermis, the outermost layer of cells covering the root surface, cortex that surrounds the stele, and the vascular tissue or stele, which occupies a central position. The root epidermis is usually a single cell layer that protects the root. The cells of epidermis can elongate to produce root-hairs. These root hairs have larger surface area and are more efficient in absorbing water. Root hairs are also the sites of Rhizobium invasion of the legumes.

The soybean root hairs (Fig. 2.1), containing the cortex cell are composed of thin-walled parenchyma cells which are frequently arranged in radial rows or concentric circles. The root cortex region frequently functions as a major storage region, its parenchyma cells are packed with starch grains or other compounds. The innermost layer of the cortex is endodermis. The endodermis is a single cellular layer enclosing the vascular cylinder.

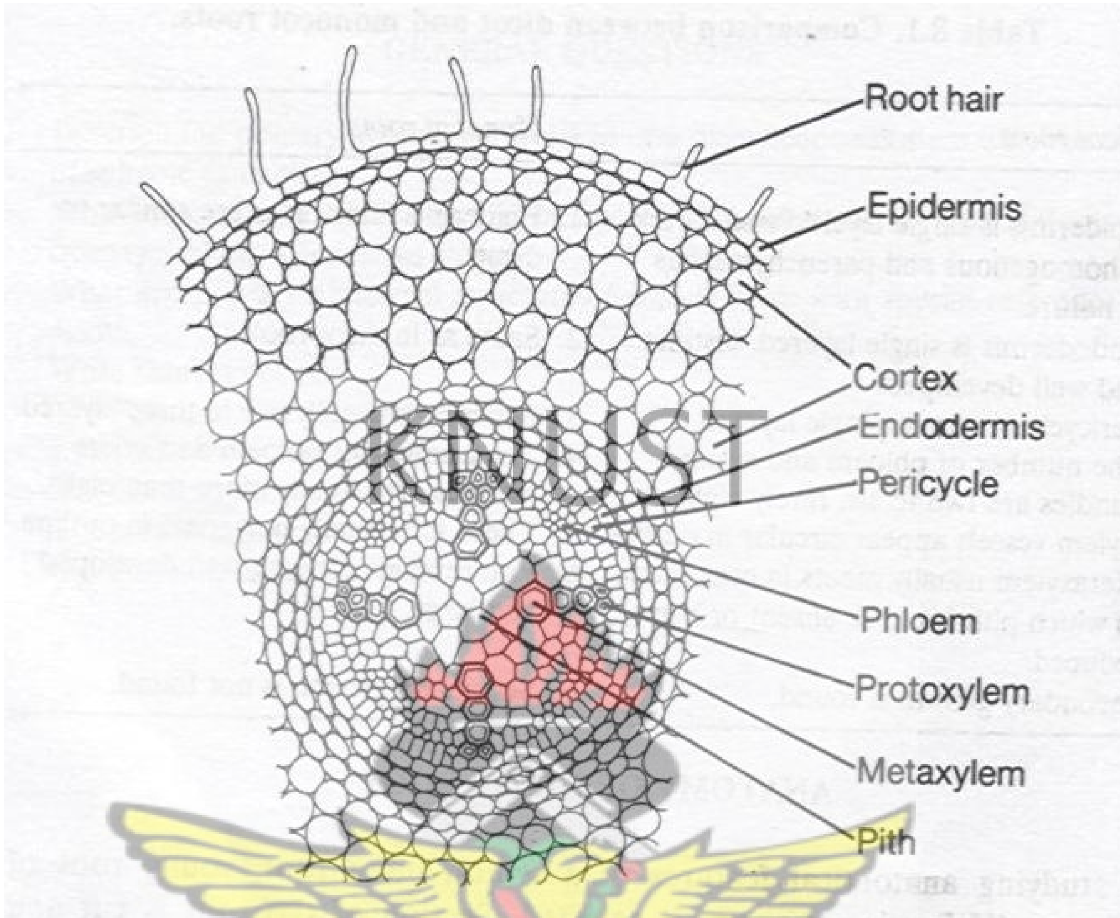

Fig. 2.1 A cellular enlarged portion of T.S. of root of sunflower (*Helianthus annuus*) (Dicot)

Source: Pandey and Chadha (2008)

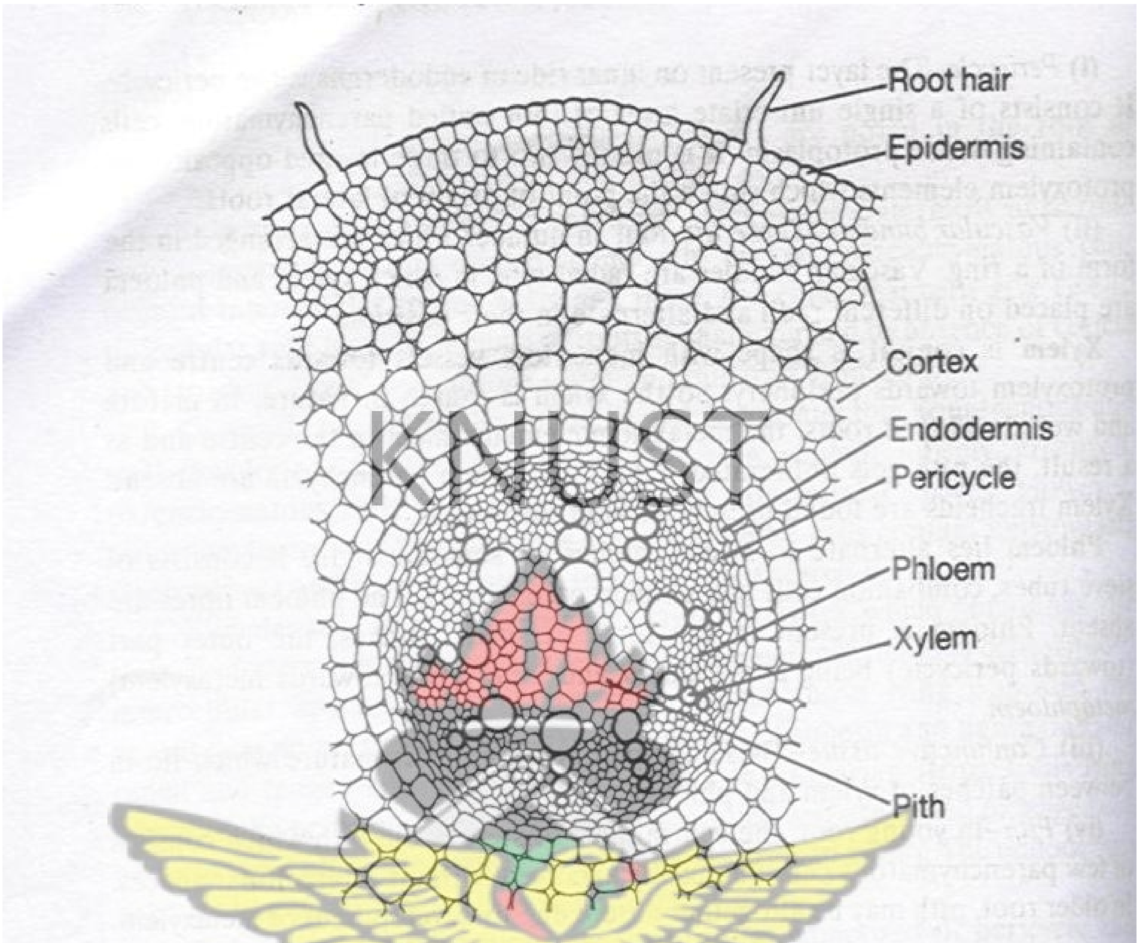

Fig. 2.2 A cellular enlarged portion of T.S. of root of Commelina showing cells of inner cortex arranged in concentric rings (monocot)

Source: Pandey and Chadha (2008)

The central region of the root (stele) consists of xylem, phloem and associated parenchyma cells. The number of phloem and xylem bundles are two to six, pericycle (single layered in dicots and two to three layered in monocots (Fig. 2.2)), rarely eight in dicots, and usually more than eight in monocots. When xylem occupies the centre of the root, it has variable number of extensions projecting outward towards the endodermis. The phloem tissue lies between these radiating arcs of xylem. In Monocots, where pith is present, the vascular tissue takes the form of discrete strands of xylem with alternating strands of phloem, like in the roots of corn, grains, turf and other grasses.

The main function of xylem is the upward transport of water and dissolved nutrients. The phloem is the tissue through which photosynthate manufactured by the leaves and other green parts of the plant is translocated to other regions of the plant (Teplitski and McMahon, 1999).

2.6 Soil Compaction, Root Structure and Anatomy

There are two main ways by which soil compaction can influence the anchorage strength of plants. Firstly soil compaction affects soil strength which is an integral component of all anchorage models for cereals. Depending on the mechanism of root lodging soil strength affects either the resistance of the root-soil bond to failure by axial or shearing root movements (Ennos, 1989; Ennos, 1991 and Easson *et al.,* 1995).

Secondly, soil compaction affects root growth and thus the ability of root systems to provide anchorage to a plant. Roots are generally unable to penetrate pores narrower than their own diameter (Lampurlanés and Cantero-Martinez, 2003). Plant roots respond to compacted layers by thickening and/or deflection. Materechera *et al*. (1991) showed that thickening of roots was a significant response for both monocotyledons and dicotyledons. By thickening, the root is able to exert a greater axial pressure and thereby perhaps be able to penetrate the layer (Misra *et al.,* 1986). When the root deflects, it often grows horizontally until it finds a vertical pore as reported by Stirzaker *et al*. (1996) and Munkholm, (2000).

Plants are able to modify their root growth in heterogenous soil to more efficiently take up water and nutrients (Walch-Liu *et al*., 2006). As the resistance to root penetration increases, the rate of root growth is reduced, the morphology of the root is changed and important processes occurring in the shoot are adversely affected (Young *et al*., 1997 and Passioura, 2002).

The decrease in macroporosity causes mechanical impedance and subsequently morphological changes to plant root systems (Goodman and Ennos, 1999). The branches of the mature bare roots in compacted soils are mostly short and fine (Varney *et al*., 1991) and have lost their tips (Varney and McCully, 1991).

Dawkins *et al*. (1983) found that the shoot: root ratio in peas was smaller when roots were growing in compacted soils than in loosened soils, suggesting that shoot growth might be more susceptible to soil compaction than root growth.

Masle and Passioura, (1987) grew wheat seedlings for 22 days in small cores of compacted soil and found that shoot growth and development were severely restricted. Russell and Goss, (1974) reported that root mass is not as strongly affected by mechanical impedance as root length.

Root diameters of maize (Barley *et al*., 1965), rice and barley (Abdalla *et al*., 1969) and cotton and peas (Taylor and Ratliff, 1969) increased when roots were mechanically impeded under controlled conditions.

Wilson *et al*. (1977) studied the anatomical changes in roots of barley and found that the cells of the inner and outer cortex were affected differently and even stelar dimensions might be altered by mechanical impedance. Cells are continuously released from the periphery of the root cap. Together with the root-cap mucilage, to which these cells are associated, a boundary layer is created between the plant root and the soil. The number of cells released into this boundary layer from caps of maize (*Zea mays*) root was found to increase 1.7 fold when the roots were grown in compacted sand compared with the number of cells obtained from the caps of roots grown in loose sand (Iijima *et al*., 2000).

It is well known that when plant roots are grown in compacted soil, they become thickened (Iijima and Kono, 1992; Iijima *et al*., 1991) and the root surface is often distorted (Baligar *et al*., 1975).

According to Kirby and Bengough (2002) the dimensions of the root cap have not been analyzed fully, even though the cap is the portion of the root apex that experiences the peak mechanical stress during its passage through the soil. One possible consequence of impedance is that soil particles more readily abrade cells from the surface of the cap.

Mechanical impedance causes a decrease in the root elongation rate, an effect which persists for several days even after the impedance is removed (Goss and Russell, 1980; Croser *et al*., 2000). This slowing of root elongation is associated with both a decrease in final cell length and slower rate at which new cells are produced and added to the cell files that comprise the meristems (Croser *et al*., 1999).

According to Russell (1977), in compacted soils the spaces (pores) between soil particles are reduced either in number and/or in size. Root penetration into these pores may be inhibited because of mechanical resistance of the soil, and there may be attendant changes in the structural characteristics of impeded roots which typically reduce growth rates of the root, and thickened roots (Russell and Goss, 1974; Wilson *et al.*, 1977).

Typical structural modifications observed include changes in the size of the vascular tissue, changes in number and size of epidermal cells; increases in diameter and often in number of cortical cells and modification in the branching patterns of lateral roots. Each of these changes may be brought about by exposing roots to small increases in pressure (Goss, 1977; Greacen and Oh, 1972).

Root development is often limited to the upper soil layers because of compaction (Logsdon *et al*., 1987). In controlled conditions, Bengough and Young (1993) suggested that the effect of bulk density on root elongation in pea seedlings also depended on the supply of assimilate to the root, which varied according to crop requirement and the interaction between weather and soil conditions. Boone and Veen (1994) observed that soil compaction effects extend beyond root morphology to affect both shoot morphology and general plant physiology. A reduction in leaf area and shoot biomass was observed in maize plants grown on compacted soils (Ekwue and Stone, 1995).

2.7 Soil Compaction and Plant Growth and Yield

Soil compaction results in increased soil bulk density and reduced porosity and may negatively affect plant growth through the consequent increase in soil penetration resistance and reduction in aeration (Kirkegaard *et al*., 1992b; Hoffmann and Jungk, 1995; Misra and Gibbons, 1996; Ishaq *et al*., 2001 and Passioura, 2002).

Top soil compaction can cause reduction in water infiltration rate and root growth and development thereby inducing severe problems to crop growth and yield. Compaction may significantly impair the productive capacity of a soil. Evidence exists to show that soil compaction originating from anthropogenic or natural causes exerts an enormous impact on the establishment, growth and yield of crops in tropical regions (Kayambo and Lal, 1994). According to Glinski and Lipiec (1990) and Townsend *et al*. (1996), mechanical impedance of soil is an important constraint to root and shoot growth. Compaction can reduce plant growth, root penetration, restrict water and air movement in the soil, induce nutrient stress and cause slow seedling emergence with resultant low yields.

McGarry (2001), reported that although soil compaction is regarded as most serious environmental problem caused by conventional agriculture, it is the most difficult type of degradation to locate and rationalize since it may show no evidence marks on the soil surface, unlike erosion and salinity that gives strong surface evidence of the presence of land degradation.

A reduction in pore size and continuity increases the probability that plant roots will encounter and penetrate soil aggregates thus creating new root channels in which they will have complete contact with the surrounding soil matrix (Kooistra *et al*., 1992). According to Motavalli *et al*. (2003) surface compaction in clay pan soil reduced both corn silage grain yield approximately 47% in 2000 and 20% in 2001.

Mulholland *et al*. (1999), Roberts *et al*. (2002) and Busscher and Bauer (2003) reported that roots encountering high soil strength slowed both shoot and root growth.

Coelho *et al.* (2000) working with irrigated cotton (*Gossypium hirsutum* L.) and loam soil in Southern Spain reported a yield reduction of 28% due to a compacted soil layer.

Daddow and Warrington (1993) summarised numerous studies and delineated 1.75 Mg m^{-3} as growth limiting bulk density.

Reeves *et al.* (1984) found that spring wheat in Australia grown in soil with bulk density of 1.52 Mg m^{-3} in the 0-20 cm depth had less root growth than grown in soil with a bulk density of 1.32 Mg m^{-3}.

Canarache *et al.* (1984) found that for a unit increase in bulk density, a decrease in maize grain yield was 18% relative to the yield on non compacted plot.

A degraded soil physical environment due to compaction retards root and shoot growth which results in low crop yields. Compacting a clay loam soil to a density of 1.52 Mg m^{-3} from an initial density of 1.33 Mg m^{-3} reduced the grain and straw yields of wheat by 12-23% and 4-20% respectively (Oussible *et al.*, 1992).

In another study, Ishaq *et al.* (2001) observed 38 and 9% reductions in grain and straw yields respectively of wheat when soil was compacted to a bulk density of 1.93 Mg m^{-3} from an initial bulk density of 1.65 Mg m^{-3}. A greater radial expansion at the root tip can reduce the resistance to penetration at that point allowing the subsequent lengthening of the elongation root zone (Hettiaratchi, 1990). Despite species-specific variations according to Vepraskas (1994), root growth is inhibited by penetration resistance values of around I.0 Mpa and mostly stops when the value exceeds 3.0 Mpa. Nadian *et al.* (1997) reported that increasing bulk density of the soil from 1.1 to 1.6 Mg m^{-3} significantly decreased root length and shoot dry mass but increased the diameter of both main axes and first order lateral roots of cover plants regardless of phosphorus application.

The values of penetrometer resistance of which reduction in root growth begins vary from 1.0 Mpa (low root strength) to 1.7 Mpa (high root strength) while those stopping root growth vary from 3 to 4 Mpa. The critical strengths may vary depending on soil texture, macroporosity, depth and crop type (Gliński and Lipiec, 1990 and Pabin *et al*., 1998).

Root distribution in heavily compacted horizons are quite different from those in uncompacted soil horizons and this is shown quite clearly for maize (*Zea mays*). Although the total biomass of maize was similar for both cases, the uncompacted profile had a greater proportion of deep roots (Whalley *et al*., 1995). A similar observation was reported by Boone *et al*. (1978) for potato (*Solanum tuberosum* L.).

It has been observed that roots which have been growing in strong soils tend to have larger diameters than those in weak soils (Abdalla *et al.,* 1969; Atwell, 1988; Materechera *et al*., 1991). According to Kozlowski, (1999) greater mechanical resistance increases the force required for plant root to push its way through the soil. This is compounded by the reduction in size and continuity of soil macropores through which roots preferentially grow, leading to slower root elongation, reduced root length and reduction in soil volume exploited (Materechera *et al*., 1991; Panayioto poulos *et al*., 1994).

Research on comparison of wheat and chicken pea under different tillage methods has shown that the legume crop is more sensitive than wheat to soil compaction in terms of root distribution (Pardo, 1998).

Ishaq *et al*. (2001) reported that crop yields can be reduced by soil compaction due to increased resistance to root growth and decrease in water and nutrient use efficiencies.

Bailey *et al.* (1986) reported that excessive compaction may cause such undesirable effects as restriction of root growth and increased runoff.

Laboski *et al.* (1998) found that a compacted soil layer confined roots of corn almost entirely to the top 60 cm of the soil. However, the effect of soil compaction on root biomass depends on the degree of soil water status and soil physical properties.

On the other hand, Whitley and Dexter (1984) observed that root growth of plants with thick tap roots (example sunflower - *Helianthus annuus*) was more affected in compacted soils than plants with numerous thin seminal roots (example wheat - *Triticum aestivum*).

Decreased crop yields due to compaction may be partially a result of lower nitrogen availability. Several studies have observed decreased nitrogen uptake by crops in compacted soils (Lipiec and Stepniewski, 1995 and Wolkowski, 1990). The primary reasons for changes in Nitrogen (N) availability in compacted soils include: i) decreased soil aeration resulting in increased denitrification, reduced N mineralisation and decreased symbiotic N fixation; ii) changes in soil water properties affecting N-transport and leaching and iii) changes in soil structure altering root dynamics (Lipiec and Stepniewski, 1995). Shoot growth is usually more reduced than root growth in compacted soils. Soil compaction affects the development and distribution of roots and increasing soil resistance causes the cluster growth of roots in parts of the soil which are less resistant (Tardieu and Manichon 1987; Amato, 1991; Pardo *et al*., 2000). Lower levels of soil compaction may enhance corn growth through providing a suitable medium for seed growth and also due to the improvement of soil structure resulting in decreased soil erosion under field conditions (Bouwman and Arts, 2000; Passioura, 2002; Miransari *et al.,* 2004).

CHAPTER THREE

3. MATERIALS AND METHODS

3.1 Experimental Site

The study was carried out at the Soil Research Institute, Kwadaso, Kumasi. The soil used for the study was taken from the institute's experimental field and it 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.

3.2 Experimental Design

Two experiments, using maize (*Zea mays* L.) and soybean (*Glycine max* L.) as test crops were conducted. Each experiment was a 5 x 3 factorial arranged in a Complete Randomized Design (CRD) with 3 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 3 varieties each of maize and soybean.

3.3 Test Crops

The maize varieties were Enibi (V_1), Mamaba (V_2) all hybrids and Obatampa (V_3), an open pollinated variety whilst the soybean varieties were Ahoto (V_1), Anidaso (V_2) and Nangbaar (V_3).

3.4 Soil Chemical Analysis

3.4.1. Soil pH

Soil pH was measured in a 1:1 soil-water ratio using a glass electrode (H19017 Microprocessor) pH meter. Approximately 25g of soil was weighed into a 50 ml polythene beaker and 25 ml of distilled water was added to the soil. The soil-water solution was stirred thoroughly and allowed to stand for 30 minutes. After calibrating the pH meter with buffers of pH 4.01 and 7.00, the pH was read by immersing the electrode into the upper part of the soil solution and the pH value recorded.

3.4.2. Soil organic carbon

Soil organic carbon was determined by the modified Walkley-Black method as described by Nelson and Sommers (1982). The procedure involves a wet combustion of the organic matter with a mixture of potassium dichromate and sulphuric acid. After the reaction, the excess dichromate is titrated against ferrous sulphate. Approximately 1.0 g of air-dried soil was weighed into a clean and dry 250 ml Erlenmeyer flask. A reference sample and a blank were included. Ten ml 0.1667 M potassium dichromate ($K_2Cr_2O_7$) solution was accurately dispensed into the flask using the custom laboratory dispenser. The flask was swirled gently so that the sample was made wet. Then using an automatic pipette, 20 ml of concentrated sulphuric acid (H_2SO_4) was dispensed rapidly into the soil suspension and swirled vigorously for 1 minute and allowed to stand on a porcelain sheet for about 30 minutes, after which 100 ml of distilled water was added and mixed well. Ten ml of orthophosphoric acid and 1 ml of diphenylamine indicator was added and titrated by adding 1.0 M ferrous sulphate from a burette until the solution turned dark green at end-point from an initial purple colour. About 0.5 ml 0.1667 M $K_2Cr_2O_7$ was added to restore excess $K_2Cr_2O_7$ and the titration completed by adding $FeSO_4$ drop-wise to attain a stable end-point. The volume of $FeSO_4$ solution used was recorded and % C calculated.

Calculation:

The organic carbon content of soil was calculated as:

$$\% \text{ O.C} = M \times 0.39 \times mcf \times \frac{(V_1 - V_2)}{s} \qquad (1)$$

where:

M = molarity of ferrous sulphate solution.

V_1 = ml of ferrous sulphate solution required for blank.

V_2 = ml of ferrous sulphate solution required for sample.

s = mass of air-dry sample in grams.

mcf = moisture correcting factor $\frac{(100 + \% \text{ moisture})}{100}$

0.39 = 3 x 0.001 x 100 % x 1.3 (3 = equivalent mass of carbon).

1.3 = a compensation factor for the incomplete combustion of the organic carbon.

3.4.3. Total nitrogen

Total nitrogen was determined by the Kjeldahl digestion and distillation procedure as described in Soil Laboratory Staff (1984). Approximately 0.2 g of soil was weighed into a Kjeldahl digestion flask and 5 ml distilled water added. After 30 minutes a tablet of selenium and 5 ml of concentrated H_2SO_4 were added to the soil and the flask placed on a Kjeldahl digestion apparatus and heated initially gently and later vigorously for at least 3 hours. The flask was removed after a clear mixture was obtained and then allowed to cool. About 40 ml of distilled water was added to the digested material and transferred into 100ml distillation tube. 20 ml of 40 % NaOH was also added to the solution and then distilled using the Tecator Kjeltec distiller. The digested material was distilled for 4 minutes and the distillate received into a flask containing 20 ml of 4 % boric acid (H_3BO_3) prepared with PT5 (bromocresol green) indicator producing approximately 75 ml of the distillate. The colour change was from pink to green after distillation, after which the content of the flask was titrated with 0.02 M HCl from a burette. At the end-point when the solution changed from weak green to pink the volume of 0.02 M HCl used was recorded and % N calculated. A blank distillation and titration was also carried out to take care of traces of nitrogen in the reagents as well as the water used.

Calculation:

The percentage nitrogen in the sample was expressed as:

$$\% N = \frac{(N \times (a - b) \times 1.4 \times mcf)}{s} \qquad (2)$$

where

N = concentration of hydrochloric acid used in titration.

a = volume of hydrochloric acid used in sample titration.

b = volume of hydrochloric acid used in blank titration.

s = mass of air-dry sample in gram.

mcf = moisture correcting factor $\frac{(100 + \% \text{ moisture})}{100}$

1.4 = 14 x 0.001 x 100 % (14 = atomic mass of nitrogen)

3.4.4. Bray's No. 1 Phosphorus (Available phosphorus)

The readily acid-soluble forms of phosphorus were extracted with a HCl:NH_4F mixture called the Bray's no.1 extract as described by Bray and Kurtz (1945) and Olsen and Sommers (1982). Phosphorus in the extract was determined on a spectrophotometer by the blue ammonium molybdate method with ascorbic acid as reducing agent. Approximately 5 g of soil was weighed into 100 ml extraction bottle and 35 ml of extracting solution of Bray's no. 1 (0.03 M NH_4F in 0.025 M HCl) was added. The bottle was placed in a reciprocal shaker and shaken for 10 minutes after which the content was filtered through Whatman no.42 filter paper. The resulting clear solution was collected into a 100 ml volumetric flask.

An aliquot of about 5 ml of the clear supernatant solution was pipetted into 25 ml test tube and 10ml colouring reagent (ammonium paramolybdate) was added as well as a pinch of ascorbic acid and then mixed very well. The mixture was allowed to stand for 15 minutes to develop a blue colour to its maximum. The colour was measured photometrically using a spectronic 21D spectrophotometer at 660 nm wavelength. Available phosphorus was extrapolated from the absorbance read.

A standard series of 0, 1.2, 2.4, 3.6, 4.8 and 6 mg P/l was prepared from a 12 mg/l stock solution by diluting 0, 10, 20, 30, 40 and 50 ml of 12 mg P/l in 100 ml volumetric flask and made to volume with distilled water. Aliquots of 0, 1, 2, 4, 5 and 6 ml of the 100 mg P/l of the standard solution were put in 100 ml volumetric flasks and made to the 100 ml mark with distilled water.

Calculation:

$$P\ mg\ kg^{-1} = \frac{(a - b) \times 35 \times 15 \times mcf}{s} \quad (3)$$

where

a = mg/l P in sample extract.

b = mg/l P in blank.

s = sample mass in gram.

mcf = moisture correcting factor

35 = volume of extracting solution

15 = final volume of sample solution

3.4.5. Determination of available Potassium

Available potassium extracted using the Bray's no. 1 solution was determined directly using the Gallenkamp flame analyzer. Available potassium concentration was determined from the standard curve. Potassium standard solutions were prepared with the following concentrations: 0, 10, 20, 30, and 50 μg K per litre of solution. The emission values were read on the flame analyzer. A standard curve was obtained by plotting emission values against their respective concentrations.

Calculation:

$$K\ mg\ kg^{-1} = \frac{(a - b) \times 35 \times mcf}{s} \qquad (4)$$

where

a = ppm K in the sample

b = ppm K in the blank

35 = volume of extracting solution

mcf = moisture correcting factor

s = sample mass in gram

3.4.6. Exchangeable cations

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).

3.4.6.1. Extraction of the exchangeable bases

A 5 g sample was transferred into a leaching tube and leached with 100 ml of buffered 1.0 M ammonium acetate (NH_4OAc) solution at pH 7.

3.4.6.2. Determination of calcium and magnesium

For the determination of the calcium plus magnesium, a 25 ml of the extract was transferred into an Erlenmeyer flask. A 1.0 ml portion of hydroxylamine hydrochloride, 1.0 ml of 2.0 per cent potassium cyanide buffer (from a burette), 1.0 ml of 2.0 per cent potassium ferrocyanide, 10.0 ml ethanolamine buffer and 0.2 ml Eriochrome Black T solution were added. The solution was titrated with 0.01 M EDTA (ethylene diamine tetraacetic acid) to a pure turquoise blue colour. A 20 ml 0.01 M magnesium chloride solution was also titrated with 0.01 M EDTA in the presence of 25 ml of 1.0 M ammonium acetate solution to provide a standard blue colour for the titration.

3.4.6.3. Determination of calcium

A 25 ml portion of the extract was transferred to an Erlenmeyer flask. Hydroxylamine hydrochloride (1.0 ml), potassium cyanide (1.0 ml of 2 % solution) and potassium ferrocyanide (1.0 ml of 2 %) were added. After a few minutes, 4 ml of 8 M potassium hydroxide and a spatula of murexide indicator were added. The solution obtained was titrated with 0.01 M EDTA solution to a pure blue colour. Twenty milliliters of 0.01 M calcium chloride solution was titrated with 0.01 M EDTA in the presence of 25 ml 1.0 M ammonium acetate solution to provide standard pure blue colour.

Calculation:

The calculation of the concentration of calcium + magnesium or calcium follows the equation:

$$\text{Ca} + \text{Mg (Ca) (cmol / kg soil)} = \frac{0.01 \times (V_a - V_b) \times 1000}{0.1 \times s} \quad (5)$$

where:

s = mass in grams of oven-dry soil extracted

V_a = ml of 0.01 M EDTA used in the titration

V_b = ml of 0.01 M EDTA used in blank titration

0.01 = concentration of EDTA used

$$Ca = Mg \text{ (or Ca) (cmol / kg soil)} = \frac{0.01 \times (V_a - V_b) \times 1000}{0.1 \times s} \quad (6)$$

3.4.6.4. Exchangeable potassium and sodium determination

Potassium and sodium in the percolate were determined by flame photometry. A standard series of potassium and sodium were prepared by diluting both 1000 mg/l potassium and sodium solutions to 100 mg/l. This was done by taking a 25 ml portion of each into one 250 ml volumetric flask and made to volume with water. Portions of 0, 5, 10, 15 and 20 ml of the 100 mg/l standard solution were put into 200 ml volumetric flasks respectively. One hundred millilitres of 1.0 M NH_4OAc solution was added to each flask and made to volume with distilled water. The standard series obtained was 0, 2.5, 5.0, 7.5, 10.0 mg/l for potassium and sodium. Potassium and sodium were measured directly in the percolate by flame photometry at wavelengths of 766.5 and 589.0 nm respectively.

Calculations:

$$\text{Exchangeable K (cmol/kg soil)} = \frac{(a - b) \times 250 \times mcf}{10 \times 39.1 \times s} \quad (7)$$

$$\text{Exchangeable Na (cmol/kg soil)} = \frac{(a - b) \times 250 \times mcf}{10 \times 23 \times s} \quad (8)$$

where

a = mg/l K or Na in the diluted sample percolate

b = mg/l K or Na in the diluted blank percolate

s = air-dried sample mass of soil in gram

mcf = moisture correcting factor

3.4.6.5. Exchangeable acidity

Exchangeable acidity is defined as the sum of Al + H. The soil sample was extracted with unbuffered 1.0 M KCl, and the sum of Al + H was determined by titration. Ten grams of soil sample was put in a 100 ml bottle and 50 ml of 1.0 M KCl solution added. The bottle was capped and shaken for 1.0 hour and then filtered. Twenty five milliliters portion of the filtrate was taken with a pipette into a 250 ml Erlenmeyer flask and 2 – 3 drops of phenolphthalein indicator solution added. The solution was titrated with 0.1 M NaOH until the colour just turned permanently pink. A blank was included in the titration.

Calculation:

$$\text{Exchangeable acidity (cmol/kg soil)} = \frac{(a - b) \times M \times 2 \times 100 \times mcf}{s} \qquad (9)$$

where:

a = ml Na OH used to titrate with sample

b = ml Na OH used to titrate with blank

M = molarity of NaOH solution

s = air-dried soil sample mass in gram

2 = 50/25 (filtrate / pipetted volume)

mcf = moisture correction factor [(100 + % moisture) / 100]

3.4.6.6. Effective cation exchange capacity (ECEC)

Effective cation exchange capacity was determined by the sum of exchangeable bases (Ca^{2+}, Mg^{2+}, K^{+} and Na^{+}) and exchangeable acidity (Al^{3+} + H^{+}).

3.5. Soil Physical Analysis

3.5.1. Soil texture

The soil texture was determined by the Hydrometer method (Bouyoucos, 1962). Approximately 40 g of soil was weighed into 250 ml beaker and oven dried at 105 ^{0}C over night. The sample was removed from the oven and then placed in a desiccator to cool, after, which it was weighed and the oven dry mass taken. A 100 ml of dispersing agent commonly known as Calgon (Sodium Bicarbonate and Sodium Hexa-metaphosphate) was measured and added to the soil. It was then placed on a hot plate and heated until the first sign of boiling was observed. The content in the beaker was washed completely into a shaking cup and then fitted to a shaking machine and shaken for 5 minutes. The sample was sieved through a 50 microns sieve mesh into a 1.0 L cylinder. The sand portion was separated by this method while the silt and clay went through the sieve into the cylinder. The sand portion was dried and further separated using graded sieves of varying sizes into coarse, medium and fine sand. These were weighed and their masss taken.

The 1.0 L cylinder containing the dispersed sample was placed on a vibrationless bench and then filled to the mark. It was covered with a watch glass and allowed to stand over night. The Hydrometer method was used to determine the silt and the clay contents. The cylinder with its content was agitated to allow the particles to be in suspension, it was then placed on the bench and hydrometer readings taken at 30 seconds, 4 minutes, 1 hour, 4 hours and 24 hours intervals. At each hydrometer reading the temperature was also taken. Coarse silt, medium silt, fine silt and clay portions were then calculated graphically. The various portions were expressed in percentage and using the textural triangle the texture was determined.

3.5.2. Bulk density

Bulk density in the field at 0 – 20 cm depth was determined by the core method described by Blake and Hartge (1986). A cylindrical metal sampler of 5 cm diameter and 15 cm long 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 two days and reweighed. Bulk density was computed as:

$$\rho_b = M_s / V_t \qquad (10)$$

where:

ρ_b = soil bulk density (Mg m^{-3})

M_s = mass of the oven dry soil (Mg)

V_t = total volume of soil (m^3)

3.5.3 Water content

Gravimetric water content (θ_m)

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 dried at 105^0C in an oven for 24 hours. After drying, the dry mass of the soil was taken and this was subtracted from the initial mass to give the percentage moisture content calculated as: %

$$\theta m = \frac{Mw}{Ms} \times 100 \tag{11}$$

Where

θm = Mass of water/mass of oven dry soil x 100.

Mw = mass of water loss (g)

Ms = mass of dry soil (g)

Volumetric water content (θ_v)

Volumetric water content was calculated as:

$$\theta_v = \theta_m \times \frac{\rho_b}{\rho_w} \tag{12}$$

Depth of water (θ_h)

θ_h is calculated as: $\theta_h = \theta_v \times h = \theta_m \times \frac{\rho_b}{\rho_w} \times h$ (13)

θ_v = volumetric water content ($m^3\ m^{-3}$)

θ_m = gravimetric water content ($m^3\ m^{-3}$)

ρ_b = dry bulk density (Mg m^{-3})

ρ_b = density of water (Mg m^{-3})

θ_h = depth of water (m)

h = depth of soil (m)

3.6 Preparation of Pots for the Plants

PVC plastic cylinders having a diameter of 8.54cm wide and a height of 15.5cm were used for the experiment. Three cylinders having a height of 2.5 cm, 5 cm and 8 cm were cut from the PVC pipe and stacked together. Each 3-layered container consisted of a top core of 2.5 cm, middle core of 5 cm and a bottom core of 8 cm length. The bottom of the cylinders were shielded with a flat wooden plate and holes perforated on the wooden plates to allow drainage.

Fig. 3.1 PVC plastic cylinder with soybean seedlings

Fig. 3.2 PVC plastic cylinder with maize seedlings

3.6.1 Standardization of bulk density

The bulk densities used were 1.1 Mg m^{-3} for the top and bottom cores 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 core. 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 volume of the containers was obtained from the relationship $\pi r^2 h$ where r, the internal radius and h, the height in cm were measured with a vernier calliper. The mass of soil to be packed into the cylinders to give the desired bulk density (Equation 15) was calculated from the expression (Hillel, 1995) (Equation 14):

$$\rho_b = \frac{M_s}{V_t} \qquad (14)$$

$$M_s = \rho_b V_t \quad (15)$$

Where:

ρ_b = Dry bulk density (Mg m^{-3})

M_s = Mass of dry soil (Mg)

V_t = Total volume (core volume) m^3

Packing of the soil in the cores 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. 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, core samples were taken using a metal cylinder and dried in an oven at 105°C. Bulk density was then calculated from Equation 14. 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 cores from 2 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.

3.6.2 Determination of field 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 cores 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 cores were sealed together into one airtight and water tight soil container with celotape. The soil container assemblies with the surface of the soil covered with polythene sheets were saturated from below and drained for 48 hours. The containers were then weighed to obtain their mass at field capacity.

3.6.3 Infiltration rate

The infiltration rate of the set up was also determined by using the mini-disk infiltrometer. This was done to determine the infiltration rate for the various bulk densities and the soil hydraulic conductivity calculated.

3.6.4 Porosity

Porosity of the core was determined using the expression below;

$$\% f = (1 - \frac{\rho_b}{\rho_s}) \times 100 \qquad (16)$$

Where:

ρ_b = bulk density (Mg m^{-3})

f = total porosity (%)

ρ_s = particle density (2.65 Mg m^{-3})

3.6.5 Effective porosity

Effective porosity was determined using the expression below;

Effective porosity = % porosity - % θ_m (17)

Where θ_m = moisture at field capacity

3.6.6 Air-filled porosity

Air-filled porosity was determined using the expression below;

Air-filled porosity (fa) = f - θ_v (18)

Where:

fa = air-filled porosity (%)

f = total porosity (%)

θ_v = volumetric water content (%)

3.7 Planting

The set up was carried out at the plant house at the Kwadaso Soil Research Institute, Kwadaso, Kumasi. They were arranged according to the experimental design. Three seeds were then sown per soil core assembly. This was thinned to two seedlings per pot after 7 days. Earlier on, germination test was conducted for the maize and the soybean varieties to determine viability. After sowing; water loss was estimated and compensated by weighing every 2 days and plants were watered using an improvised watering can.

3.8 Plant parameters measured

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

3.8.1 Plant height

A ruler was used to measure the height of the seedlings every 2 days till the seedlings were harvested.

3.8.2 Fresh shoot and root mass

The fresh shoot mass was taken after cutting the shoots above the soil level and labelled in an envelope. The fresh root mass was also obtained after cutting the core cylinder into its three parts, that is, the top layer, middle layer and bottom layers. The soil was washed off the roots after it was stained with methylene blue for easy identification and selection, then the mass taken for both the soybean and the maize.

3.8.3 Shoot and root dry mass

After the fresh mass, the shoot and the roots were put in an oven at 70^0C for 48 hours and the dry mass of the shoots and roots taken.

3.8.4 Root length

After washing the soil from the roots using a 2mm 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 = The total root length

A = Area of grid sheet

N = Number of intersections between the roots and random straight lines of the grid sheet

H = Total length of straight lines.

A 2 cm grid sheet (graph sheet) was used. The washed roots were cut and spread randomly over the sheet and the intersections by the roots across the lines (N) were counted and recorded and root length calculated using R = 1.5714 as this figure is Newman constant for 2cm grid sheet, which is equivalent to

$$\frac{\pi A}{2H}$$

According to Newman's constant every grid size has its own conversion factor. Below are some of the grid sizes and their conversion factors.

Grid size (cm)	**Conversion factor**
0.5	0.3928
1.0	0.7857
2.0	1.5714
3.0	2.3571

For the total root length, all the separated layers that is, top layer, middle layer and the bottom layer were summed together to arrive at the total root length.

3.8.5 Root penetration ratio (RPR)

Root penetration ratio (RPR) is defined as the number of roots that entered the compacted middle core divided by the number of roots that exited the same core. Root penetration ratio was obtained by counting the number of roots that entered the top of the bottom core 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.

3.8.6 Relative root length (RRL)

Relative root length (RRL) was calculated as the ratio of the root length in each core to the total root length in the three cores (top, middle and bottom) expressed as a percentage.

3.8.7 Root anatomy

The roots were washed and stored in 70% alcohol and transported to University of Ghana, Legon, Botany Department for sectioning and staining.

The roots were embedded in a half split carrot and mounted on sliding microtome and sectioning done on 40 microns. After sectioning, the tissues were stained using 1% Safranin for 10 minutes. The tissues were dropped into 70% alcohol for 1 minute and then transferred into absolute alcohol for 5 minutes. The tissues were then stained in light green stainer for 30 seconds and finally cleared and washed in Clove oil and mounted in Canada Balsam. The prepared slides were then examined under Motic 2.0 photomicroscope for anatomical features and pictures taken.

3.9 Data Analysis

The data obtained in this study were analysed by 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. Regression analysis was carried out to establish the correlation between soil bulk density, total porosity, air-filled porosity, root penetration ratio and measured plant parameters and to generate empirical equations for prediction.

CHAPTER FOUR

4.0 RESULTS

4.1 Characteristics of Ferric Acrisol (Asuansi Series)

The results of the chemical and physical properties of the soil used for the experiment are presented in Table 4.1. The soils were taken from a 0 – 20 cm depth. Landon's (1991) guidelines were used to interpret the results. The analyses indicated that the soil is sandy loam which is moderately acidic, with very low organic carbon content, low nitrogen and medium level of phosphorus and potassium. The bulk density accords with normal range for non-compacted mineral soil.

Table 4.1 Physico-chemical properties of Asuansi Ferric Acrisol at Kwadaso before the start of the experiment

Parameter	Description
pH (H_20)	5.50
Org. Carbon (%)	1.26
Org. Matter (%)	2.17
Ca. (me/100g)	5.74
Mg. (me/100g)	2.27
Na. (me/100g)	0.07
K (me/100g)	0.33
P (ppm)	22.90
N (%)	0.21
Acidity (Al + H)	0.10
CEC (me/100 g)	8.41
ECEC (me/100 g)	8.51
Base Saturation (%)	98.82
Particle size distribution	

Sand (%)	60.50
Silt (%)	29.46
Clay (%)	10.04
Texture	Sandy loam
Bulk Density	1.42 Mg m^{-3}

4.2 The Effect of Compaction on Porosity, Field Capacity and Saturated Hydraulic Conductivity

The growth of crops depends not only on the chemical fertility of the soil but also on the physical fertility. Important variables of the latter include total porosity, air-filled porosity, moisture content at field capacity and hydraulic conductivity. Consequently, the impacts of bulk density, as a measure of compaction, on these variables were examined. The results are presented in Table 4.2.

Total porosity ranged from 28.3 to 58.5 per cent for the bulk density of 1.9 and 1.1 Mg m^{-3} respectively. The respective air-filled porosities were -4.46 and 27.09 percent. Both total and air-filled porosity generally decreased as bulk density increased. The total porosity of 58.5 percent at 1.1 Mg m^{-3} decreased by 13, 26, 39 and 52 per cent 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 per cent at 1.1 Mg m^{-3} were 28.72, 38.05, 80.25 and 116 per cent.

As air-filled porosity decreased with increasing bulk density 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 by 6.6, 12.9, 32.6 and 42.1 per cent as bulk density increased from 1.1 to 1.3, 1.5, 1.7 and 1.9 Mg m^{-3} respectively.

Moisture content at field capacity was 17.24 per cent at 1.9 Mg m^{-3} and 28.55 per cent at 1.1 Mg m^{-3}. Estimation of depth of water at field capacity for 150 mm depth gave 43, 37, 27, 27 and 26 and 28 mm for the bulk densities of 1.1, 1.3, 1.5, 1.7 and 1.9 Mg m^{-3} respectively. 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. These values have implications for water availability to plants.

Table 4.2 Effects of bulk density on porosity, field capacity and saturated hydraulic conductivity of the soil sample used

Bulk Density Mg m^{-3}	Porosity (f) (%)	% Moisture at Field Capacity	Effective Porosity (%)	Air Filled Porosity (fa) (%)	Saturated Hydraulic Conductivity (mmh^{-1})	Volumetric Water Content (θ_v) (%)
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

4.3 The Effect of Soil Compaction, Soybean Variety and their Interactions on Plant Height

The analysis of variance showed soil compaction, soybean variety and their interactions to significantly influence plant height. The mean soybean plant height (in centimeters) (Table 4.3a) followed the normal growth curve of plants with time by increasing from 7 days after planting (DAP) to 15 DAP. The mean plant height at 15 DAP (Table 4.3a) ranged from 14.84 to 24.86 cm for bulk densities of 1.9 and 1.1 Mg m^{-3}. The plant height of the 1.1 to 1.5 Mg m^{-3} was significantly greater than that of the 1.7 and 1.9 Mg m^{-3}.

Table 4.3a Effects of soil compaction and soybean (*Glycine max*) variety on plant height

Bulk density (Mg m^{-3})	Days after planting (DAP)				
	7	**9**	**11**	**13**	**15**
1.1	11.96	14.39	18.47	21.72	24.86
1.3	11.86	14.79	18.82	21.83	24.57
1.5	11.34	14.31	17.67	21.23	23.30
1.7	10.21	12.28	14.97	17.57	18.81
1.9	8.74	10.92	12.67	14.63	14.84
LSD (P < 0.05)	0.72	0.92	1.37	1.63	1.76
Soy bean variety					
Anidaso	11.25	13.98	17.48	20.29	22.55
Nangbaar	10.60	12.95	16.09	19.01	20.49
Ahoto	10.61	13.08	15.98	18.89	20.80
LSD (P < 0.05)	0.56	0.71	1.06	1.26	1.37
CV (%)	6.94	7.17	8.60	8.73	8.61

Whilst the plant height of the former bulk densities did not differ significantly, the differences in the latter two densities were significant (P<0.05).

At 15 DAP plant height also differed among the soybean varieties in the order of Anidaso>Ahoto>Nangbaar. Anidaso had significantly (P<0.05) greater plant height than the other two varieties which had no significant differences in plant height. The bulk density × soybean variety interaction (Table 4.3b) effected significant differences (P<0.05) in plant height.

Table 4.3b shows the mean height of the interactions and the mean separation (Appendix 1) indicates which of them are significant. Apart from three cases, the means of the three soybean varieties and bulk densities 1.1 to 1.5 Mg m^{-3} did not differ significantly. However, they were significantly greater than those at bulk densities 1.7 and 1.9 Mg m^{-3}.

Table 4.3b Effects of interaction of bulk density and soybean (Glycine max) variety on plant height

Bulk density x variety	Means (cm)				
	7DAP	9DAP	11DAP	13DAP	15DAP
Bd1V1	11.17	13.83	17.30	21.27	24.77
Bd1V2	12.03	15.27	18.93	22.57	26.30
Bd1V3	10.83	14.07	16.77	21.33	23.50
Bd2V1	11.60	13.57	17.93	21.27	24.00
Bd2V2	12.60	15.27	20.17	22.87	25.70
Bd2V3	11.67	14.10	18.37	21.37	24.03
Bd3V1	11.60	15.43	17.57	21.20	22.87
Bd3V2	12.43	14.83	19.33	22.13	24.83
Bd3V3	11.53	14.10	18.50	20.37	22.20
Bd4V1	10.10	12.03	14.77	17.13	18.27
Bd4V2	10.43	12.60	15.53	18.67	19.80
Bd4V3	10.10	12.20	14.60	16.90	18.37
Bd5V1	8.60	10.53	12.33	13.60	14.10
Bd5V2	9.10	11.93	13.43	15.23	16.10
Bd5V3	8.53	10.30	12.23	15.07	14.33
LSD	1.25	1.60	2.37	2.82	3.05
CV%	6.94	7.17	8.60	8.73	8.61

Variety (V)	Bulk Density (Bd) Mg m^{-3}
V1 – Ahoto	Bd1 = 1.1
V2-Anidaso	Bd2 = 1.3
V3-Nangbaar	Bd3 = 1.5
	Bd4 = 1.7
	Bd5 = 1.9

4.4 The Effect of Soil Compaction and Soybean Variety and their Interactions on Shoot Mass

The analysis of variance indicated that soybean fresh shoot mass is influenced by soil compaction, soybean variety and their interactions. The mean soybean fresh shoot mass (Table 4.4a) as affected by bulk density ranged from 0.94 to 2.5 g with a rank of 1.3>1.1>1.5>1.7>1.9 Mg m^{-3}. The fresh shoot mass of 1.1, 1.3 and 1.5 Mg m^{-3} did not differ significantly. However the shoot mass of these bulk densities were significantly ($P<0.05$) greater than those of 1.7 and 1.9 Mg m^{-3}. The shoot mass recorded under 1.7 Mg m^{-3} was significantly greater than that of the 1.9 Mg m^{-3}. Fresh shoot mass decreased as bulk density increased. The reduction in fresh shoot mass as bulk density was increased from 1.3 to 1.5, 1.7 and 1.9 Mg m^{-3} was 6.4, 50 and 63 percent. The reduction in the dry root mass were 7.8, 53 and 65 percent for a bulk density change of 1.3 to 1.5, 1.7 and 1.9 Mg m^{-3} respectively.

The soybean varietal mean values showed fresh shoot mass of Anidaso to be significantly ($P<0.05$) greater than those of Nangbaar and Ahoto in the order of Anidaso>Ahoto>Nangbaar. The bulk density × soybean variety interaction (Table 4.4b and Appendix 2) showed Anidaso to be superior to the others in fresh shoot yield at all bulk densities. However at 1.5 to 1.9 Mg m^{-3} the above varietal trend in fresh shoot mass changed in favour of Nangbaar in the order of Anidaso>Nangbaar>Ahoto, although the differences in the latter two varieties were not significant.

The effect on bulk density, soybean variety and their interactions on soybean dry shoot mass (Table 4.4a and Appendix 3) followed the same trend as the fresh shoot mass. The mean dry shoot mass (Table 4.4a) ranged from 0.18g to 0.51g for the 1.9 and 1.3 Mg m^{-3} bulk densities respectively. The dry maases showed the mean moisture content of the shoots, on fresh mass basis, to be about 80 percent.

As observed in the case of fresh shoot mass, the bulk density × soybean varietal interaction showed Anidaso to outyield all the other varieties in dry shoot mass at all bulk densities. However, whilst Ahoto recorded greater shoot mass than Nangbaar at the 1.1 and 1.3 Mg m^{-3}, the latter outyielded the former at the higher bulk densities. Nangbaar therefore appears to better tolerate greater soil compaction than Ahoto.

Table 4.4a Effect of soil compaction (bulk density) and soybean variety on fresh and shoot mass sampled 15 days after planting (DAP)

Bulk density (Mg m^{-3})	Fresh Shoot Mass/Plant (g)	Dry Shoot Mass/Plant (g)
1.1	2.45	0.47
1.3	2.51	0.51
1.5	2.35	0.47
1.7	1.25	0.24
1.9	0.94	0.18
LSD (P<0.05)	0.255	0.06
Soybean Variety		
V2 = Anidaso	2.17	0.43
V3 = Nangbaar	1.75	0.35
V1 = Ahoto	1.78	0.34
LSD (P < 0.05)	0.20	0.1
CV (%)	13.89	17.25

Table 4.4b Interaction effect of soil compaction (bulk density) and soybean variety interactions on fresh and dry shoot mass

Treatment (Bulk density x Variety)	Mean Fresh Shoot Mass/Plant (g)	Mean Dry Shoot Mass/Plant (g)
Bd1V1	2.35	0.43
Bd1V2	2.74	0.51
Bd1V3	2.27	0.45
Bd2V1	2.43	0.49
Bd2V2	2.92	0.59
Bd2V3	2.19	0.44
Bd3V1	2.13	0.43
Bd3V2	2.72	0.55
Bd3V3	2.15	0.43
Bd4V1	1.14	0.21
Bd4V2	1.38	0.29
Bd4V3	1.22	0.23
Bd5V1	0.87	0.14
Bd5V2	1.06	0.23
Bd5V3	0.89	0.19
LSD ($P < 0.05$)	0.13	0.04
CV (%)	13.89	17.25

4.5 The Effect of Compaction, Soybean Variety and their Interactions on Root Mass

The analysis of variance showed that soybean root Mass is significantly influenced by soil compaction and soybean variety. Fresh root mass (Table 4.5a) varied from 0.11 to 0.28 g at bulk densities of 1.9 and 1.3 Mg m^{-3} and ranked as 1.9<1.7<1.5<1.1<1.3.

Fresh root mass generally decreased as bulk density increased. Fresh root mass at 1.1 and 1.3 Mg m^{-3} was significantly (P<0.05) greater than that of the remaining densities. The differences in 1.7 and 1.9 Mg m^{-3} with respect to fresh root mass were not significant but were significantly (P<0.05) less than that at 1.5 Mg m^{-3}. The highest root fresh mass was recorded at 1.3 Mg m^{-3} as observed for the shoot mass.

The main effect of soybean variety showed Anidaso to significantly (P<0.05) record greater fresh root mass than either Ahoto. Apart from this, there was no significant differences in the fresh root mass. The varietal root mass ranked as Anidaso>Nangbaar>Ahoto. The bulk density × soybean variety interaction (Table 4.5b and Appendix 4) did not effect significant differences in the soybean fresh root mass although greater masses were recorded at the densities of 1.1 to 1.5 Mg m^{-3}. The dry root mass (Table 4.5a) 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 to 0.05 g. The differences were significant (P<0.05). The increase of bulk density from 1.3 to 1.9 Mg m^{-3} decreased dry root mass by 40%. The mean moisture content of the roots, on fresh mass basis, was about 81 per cent. The soybean varietal effect showed dry root mass of Anidaso to be superior (P<0.05) to Ahoto and Nangbaar which recorded similar root dry mass. The bulk density × variety interaction (Table 4.5b), however, did not cause any significant differences in root dry mass (Appendix 5) at the lower bulk densities and the higher (1.7 and 1.9 Mg m^{-3}) bulk densities. However, the interaction means at the 1.1 to 1.5 Mg m^{-3} bulk densities were significantly higher (P<0.05) than those at the 1.7 and 1.9 Mg m^{-3}.

Table 4.5a Effect of soil compaction (bulk density) and soybean variety on fresh and dry root mass sampled 15 DAP

Treatment (Bulk density) ($Mg\ m^{-3}$)	Fresh Root Mass/Plant (g)	Dry Root Mass/Plant (g)
1.1	0.27	0.05
1.3	0.28	0.05
1.5	0.23	0.04
1.7	0.13	0.03
1.9	0.11	0.03
LSD ($P < 0.05$)	0.03	0.005
Soybean Variety		
Anidaso	0.22	0.04
Nangbaar	0.2	0.04
Ahoto	0.19	0.04
LSD ($P < 0.05$)	0.03	0.01
CV (%)	15.90	15.94

Table 4.5b Interaction effect of bulk density and soybean variety on fresh and dry root mass

Treatment	Mean Fresh Root Mass/Plant (g)	Mean Dry Root Mass/Plant (g)
Bd1V1	0.26	0.05
Bd1V2	0.29	0.05
Bd1V3	0.26	0.05
Bd2V1	0.27	0.05
Bd2V2	0.3	0.05
Bd2V3	0.27	0.05
Bd3V1	0.22	0.04
Bd3V2	0.24	0.04
Bd3V3	0.23	0.04
Bd4V1	0.11	0.03
Bd4V2	0.15	0.03
Bd4V3	0.14	0.03
Bd5V1	0.1	0.03
Bd5V2	0.11	0.03
Bd5V3	0.11	0.03
LSD ($P < 0.05$)	0.21	0.02
CV (%)	15.9	15.94

4.6 The Effect of Compaction on Soybean Root : Shoot Ratio

The root : shoot ratios were calculated from the soybean shoot and root dry masses to show how much dry matter is incorporated in the roots relative to the shoots (Table 4.6). The ratios ranged from 0.085 to 0.167 with the higher values associated with the higher bulk densities of 1.7 and 1.9 Mg m^{-3}. The results in Table 4.6 further showed the increase in bulk density to depress shoot growth more than root growth. This was indicated by the magnitude of reduction in the shoot and root dry masses.

Table 4.6 Percentage reduction in soybean dry matter yield with increasing soil compaction

Bulk density	Increase in bulk density* (%)	Dry shoot mass (g/plant)	Reduction (%)	Dry root mass (g/plant)	Reduction (%)*	Root : Shoot ratio
1.1	-	0.47	-	0.05	-	0.016
1.3	-	0.51	-	0.05	-	0.098
1.5	13.3	0.47	7.8	0.04	20	0.085
1.7	23.5	0.24	53	0.03	40	0.125
1.9	31.6	0.18	65	0.03	40	0.167

* Percentage increment/reduction relative to 1.3 Mg m^{-3}

4.7 The Effect of Soil Compaction, Soybean Variety and their Interactions on Root Penetration Ratio

The root penetration ratio (RPR), defined as the number of roots that exit the compacted middle core divided by the number of roots that penetrate the same core, was found to be influenced by soil compaction through the analysis of variance.

The mean values of RPR (Table 4.7a) showed that as bulk density increases, root penetration ratio decreases. The range of RPR was from 0.02 to 0.88 in the order of

1.1>1.3>1.5>1.7>1.9 Mg m^{-3}. Root penetration ratio at 1.1 and 1.3 Mg m^{-3} did not differ significantly, but was higher ($P<0.05$) than that of the remaining three densities which also differed significantly. For a percentage increase in bulk density of 27, 35 and 42 at 1.5, 1.7 and 1.9 Mg m^{-3} relative to 1.1 Mg m^{-3}, root penetration ratio respectively decreased by 30, 72 and 98 per cent. A relatively small increase in soil compaction therefore tends to cause large decreases in RPR.

Soybean varietal differences did not cause any significant variations in RPR. Nevertheless Anidaso recorded the highest RPR. The bulk density × soybean variety interactions (Table 4.7b and Appendix 6) significantly ($P<0.05$) influenced RPR. The interactions means at the lower bulk densities did not differ significantly. However, at the higher bulk densities, the interactions became significant ($P<0.05$). At each level of compaction (4.7b), Anidaso had the highest RPR. The results further showed that at bulk density 1.7 and 1.9 Mg m^{-3} Ahoto recorded zero RPR. At the latter bulk density, Anidaso also could not penetrate the compacted layer and Nangbaar recorded RPR as low as 0.05. The implication is that all the three soybean varieties cannot tolerate a bulk density of 1.9 Mg m^{-3}. These impacts, which are confounded when only the main effects of the factors are examined, are revealed when the interactions are studied.

Table 4.7a Effect of soil compaction (bulk density) and soybean variety on root penetration ratio sampled 15 DAP

Treatment (Bulk density) ($Mg\ m^{-3}$)	Root Penetration Ratio Mean (g)
1.1	0.88
1.3	0.88
1.5	0.62
1.7	0.25
1.9	0.02
LSD ($P < 0.05$)	0.11
Soybean Variety	
Anidaso	0.57
Nangbaar	0.54
Ahoto	0.47
LSD ($P < 0.05$)	0.08
CV (%)	21.04

Table 4.7b Interaction of bulk density and soybean variety on root penetration ratio (RPR)

Treatment	Root Penetration Ratio Mean (g)
Bd1V1	0.87
Bd1V2	0.89
Bd1V3	0.87
Bd2V1	0.88
Bd2V2	0.89
Bd2V3	0.87
Bd3V1	0.61
Bd3V2	0.65
Bd3V3	0.59
Bd4V1	0.00
Bd4V2	0.44
Bd4V3	0.29
Bd5V1	0.00
Bd5V2	0.00
Bd5V3	0.05
LSD (P<0.05)	0.11
CV (%)	21.04

4.8 The Effect of Soil Compaction and Soybean Variety on Root Length

Root length is very important in the uptake of soil water and nutrients for plant growth. The analysis of variance showed that root length is significantly ($P<0.05$) influenced by soil compaction. With a range of 22.79 to 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 4.8a). The differences in root length between 1.1 and 1.3 Mg m^{-3} and 1.7 and 1.9 Mg m^{-3} were not significant. Relative to 1.3 Mg m^{-3} which recorded the greatest 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 per cent respectively.

Soybean varietal differences in root length were not significant but followed the trend of Anidaso>Nangbaar>Ahoto. Relative root length was used to assess root distribution in the three soil cores. Relative root length was calculated as the ratio of the root length in each core to the total length in the three soil cores expressed as percentage. The results (Table 4.8b) showed that as bulk density in the middle core increases, roots tend to accumulate in the topsoil core. Thus, the mean relative root lengths of the top core were 11.97, 13.22, 19.78, 52.59 and 76.98 percent 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 core were 47.05, 46.72, 46.96, 37.95 and 19.64 percent. The roots reaching the bottom core, however, decreased significantly as the density of the middle core increased. The mean values for the bottom core were 40.97, 40.06, 33.26, 9.23 and 3.38 for the 1.1, 1.3, 1.5, 1.7 and 1.9 Mg m^{-3} respectively.

Table 4.8a Effect of soil compaction (bulk density) and soybean variety on root length sampled 15 DAP

Treatment (Bulk density) ($Mg\ m^{-3}$)	Root Length Mean (cm)
1.1	78.74
1.3	83.20
1.5	66.27
1.7	33.88
1.9	22.79
LSD (P<0.05)	12.52
Soybean Variety	
Anidaso	58.67
Nangbaar	57.67
Ahoto	54.58
LSD (P<0.05)	19.40
CV (%)	22.82

Table 4.8b 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	11.7	48.14	40.69
1.1	Nangbaar	13.26	46.46	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**

4.9 The Effect of 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. The mean root length is presented in Table 4.9. The difference in the root length of the soybean varieties at bulk densities 1.1 and 1.3 Mg m^{-3} were not significant (Appendix 7). However, root length at these bulk densities for each variety differed significantly ($P<0.05$) from those of 1.5, 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. The trend for Ahoto and Nangbaar was, however, not consistent.

Table 4.9 Interaction effect of bulk density and variety on root length of soybean

Treatment	Mean Root Length (cm)
Bd1V1	77.79
Bd1V2	79.61
Bd1V3	78.83
Bd2V1	83.81
Bd2V2	84.07
Bd2V3	81.72
Bd3V1	59.98
Bd3V2	70.19
Bd3V3	68.62
Bd4V1	30.65
Bd4V2	36.93
Bd4V3	34.05
Bd5V1	18.60

Bd5V2	25.15
Bd5V3	24.62
LSD (P<0.05)	10.6
CV (%)	22.82

V_1 = Ahoto, V_2 = Anidaso, V_3 = Nangbaar

4.10 The Effect of Soil Compaction and Maize Variety and their Interactions on Plant Height

The analysis of variance showed soil compaction and maize variety and their interactions to significantly influence the plant height of maize. The mean plant height as affected by bulk density and maize variety is presented in Table 4.10a. Plant height increased with time from 7 days after planting (DAP) to 21 (DAP). At 21 DAP (Table 4.10a) the mean plant height of maize ranged between 13.60 cm and 19.54 cm for bulk densities of 1.9 and 1.3 Mg m^{-3}. The plant height at 1.3 Mg m^{-3} was significantly ($P<0.05$) greater than that of all other bulk densities. The differences in plant height at 1.5, 1.7 and 1.9 Mg m^{-3} were also significant. At 21 DAP maize plant height was in the order of Obatanpa>Enibi>Mamaba (Table 4.10a). The differences were, however, not significant. The bulk density × maize variety interaction showed significant differences in plant height, especially, those of the 1.9 Mg m^{-3} and the other bulk densities (Table 4.10b). The mean separation (Appendix 8) showed no significant differences in the interaction means at bulk densities 1.1 to 1.5 Mg m^{-3}. However, at 1.9 Mg m^{-3}, the interactions means differed significantly. The interaction means at 1.5 Mg m^{-3} and those at 1.7 Mg m^{-3} also did not differ significantly.

Table 4.10a Effect of soil compaction (bulk density and maize (*Zea mays*) variety on plant height

Bulk density ($Mg\ m^{-3}$)	Days After Planting (DAP)							
	7	9	11	13	15	17	19	21
1.1	6.69	9.72	10.64	12.91	14.47	15.63	16.86	18.56
1.3	7.01	9.64	11.14	12.68	14.27	16.34	17.43	19.54
1.5	6.27	8.58	9.83	11.52	12.97	15.01	16.37	17.83
1.7	6.14	7.97	9.43	10.80	12.53	13.48	14.73	16.12
1.9	4.76	6.07	7.62	9.48	10.48	11.44	12.61	13.60
LSD ($P < 0.05$)	0.87	1.09	1.16	1.53	1.47	1.59	1.68	1.64
Maize variety								
Enibi	5.96	8.25	9.81	11.13	12.51	14.12	15.42	16.95
Mamaba	5.97	8.11	9.25	11.31	12.62	13.97	15.15	16.59
Obatanpa	6.59	8.83	10.14	11.99	13.70	15.06	16.23	17.85
LSD ($P<0.05$)	0.67	0.84	0.90	1.18	1.14	1.23	1.30	1.27
CV (%)	6.94	13.45	12.35	13.87	11.78	11.46	11.18	9.94

Table 4.10b Effects of interaction of bulk density and variety on maize plant height

Treatment	Mean Plant Height (cm)							
	7DAP	**9 DAP**	**11DAP**	**13DAP**	**15DAP**	**17DAP**	**19DAP**	**21DAP**
Bd1V1	6.53	9.70	10.37	12.63	13.93	15.37	16.93	18.43
Bd1V2	6.43	9.60	10.87	12.60	13.83	15.10	16.50	17.87
Bd1V3	7.10	9.63	10.70	12.80	15.03	16.43	17.13	19.37
Bd2V1	6.97	9.80	11.13	12.60	14.43	16.37	17.47	19.73
Bd2V2	6.70	9.00	10.70	12.93	14.27	16.00	17.23	18.87
Bd2V3	7.37	10.37	11.60	13.20	14.70	16.67	17.60	20.03
Bd3V1	6.10	8.67	10.20	11.10	12.20	14.70	16.10	17.70
Bd3V2	6.10	8.63	9.43	11.77	13.20	15.17	16.33	17.73
Bd3V3	6.60	8.43	9.86	11.70	13.50	15.17	16.67	18.07
Bd4V1	6.10	7.93	9.37	10.37	11.60	12.70	13.90	15.43
Bd4V2	6.13	7.70	8.67	10.60	12.67	13.53	41.73	16.40
Bd4V3	6.20	8.27	10.27	11.43	13.33	14.20	15.57	16.53
Bd5V1	4.10	5.17	8.00	8.97	10.37	11.47	12.70	13.47
Bd5V2	4.47	5.60	6.60	8.63	9.13	10.03	10.93	12.10
Bd5V3	5.70	7.43	8.27	10.83	11.93	12.83	14.20	15.23
LSD ($P<0.05$)	3.29	1.88	2.01	2.65	2.54	2.75	2.91	2.84
CV (%)	6.94	13.45	12.35	13.87	11.78	11.46	11.18	9.94

Variety	Bulk Density (Mg m^{-3})
V_1 – Enibi	Bd_1 – 1.1
V_2 – Mamaba	Bd_2 – 1.3
V_3 – Obatanpa	Bd_3 – 1.5
	Bd_4 – 1.7
	Bd_5 – 1.9

4.11 Effect of Soil Compaction and Maize Variety and their Interactions on Shoot Mass

The analysis of the data (ANOVA) showed that soil compaction, maize variety and their interactions significantly affected maize fresh shoot mass. The mean fresh shoot mass as influenced by bulk density and maize variety is presented in Table 4.11a. Fresh shoot mass ranged from 2.78 to 4.18 for the respective bulk densities of 1.9 Mg m^{-3} and 1.3 Mg m^{-3}. Fresh shoot mass ranked as 1.3>1.1>1.5>1.7>1.9 Mg m^{-3}. Apart from 1.1 and 1.3 Mg m^{-3} which had no significant difference in their shoot masses and out yielded the remaining bulk densities, all the differences in fresh shoot mass were significant ($P<0.05$). The maize varietal effect was in the order of Obatanpa>Mamaba>Enibi. The differences in the fresh shoot mass of the maize varieties were not significant.

Fresh shoot mass was not significantly different under both 1.1, 1.3 and 1.5 Mg m^{-3} and 1.5 and 1.7 Mg m^{-3}. However the fresh shoot mass under these bulk densities was significantly greater than that of the 1.9 Mg m^{-3}. Fresh shoot mass of maize (Table 4.11a) decreased with increasing bulk density. A 32 per cent increase in bulk density (1.3 to 1.9 Mg m^{-3}) reduced fresh shoot mass by 33 per cent.

Whilst the main effect of maize variety showed no significant differences in shoot mass, the bulk density × maize variety interaction (Table 4.11b and Appendix 9) of fresh shoot mass showed most of the interaction means to differ significantly. Obatanpa, for example significantly ($P<0.05$) outyielded Mamaba under bulk densities 1.1, 1.3 and 1.9 Mg m^{-3}. These effects are confounded when only the main effects are considered. The effect of bulk density and maize variety on dry shoot mass (Table 4.11b) was similar to that of the fresh shoot mass with values ranging from 0.44 to 0.85 g under the 1.9 and 1.3 Mg m^{-3} bulk densities, respectively and 0.65 to 0.72g for Mamaba and Obatanpa. The bulk density × variety interaction showed significant differences in dry shoot mass (Appendix 10). The interaction mean differences at bulk densities 1.1 to 1.5 Mg m^{-3} and 1.5 and 1.7 Mg m^{-3} were not significant. Similarly, most of the interactions at 1.7 and 1.9 Mg m^{-3} were not significant. The interactions between the latter two high bulk densities and those at 1.1 and 1.3 Mg m^{-3} were significant.

Table 4.11a Effect of soil compaction and maize *(Zea mays)* variety on fresh and dry shoot mass at 21 Days after planting (DAP)

Treatment (Bulk density) ($Mg\ m^{-3}$)	Fresh Shoot Mass (g)	Dry Shoot Mass (g)
1.1	3.96	0.81
1.3	4.18	0.85
1.5	3.71	0.71
1.7	3.37	0.58
1.9	2.78	0.44
LSD ($P < 0.05$)	0.48	0.12
Maize Variety		
Enibi	3.54	0.67
Mamaba	3.50	0.65
Obatanpa	3.77	0.72
LSD ($P<0.05$)	0.37	0.10
CV (%)	13.7	18.78

Table 4.11b Interaction effects of bulk density and maize variety on fresh and dry shoot mass

Treatment	Mean Fresh Shoot Mass g/Plant	Mean Dry Shoot Mass g/Plant
Bd1V1	7.87	0.82
Bd1V2	7.70	0.78
Bd1V3	8.23	0.84
Bd2V1	8.36	0.85
Bd2V2	8.15	0.82
Bd2V3	8.58	0.90
Bd3V1	7.37	0.70
Bd3V2	7.32	0.67
Bd3V3	7.57	0.75
Bd4V1	6.4	0.55
Bd4V2	6.93	0.57
Bd4V3	6.88	0.62
Bd5V1	5.35	0.42
Bd5V2	4.87	0.38
Bd5V3	6.47	0.52
LSD ($P<0.05$)	0.41	0.21
CV (%)	13.7	18.78

4.12 Effect of compaction, maize variety and their interactions on root mass

The analysis of variance showed bulk density to significantly influence fresh root mass of maize. The mean values (Table 4.12a) showed maize fresh root mass to vary from 0.7 to 1.77 g with a ranking of 1.1>1.3>1.5>1.7>1.9 Mg m^{-3}. Apart from the 1.1 and 1.3 Mg m^{-3} bulk densities which recorded no significant difference in their root masses, all other differences in fresh root mass were significant ($P<0.05$). The results further showed that for a 15, 27, 35 and 42 per cent change in bulk density from 1.1 to 1.3, 1.5, 1.7 and 1.9 Mg m^{-3} respectively, root mass decreased by 2, 25, 45 and 61 per cent.

The maize varietal effect on fresh root mass was in the order of Obatanpa>Mamaba>Enibi. The differences were, however, not significant. The bulk density × maize interaction (Table 4.12b) caused significant differences in the fresh root mass of maize. The majority of the significant differences were recorded between the interaction means at the lower and higher bulk densities (Appendices 11 and 12). However, at the 1.7 Mg m^{-3} bulk density, the trend of the main effect of maize variety changed to Mamaba> Enibi>Obatanpa. The results (Table 4.12a) further showed the root dry mass of maize to rank as 1.1=1.3>1.5>1.7>1.9 with a range of 0.08 to 0.16 g. The differences in the root dry mass under the different bulk densities were significant ($P<0.05$) except that between the 1.1 and 1.3 Mg m^{-3}. The maize varietal effect on dry root mass followed the same trend as the fresh root mass. The mean percentage moisture content on fresh mass basis was 91. Except a few interaction means at 1.1 and 1.3 Mg m^{-3} and those at 1.9 Mg m^{-3}, most of the bulk density × maize varietal interactions were not significant.

Table 4.12a Effect of soil compaction and maize (*Zea mays*) varieties on fresh and dry root mass sampled 21 DAP

Treatment (Bulk density) (Mg m^{-3})	Mean Fresh Root Mass g/Plant	Mean Dry Root Mass g/Plant
1.1	1.77	0.16
1.3	1.74	0.16
1.5	1.32	0.12
1.7	0.97	0.1
1.9	0.70	0.08
LSD (P<0.05)	0.25	0.02
Maize Variety		
Enibi	1.22	0.12
Mamaba	1.29	0.13
Obatanpa	1.40	0.13
LSD (P<0.05)	0.19	0.02
CV (%)	19.46	15.24

Table 4.12b Interaction effect of bulk density and maize varieties on fresh and dry root mass

Treatment	Mean Fresh Root Mass g/Plant	Mean Dry Root Mass g/Plant
Bd1V1	1.65	0.15
Bd1V2	1.71	0.16
Bd1V3	1.97	0.17
Bd2V1	1.65	0.15
Bd2V2	1.68	0.16
Bd2V3	1.89	0.17
Bd3V1	1.17	0.11
Bd3V2	1.27	0.12
Bd3V3	1.52	0.14
Bd4V1	0.99	0.10
Bd4V2	1.09	0.11
Bd4V3	0.83	0.11
Bd5V1	0.63	0.07
Bd5V2	0.69	0.08
Bd5V3	0.77	0.08
LSD (P<0.05)	0.42	0.08
CV (%)	19.46	15.24

4.13 The Effect of Compaction on Maize Root : Shoot Ratio

The root : shoot ratios (Tables 4.13) ranged from 0.169 to 0.198. At the lower bulk densities, the ratio decreased with increasing bulk density from 1.1 to 1.5 Mg m^{-3}. At the higher bulk densities, the ratio tended to increase as bulk density increased from 1.7 to 1.9 Mg m^{-3}. An increase in bulk density from 1.3 to 1.7 and 1.9 Mg m^{-3} caused a greater but not significant reduction in root than shoot dry matter yield of maize.

Table 4.13 Percentage reduction in maize dry matter yield with increasing soil compaction

Bulk density Mg m^{-3}	Increase in bulk density (%)*	Dry shoot mass (g/plant)	Reduction (%)	Dry root mass (g/plant)	Reduction (%)*	Root : Shoot ratio
1.1	-	0.81	-	0.16	-	0.198
1.3	-	0.85	-	0.16	-	0.188
1.5	13.3	0.71	16.5	0.12	25	0.169
1.7	23.5	0.58	31.8	0.10	37.5	0.172
1.9	31.6	0.44	48.2	0.08	50	0.182

* Percentage increment/reduction relative to 1.3 Mg m^{-3}

4.14 The Effect of Soil Compaction, Maize Variety and their Interactions on Root Penetration Ratio

The mean root penetration ratio (Table 4.14a) 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 per cent. At high bulk densities, a relatively small increase in density causes larger decreases in root penetration ratio. Root penetration ratio did not differ significantly among the varieties. However, with a range of 0.63 to 0.67, Obatanpa recorded the highest ratio. Root penetration ratio was also significantly affected by the bulk density × maize variety interaction (Table 4.14b). Appendix 13 shows that the interaction means at 1.1 and 1.3 Mg m^{-3} were not significant. However means were significantly (P<0.05) greater than those at the 1.5 to 1.9 Mg m^{-3}.

Table 4.14a Effect of soil compaction (bulk density) and maize variety on root penetration ratio sampled 21 DAP

Treatment (Bulk density) (Mg m^{-3})	Root Penetration Ratio Mean
1.1	0.89
1.3	0.89
1.5	0.74
1.7	0.49
1.9	0.25
LSD (P<0.05)	0.09
Maize Variety	
Enibi	0.63
Mamaba	0.65
Obatanpa	0.67
LSD (P<0.05)	0.07
CV (%)	14.95

Table 4.14b Interaction effect of bulk density and maize variety on Root Penetration Ratio (RPR)

Treatment	Root Penetration Ratio Mean
Bd1V1	0.88
Bd1V2	0.86
Bd1V3	0.92
Bd2V1	0.85
Bd2V2	0.92
Bd2V3	0.90
Bd3V1	0.71
Bd3V2	0.73
Bd3V3	0.78
Bd4V1	0.52
Bd4V2	0.50
Bd4V3	0.44
Bd5V1	0.19
Bd5V2	0.26
Bd5V3	0.29
LSD (P<0.05)	0.10
CV (%)	14.95

4.15 Effect of Soil Compaction, Maize Variety on Root Length

Root length plays a significant role in the efficient uptake of water and nutrients from the soil by plants. The analysis of variance showed that root length is significantly influenced by bulk density. The mean root length as influenced by bulk density (Table 4.15) ranged from 44.44 to 133.75 cm with a ranking of 1.3>1.1>1.5>1.7>1.9 Mg m^{-3}. 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 per cent. Maize varietal differences in root length, ranging from 85.54 to 94.71 were not significant but ranked as Obatanpa>Enibi>Mamaba. Root length was significantly influenced by the bulk density × maize variety interaction.

Table 4.15 Effect of soil compaction (bulk density) and maize variety on root length (RL) sampled 21 DAP

Treatment (Bulk density) (Mg m^{-3})	Mean Root Length (cm)
1.1	119.52
1.3	133.75
1.5	93.33
1.7	54.81
1.9	44.44
LSD ($P<0.05$)	12.11
Maize Variety	
Enibi	87.26
Mamaba	85.54
Obatanpa	94.71
LSD ($P<0.05$)	15.64
CV (%)	18.21

4.16 The Effect of Soil Compaction and Maize Varietal Interactions on Root Length

The analysis of variance showed bulk density × maize varietal interactions to cause significant differences in root length. The mean root length is presented in Table 4.16a. The matrix of interaction mean separation presented in Appendix 14 shows which interactions means are significant. The difference in the mean root length of V_1 (Enibi) and V_2 (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 cores as assessed by the percentage relative root length is presented in Table 4.16b. As observed in the case of soybean, maize roots tended to accumulate in the top soil core as the bulk density of the middle core increased. The mean relative root length (Table 4.16b) of the top core was 6.45, 10.56, 23.77, 52.86 and 75.29 per cent 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 core decreased significantly as the density of the middle core increased. For bulk densities of 1.1, 1.3, 1.5, 1.7 and 1.9 Mg m^{-3}, the respective relative root length in the bottom core was 49.86, 38.97, 28.48, 13.71 and 4.89 per cent. On the average the compacted middle core recorded a relative root length of 43.69, 50.48, 47.75, 33.43 and 19.82 for densities of 1.1, 1.3, 1.5, 1.7 and 1.9 Mg m^{-3} respectively.

Table 4.16a Interaction effect of bulk densities and maize varieties on root length

Treatment	Mean Root Length (cm)
Bd1V1	117.07
Bd1V2	114.98
Bd1V3	126.50
Bd2V1	129.38
Bd2V2	131.74
Bd2V3	140.13
Bd3V1	95.60
Bd3V2	85.91
Bd3V3	98.48
Bd4V1	51.81
Bd4V2	51.86
Bd4V3	60.76
Bd5V1	42.43
Bd5V2	43.22
Bd5V3	47.67
LSD (P<0.05)	29.15
CV (%)	18.22

Table 4.16b 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	43.2
1.1	Mamaba	6.71	47.93	45.36
1.1	Obatanpa	6.1	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	40.55
1.3	Obatanpa	8	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**	**28.48**
1.7	Enibi	53.96	34.34	11.7
1.7	Mamaba	49.32	33.75	16.93
1.7	Obatanpa	55.3	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	5.9
Mean		**75.29**	**19.82**	**4.89**

4.17 Relationship between Soil Compaction and Plant Parameters

The data on plant parameters were examined for correlations with bulk density and porosity and predictive equations established using regression analyses.

4.17.1 The relationship between bulk density and plant parameters

The regression analysis (Table 4.17; Appendices 15a-g) showed a negative correlation between bulk density and all the measured plant parameters. The correlation coefficients (r) for the 15 day old soybean seedlings (Table 4.17; Appendices 15a-g) were -0.94 for plant height, -0.91 for fresh shoot mass, -0.88 for dry shoot mass, -0.93 for fresh root mass, -0.95 for dry root mass, -0.94 for root length and -0.97 for root penetration ratio. The coefficient of determination (R^2) ranged from 0.78 for dry shoot mass to 0.93 for root penetration ratio making the equations suitable for predictive purposes.

In the case of the 21 day old maize seedlings, the correlation coefficients (Table 4.17; Appendices 15a-g) were -0.90 for plant height, -0.91 for fresh shoot mass, -0.94 for dry shoot mass, -0.96 for fresh root mass, -0.97 for dry root mass, -0.93 for root length, and -0.96 for root penetration ratio. The high coefficient of determination, ranging from 0.82 for plant height to 0.96 for fresh root mass, is also satisfactory for predictive purposes.

Table 4.17 Regression Equations relating Soil Bulk Density to Soybean and Maize Plant Parameters

Relation	Soybean			Maize		
	Regression Equation	Correlation Coefficient (r)	Coefficient of Determination (R^2)	Regression Equation	Correlation Coefficient (r)	Coefficient of Determination (R^2)
Bulk Density Vs. Plant Height	Y = -12.9x + 40.626	0.94	0.88	Y = -6.67x + 27.135	0.91	0.82
Bulk Density Vs. Fresh Shoot Mass	Y = -2.14x + 5.11	0.91	0.82	Y = -1.585x + 5.9775	0.92	0.84
Bulk Density Vs. Dry Shoot Mass	Y = -0.425x + 1.0115	0.88	0.78	Y = -0.505x + 1.4355	0.94	0.89
Bulk Density Vs. Fresh Root Mass	Y = -0.235x + 0.5565	0.94	0.88	Y = -1.455x + 3.4825	0.98	0.96
Bulk Density Vs. Dry Root Mass	Y = -0.03x + 0.085	0.95	0.90	Y = -0.11x + 0.289	0.97	0.95
Bulk Density Vs. Root Length	Y = -80.61x + 177.89	0.94	0.88	Y = -114.55x + 261	0.93	0.86
Bulk Density Vs. Root Penetration Ratio	Y = -1.175x + 2.2925	0.96	0.93	Y = -0.84x + 1.912	0.95	0.91

4.17.2 The relationship between porosity and plant parameters

The results of the regression analysis showed porosity to be positively correlated with the measured plant parameters. The correlation coefficient (r) of total porosity for soybean (Table 4.18; Appendices 16a-g) was 0.94 for plant height, 0.91 for fresh shoot mass, 0.89 for dry shoot mass, 0.94 for fresh root mass, 0.95 for dry root mass, 0.94 for root length and 0.97 for root penetration ratio. The coefficient of determination ranged from 0.79 for dry root mass to 0.94 for root penetration ratio.

The positive correlation coefficient (r) of total porosity in the case of maize (Table 4.18; Appendices 16a-g) was 0.91 for plant height, 0.92 for fresh shoot mass, 0.95 for dry shoot mass, 0.98 for fresh root mass, 0.94 for dry root mass, 0.93 for root length and 0.96 for root penetration ratio. The coefficient of determination (R^2) ranged from 0.84 to 0.96.

Table 4.18 Regression Equations relating Total Porosity to Soybean and Maize Plant Parameters

Relation	Soybean			Maize		
	Regression Equation	Correlation Coefficient (r)	Coefficient of Determination (R^2)	Regression Equation	Correlation Coefficient (r)	Coefficient of Determination (R^2)
Total Porosity Vs. Plant Height	Y = 0.3438x + 6.3216	0.94	0.89	Y = 0.1774x + 9.4127	0.91	0.82
Total Porosity Vs. Fresh Shoot Mass	Y = 0.0517x – 0.584	0.91	0.83	Y = 0.0421x + 1.7683	0.92	0.84
Total Porosity Vs. Dry Shoot Mass	Y = 0.0113x – 0.1195	0.89	0.79	Y = 0.0134x + 0.0946	0.95	0.90
Total Porosity Vs. Fresh Root Mass	Y = 0.0062x – 0.0678	0.94	0.88	Y = 0.0386x – 0.3783	0.98	0.96
Total Porosity Vs. Dry Root Mass	Y = 0.0008x + 0.0054	0.95	0.90	Y = 0.0029x – 0.0027	0.97	0.94
Total Porosity Vs. Root Length	Y = 2.1441x – 36.292	0.94	0.89	Y = 3.0381x – 42.988	0.93	0.86
Total Porosity Vs. Root Penetration Ratio	Y = 0.0312x – 0.8281	0.97	0.94	Y = 0.0223x – 0.32	0.96	0.92

Air-filled porosity (Table 4.19; Appendices 17a-g) also correlated positively with the plant parameters with the correlation coefficient (r) and coefficient of determination ranging from 0.91 to 0.98 and 0.84 to 0.95 respectively.

Air-filled porosity for maize (Table 4.19; Appendices 17a-g) also correlated positively with the measured plant parameters. The coefficient of correlation (r) ranged between 0.91 and 0.97 with R^2 ranging from 0.83 to 0.95.

Table 4.19 Regression Equations relating Air-filled Porosity to Soybean and Maize Plant Parameters

Relation	Soybean			Maize		
	Regression Equation	Correlation Coefficient (r)	Coefficient of Determination (R^2)	Regression Equation	Correlation Coefficient (r)	Coefficient of Determination (R^2)
Air-filled Porosity Vs. Plant Height	Y = 0.3413x + 16.903	0.97	0.95	Y = 0.1743x + 14.896	0.93	0.86
Air-filled Porosity Vs. Fresh Shoot Mass	Y = 0.0569x + 1.171	0.95	0.90	Y = 0.041x + 3.0751	0.93	0.86
Air-filled Porosity Vs. Dry Shoot Mass	Y = 0.0113x + 0.2286	0.93	0.86	Y = 0.0129x + 0.5121	0.95	0.90
Air-filled Porosity Vs. Fresh Root Mass	Y = 0.006x + 0.1267	0.94	0.89	Y = 0.0365x + 0.8324	0.96	0.93
Air-filled Porosity Vs. Dry Root Mass	Y = 0.0007x + 0.0305	0.92	0.84	Y = 0.0027x + 0.0892	0.94	0.89
Air-filled Porosity Vs. Root Length	Y = 2.0798x + 30.325	0.95	0.90	Y = 2.8717x + 52.372	0.91	0.83
Air-filled Porosity Vs. Root Penetration Ratio	Y = 0.0301x + 0.1445	0.97	0.94	Y = 0.0218x + 0.3722	0.97	0.95

4.17.3 Relationship between root penetration ratio and plant parameters

The results (Table 4.20; Appendices 18a-b) showed a positive correlation between root penetration ratio and fresh and dry shoot masses. The coefficient of correlation (r) was 0.93 and 0.91 for fresh and dry shoot masses respectively for soybean with corresponding R^2 of 0.86 and 0.84.

The correlation coefficients for maize ranged between 0.93 and 0.96 for dry and fresh shoot masses respectively with their R^2 values of 0.93 and 0.87.

Table 4.20 Regression Equations relating Root Penetration Ratio to Soybean and Maize Plant Fresh and Dry Shoot Masses

Relation	Soybean			Maize		
	Regression Equation	**Correlation Coefficient (r)**	**Coefficient of Determination (R^2)**	**Regression Equation**	**Correlation Coefficient (r)**	**Coefficient of Determination (R^2)**
Root Penetration Ratio Vs. Fresh Shoot Mass	Y = 1.8254x + 0.9359	0.93	0.86	Y = 3.8702x + 4.6877	0.93	0.87
Root Penetration Ratio Vs. Dry Shoot Mass	Y = 0.3602x + 0.1843	0.92	0.84	Y = 0.6037x + 0.2869	0.96	0.93

4.18 Effect of Bulk Density on Root Structure and Anatomy of Soybean and Maize

The limited anatomical studies of the roots of soybean and maize showed soil compaction to adversely affect not only root length, root penetration ratio and dry matter yield, but also the structure and anatomy of the roots.

Visual observation indicated roots in the highly compacted soil to be thicker, stubby and contorted. The anatomical features of the soybean root showed variable response to soil compaction. In all cases the circular nature of the transverse section of the root tended to be oval with distortions in the structure of the epidermis, cortex and vascular bundles. The magnitude of distortion was greater in the highly than less compacted soil. In the less compacted soil (Plates 1a and b) the structural integrity of the soybean root tissues were evident although somehow diffuse. In the highly compacted soil, the anatomical features were completely distorted. The vascular bundles (xylem and phloem) of the roots under the 1.9 Mg m^{-3} bulk density were hardly visible and the epidermis, cortex, endodermis and pericycle were severely damaged (Plates 2a, b and c). The damage in these tissues appeared to be relatively less in Anidaso (Plate 1b) than Ahoto and Nangbaar (Plate 2b and c).

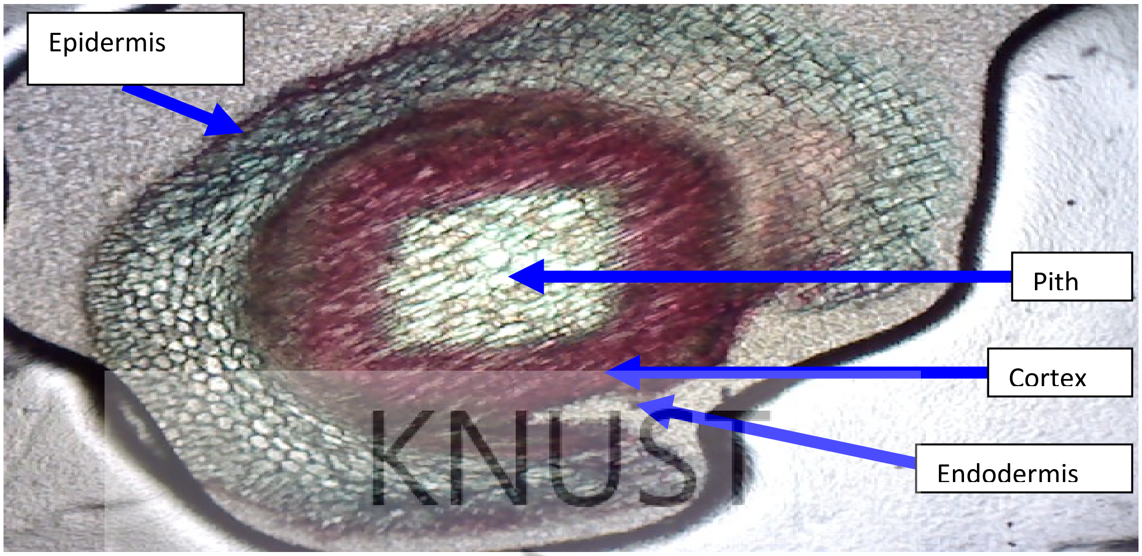

Plate 1a. Cross section of a root of soybean (Ahoto variety) at bulk density of 1.3 Mg m^{-3}

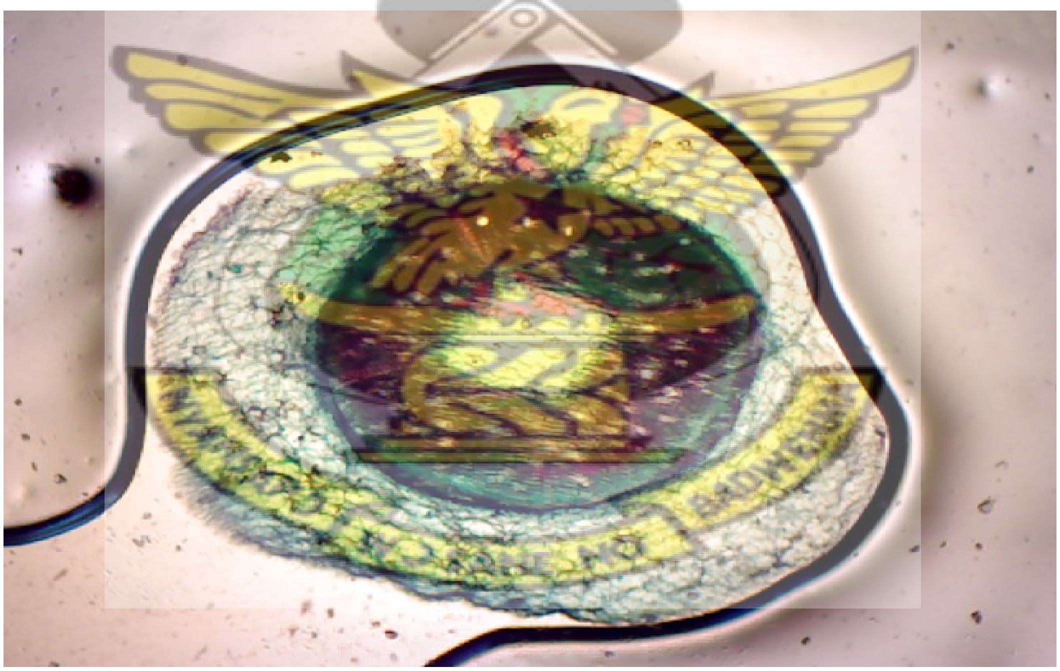

Plate 1b: Cross section of a root of soybean (Anidaso variety) at bulk density of 1.3 Mg m^{-3}

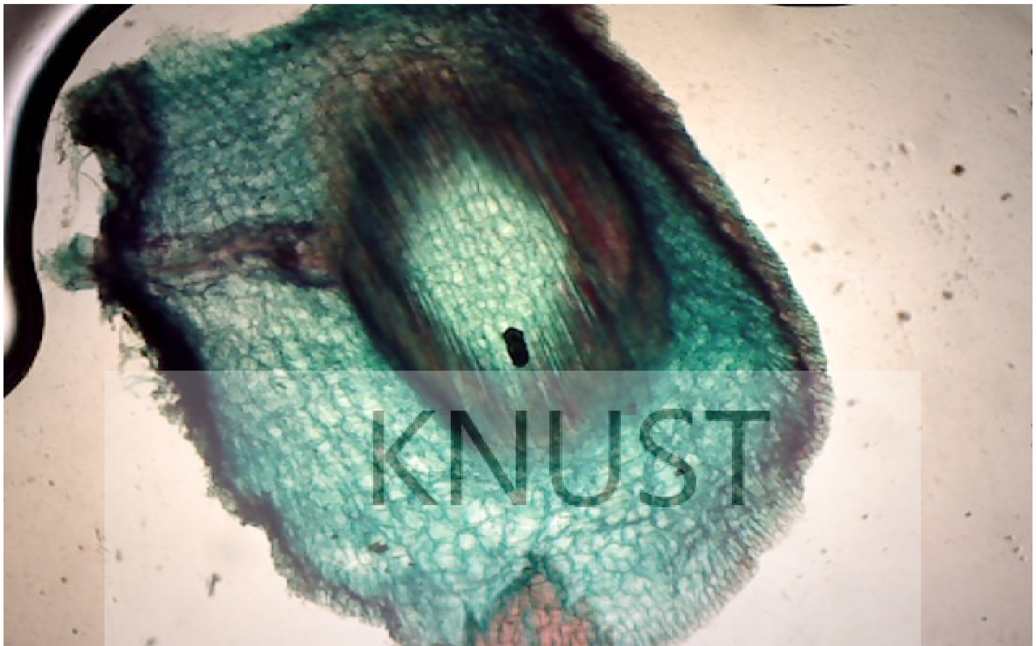

Plate 2a. Cross section of a root of soybean (Anidaso variety) at bulk density of 1.9 Mg m^{-3}

Plate 2b Cross section of a root of soybean (Ahoto variety) at bulk density of 1.9 Mg m^{-3}

Plate 2c. Cross section of a root of soybean (Nangbaar variety) at bulk density of 1.9 Mg m^{-3}

In the case of maize, the structure of the root tissues of the three varieties were normal under the bulk density of 1.3 Mg m^{-3} showing clearly the epidermis, cortex, endodermis, xylem, phloem and pith (Plates 3a, b and c). The number of xylem bundles (13) was even visible in all the three varieties, although there was a slight distortion in those of Enibi. However these tissues were completely damaged at the bulk density of 1.9 Mg m^{-3} (Plate 4c). The circular cross section became depressed into an oval shape and the tissues damaged in the order of Obatampa<Mamaba< Enibi.

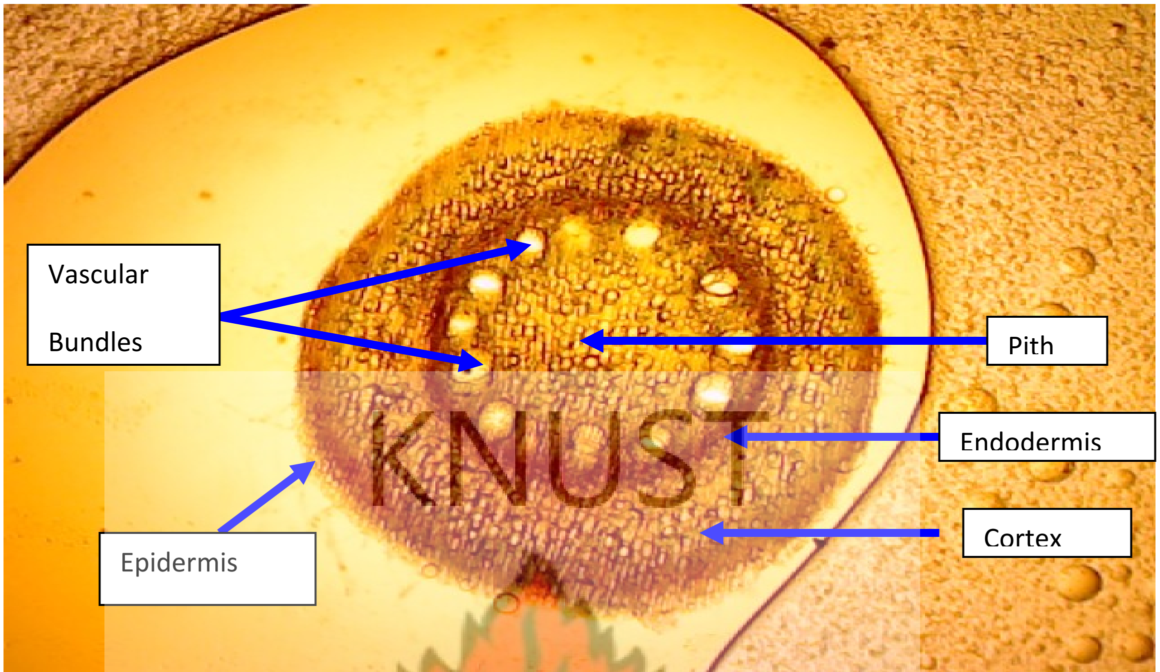

Plate 3a Cross section of a root of Maize (Obatanpa variety) at bulk density of 1.3 Mg m^{-3}

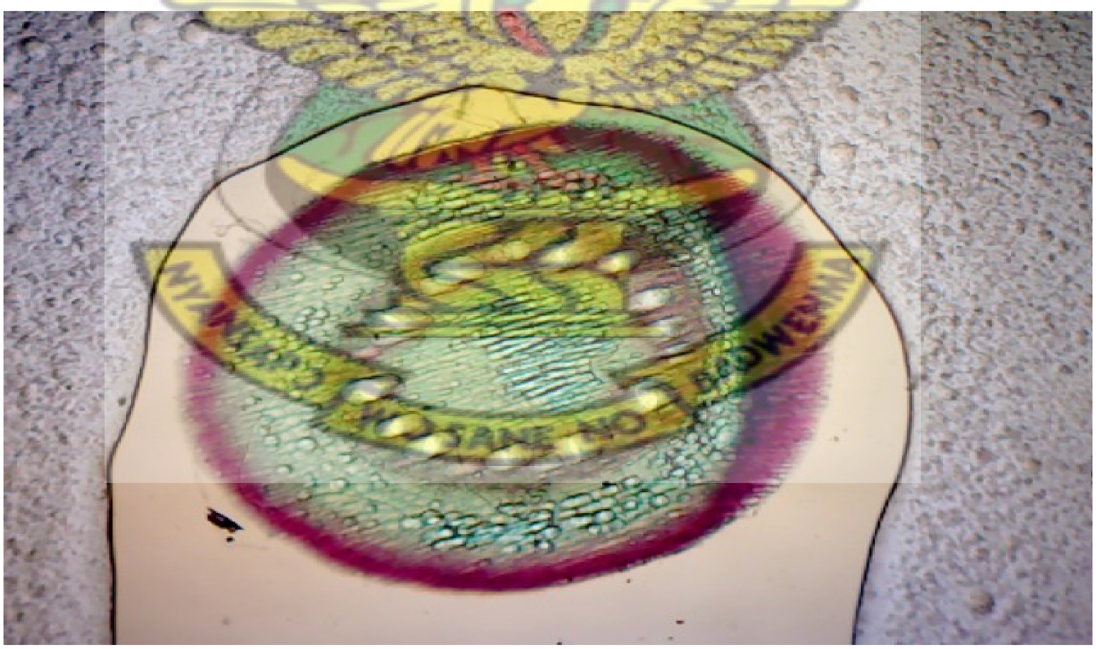

Plate 3b. Cross section of a root of Maize (Mamaba variety) at bulk density of 1.3 Mg m^{-3}

Plate 3c: Cross section of a root of Maize (Enibi variety) at bulk density of 1.3 Mg m^{-3}

Plate 4a. Cross section of a root of Maize (Obatanpa variety) at bulk density of 1.9 Mg m^{-3}

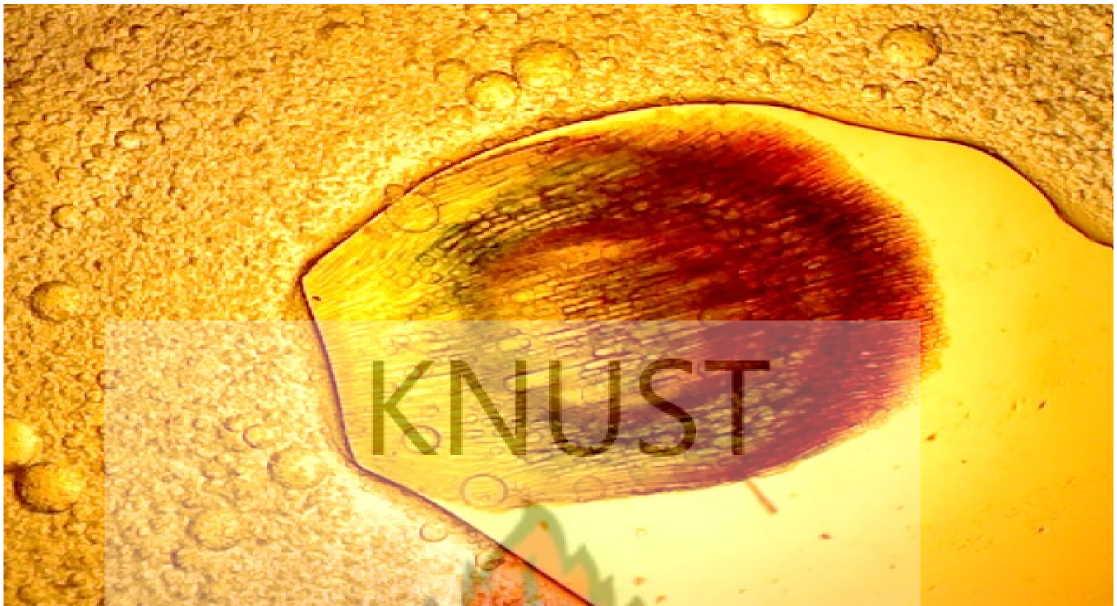

Plate 4b. Cross section of a root of Maize (Mamaba variety) at bulk density of 1.9 Mg m^{-3}

Plate 4c. Cross section of a root of Maize (Enibi variety) at bulk density of 1.9 Mg m^{-3}

CHAPTER FIVE

5.0 DISCUSSION

5.1. The Impact of Soil Compaction on Soil Physical Properties

Of the environmental factors that influence the growth and production of agricultural crops, those that affect the root atmosphere are of particular importance. These include bulk density, total porosity, air-filled porosity, moisture content and availability, infiltration and hydraulic conductivity.

In this study, the imposition of increasing levels of compaction resulted in increased bulk density. Consequently, 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 this discussion to express the impacts of the latter on the variables measured.

The results showed that as bulk density increases, there is a corresponding decrease in the total porosity of the soil. From a base value of 58.5 percent at the bulk density of 1.1 Mg m^{-3}, total porosity was progressively reduced by a range of 13 to 52 percent as bulk density increased to 1.3 Mg m^{-3} through to 1.9 Mg m^{-3}. It has been observed that as total porosity of the soil is reduced, pore size distribution shifts toward smaller pore size and pore space continuity decreases (Sands *et al.*, 1979). By altering the extent and configuration of the pore space and increasing the mechanical impedance to the growth of roots, soil compaction adversely affects the soil as a medium for plant growth. In this regard, the studies of Asady *et al.* (1985) and Barraclough and Weir (1998) showed soil compaction to reduce soil water movement and availability, nutrient uptake and aeration.

The decreasing total porosity and volumetric water content (in the range of 13 to 52 and 39.6 to 14.5 percent respectively as bulk density increased from 1.1 to 1.3 through 1.9 Mg m^{-3}) resulted in a corresponding decrease in air-filled porosity. At a base value of 27 percent at 1.1 Mg m^{-3}, air-filled porosity decreased by a range of 28.7 to 38.1 percent as bulk density increased to 1.3 and 1.5 Mg m^{-3} respectively and 80.3 to 116 percent at 1.7 and 1.9 Mg m^{-3}. The percentage reduction figures imply that air-filled porosity is more sensitive to increases in soil compaction than total porosity. The reduced air-filled porosity below the 10 percent critical value for adequate root growth (Gupta and Allmaras, 1987) recorded at the 1.7 and 1.9 Mg m^{-3}, implicitly would impede gaseous diffusion, particularly oxygen and create an unfavourable soil environment for root growth as observed by Asady *et al.* (1985).

As total porosity and air-filled porosity decreased under increasing compaction of the soil, so also did hydraulic conductivity. The base value of 44.2 mm h^{-1} at 1.1 Mg m^{-3} was reduced by a range of 6.6 to 42 percent with a value of 25.6 mm h^{-1} at a bulk density of 1.9 Mg m^{-3}. 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 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 on hydraulic conductivity. Reduced water uptake and hence water availability to a crop has important implications for both shoot and root growth as well as the final yield.

Growth of plants is controlled by the rates of cell division and enlargement and by the supply of organic and inorganic compounds required for synthesis of new protoplasm and cell walls. Cell enlargement is particularly dependent on at least a minimum degree of cell turgor and stem and leaf elongation are quickly checked or stopped by water deficits. Decreasing water content is accompanied by loss of turgor and wilting, cessation of cell enlargement, closure of stomata, reduction in photosynthesis and interference with many basic metabolic processes (Kramer, 1969).

5.2. The Effect of Soil Compaction, Crop Genotype and their Interactions on Root Growth

Root systems have four important functions, namely, absorption, anchorage, storage and synthesis of organic compounds. Practically all water and nutrients absorbed by terrestrial plants enter through their roots (Kramer, 1969). However the successful growth of roots and their functioning as absorbing surfaces depend on many factors in the soil environment, especially those affecting mechanical resistance to root extension, water supply, aeration and the chemical composition of the soil solution.

There seems to be little doubt that increasing bulk density decreases root growth, but it is probable that in many instances the reduced growth may be due to the effect of increasing bulk density on other factors. To single out bulk density as the cause of reduced root development therefore becomes contentious. The question arises as to whether observed decreases in root development is due to the direct effect of bulk density, soil strength, reduced porosity, rigidity of the pore system or the indirect adverse effect of bulk density on aeration, moisture availability and nutrient uptake.

From the expressed view of several authors (Asady *et al.,* 1985; Bengough and Mullins, 1990; Lipiec and Hakansson, 2000; Wolfe *et al.,* 1995; Lipiec *et al.,* 2003; Glab, 2007), it can be concluded that the relative magnitude of the dependence of growth on the above listed factors is variable and subject to the influence of their interaction. It also shows that studies on soil compaction should take cognizance of its interaction with other factors when interpreting results.

The results of this study have clearly shown that soil compaction has adverse effects on all the plant parameters studies. The **fresh and dry root** masses of both soybean and maize decreased as the dry bulk density of the soil increased. For a 13, 24 and 32 percent change in bulk density from 1.3 to 1.5, 1.7 and 1.9 Mg m^{-3} respectively, root fresh mass of soybean seedlings decreased by 20, 54 and 61 percent. The corresponding reduction in **dry root mass** was 20, 40 and 40 percent. In the case of maize, the above percentage increase in bulk density decreased fresh root mass by 24, 44 and 60 percent and dry root mass by 25, 38 and 50 percent. The implication of the figures is that small increases in bulk density cause large reductions in root growth.

The reduction in root dry matter yield due to soil compaction has been reported by several researchers (Asady *et al.,* 1985; Lowery and Schular, 1991; Lipiec and Hakansson, 2000). The reduction in the root growth and yield has been alluded to the adverse impacts of compaction on soil properties. These include increased mechanical impedance, reduction in the volume and continuity of the large soil pores which are most conducive to water and air movement, reduction in water availability, soil-air capacity, infiltration, percolation and hydraulic conductivity. In addition the supply of oxygen, water and nutrient is restricted (Asady *et al.,* 1985; Bengough and Mullins, 1990; Cook *et al.,* 1996; Lipiec and Stepniewski, 1995).

Mechanical impedance, induced by soil compaction, increases with increasing bulk density. 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).

In this study, soil compaction reduced total porosity, air-filled porosity and hydraulic conductivity at the base values at the 1.1 Mg m^{-3} bulk density by up to 59, 80-116 and 42 percent respectively at the higher bulk densities of 1.7 and 1.9 Mg m^{-3}. Air-filled porosity was less than the 10 percent critical value required for adequate root growth. According to Bengough and 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. On the other hand, Asady *et al.* (1985) observed that when air-filled porosity decreased to 6 percent, the diffusion of oxygen was too low to support optimum aerobic 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, may account for the recorded reductions in the root dry matter yield as well as 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 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 $m^{-3}$are 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 and Lipiec (1990) pointed out that the growth of roots in compacted soil requires much greater energy to form and sustain a unit root length.

A common response of a root system to increasing bulk density is to decrease its length, concentrating roots in the upper uncompacted layer and decreasing root depth (Glinski and Lipiec, 1990; Lipiec *et al.,* 1991; 1992; Marschner, 1995).

The percentage relative root length, which was used to assess root distribution in the three soil cores showed concentration of roots in the uncompacted topsoil core as the bulk density of the middle core increased. The relative root length at the 1.1 to 1.5 Mg m^{-3} bulk density ranged from 12 to 20 percent and 53 to 77 percent for the 1.7 and 1.9 Mg m^{-3} under soybean. The corresponding values for maize were 6 to 24 percent and 53 to 75 percent. Similar observations have been reported by several researchers (Lipiec *et al.,* 2003; Asady *et al.,* 1985; Glab, 2007). According to Lipiec *et al.* (2003) the concentration of roots in the upper layer of compacted soil can be due to more horizontal growth. In a severely compacted soil, similar to the 1.7 and 1.9 Mg m^{-3} in this study, such root distribution can be partly attributed to the horizontal orientation of pores (Slowiska-Juriewicz and Domzal, 1991). Deeper but reduced root growth was attributed to excessive mechanical impedance, especially in the dry season and insufficient aeration (air-filled porosity <10%) in the wet season (Lipiec and Hakansson, 2000). 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 core assembly in this 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/CO_2) becomes a limiting factor for root growth and activity because of a high rooting density in the loose soil zone (Asady and Smucker, 1989).

Because these conditions prevailed at the 1.7 and 1.9 Mg m^{-3} bulk densities, it is not surprising that the relative root length in the bottom core beyond the middle compacted core was reduced to 9 and 3 percent for soybean and 14 and 5 percent for maize, respectively. These figures compare with a range of 33 to 41 percent for soybean and 28 to 44 percent for maize at the bulk density range of 1.1 to 1.5 Mg m^{-3}. Excessive soil compaction therefore drastically reduced the percentage of roots exiting the compacted zone.

For the same reasons of high impedance and inferred insufficient aeration at the 1.7 and 1.9 Mg m^{-3}, the root penetration ratios of both soybean and maize decreased with increasing bulk density. The percentage reduction in root penetration ratio as bulk density increased from 1.3 Mg m^{-3} to 1.5, 1.7 and 1.9 Mg m^{-3} was 30, 72 and 98 respectively. The corresponding values for maize were 17, 45 and 72 percent. The implications are that small increases in bulk density cause significant reductions in root penetration ratio and root penetration ratio of soybean is more sensitive to soil compaction than maize.

In a similar soil core experiment, Asady *et al.* (1985) found that as bulk density of the middle core increased, root penetration ratio decreased. The reduction was attributed to reduced air-filled porosity, as recorded in this study, 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.

The interaction means showed no significant differences in the root dry mass of the soybean varieties at each level of bulk density. However the root dry mass of each variety at the 1.1 to 1.3 Mg m^{-3} bulk densities was significantly ($P<0.05$) greater than their counterparts at the 1.7 and 1.9 Mg m^{-3}. A change of bulk density from 1.3 to 1.5 Mg m^{-3} reduced root dry mass of each variety by 20 percent and 40 percent each at the 1.7 and 1.9 Mg m^{-3}. Implicitly the lower bulk densities favoured root growth in all the varieties whilst the high bulk densities exhibited adverse impacts on root growth.

The root penetration ratios of soybean varieties at 1.1, 1.3, 1.5 and 1.9 Mg m^{-3} bulk densities also did not differ significantly. At the 1.7 Mg m^{-3}, however, the varieties differed significantly ($P<0.05$) in the root penetration ratio with a rank of Anidaso>Nangbaar>Ahoto. Ahoto could not penetrate the compacted core of 1.7 and 1.9 Mg m^{-3}. At the former bulk density, the root penetration of Anidaso was 34 percent greater than Nangbaar. On the other hand, neither Ahoto nor Anidaso could penetrate the 1.9 Mg m^{-3} soil core. Each soybean variety at 1.1 and 1.3 Mg m^{-3} bulk densities recorded significantly greater root penetration ratio than those at the 1.5 to 1.9 Mg m^{-3}.

The base value of root penetration ratio of Ahoto at 1.3 Mg m^{-3} was reduced by 27 percent at 1.5 Mg m^{-3} and 100 percent each at 1.7 and 1.9 Mg m^{-3}. The root penetration ratios of Anidaso and Nangbaar were reduced by 27, 51 and 100 percent and 32, 49 and 94 percent respectively at 1.5, 1.7 and 1.9 Mg m^{-3} bulk densities. The impact of the latter two bulk densities appear to be severer on Ahoto and Anidaso than Nangbaar. However, with over 50 percent reduction in root penetration ratio, a compacted soil of 1.7 and 1.9 Mg m^{-3} bulk densities could be a critical limit for the cultivation of soybean.

The unsuitability of the 1.7 and 1.9 Mg m^{-3} bulk densities for soybean root growth is further supported by the significant reduction of its root length at these bulk densities. The root length of the three soybean varieties at each level of bulk density did not differ significantly. However, the root length of each variety at the 1.1 and 1.3 Mg m^{-3} was significantly greater ($P<0.05$) than their counterparts at the three remaining bulk densities. Root length at 1.3 Mg m^{-3} was reduced by 28, 17 and 16 percent at 1.5 for Ahoto, Anidaso and Nangbaar respectively. The corresponding percentage reduction values at 1.7 Mg m^{-3} were 63, 56 and 58 and 78, 70, 70 at 1.9 Mg m^{-3}. Based on the values of root dry mass, root penetration ratio and root length, the ideal growth conditions for soybean seedling root growth fall within a preferable range of 1.1 to 1.3 Mg m^{-3} bulk density.

The findings revealed in the discussion of the bulk density × soybean variety interaction, are often confounded and not discernible by examining only the main effects of the interacting factors. This underscores the need to pay attention to a detail examination and interpretation of significant interaction of factors which are often neglected in research but pertinent to making agronomic recommendations. The main effect of maize varieties showed no significant differences in the varieties with respect to root dry mass, root penetration ratio and root length as similarly observed under soybean.

The bulk density × maize variety interaction also showed no significant differences in the root dry mass of the three varieties at each level of bulk density. Similarly the differences in the root dry mass of each variety at the bulk densities of 1.1, 1.3, 1.5 and 1.7 Mg m^{-3} were not significant. However, each variety at the 1.1 and 1.3 Mg m^{-3} recorded significantly greater root dry mass than those at 1.9 Mg m^{-3}. At the base values at the 1.3 Mg m^{-3} bulk density, root dry mass was reduced by 27, 25 and 18 percent 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 interaction means further showed no significant differences in the root penetration ratios of the varieties at the 1.1 to 1.7 Mg m^{-3} bulk densities. At the 1.9 Mg m^{-3} bulk density, root penetration ratio ranked as Obatanpa>Mamaba>Enibi with the difference between Obatanpa and Enibi being significant ($P<0.05$). However, root penetration of each variety at the 1.1 and 1.3 Mg m^{-3} was significantly greater ($P<0.05$) than their counterparts at 1.5 to 1.9 Mg m^{-3} with the differences in the latter range of bulk densities also being significant ($P<0.05$).

The base values of root penetration ratio of the varieties at 1.3 Mg m^{-3} were reduced by 28, 21 and 13 percent for Enibi, Mamaba and Obatanpa respectively at the 1.5 Mg m^{-3} bulk density. The corresponding values at the 1.7 and 1.9 Mg m^{-3} were 39, 46 and 51 percent; and 78, 72 and 68 percent.

The mean root length of the varieties at each level of bulk density did not differ significantly, so also were the differences between the varieties at the different levels of 1.1 and 1.5 Mg m^{-3}. However, root length of each variety at the 1.1 to 1.5 Mg m^{-3} bulk densities was significantly ($P<0.05$) greater than those at 1.7 and 1.9 Mg m^{-3} which did not differ significantly. 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 percent at 1.5 Mg m^{-3}; 60, 96 and 57 percent at 1.7 Mg m^{-3}; and 67, 67 and 66 percent at 1.9 Mg m^{-3}. As observed under soybean, a preferable bulk density range of 1.1 to 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.

5.3 The Effect of Soil Compaction, Crop Genotype and Interactions on Shoot Growth

Roots and shoots are dependent on each other in various ways. In addition to supplying carbohydrates, the shoots supply the roots with hormones, thiamin, niacin and pyridoxine, sometimes collectively referred to as rhizoclines. On the other hand, the synthetic activities of roots result in the supply of organic compounds and probably hormones necessary for shoot growth (Kramer, 1969).

Because of the close relationship between root and shoots, any factor, such as soil compaction, affecting the growth of one also influences the other. The reduction in root growth due to compaction reported in this study would therefore impact adversely on shoot growth.

The effect of soil compaction revealed a decreasing shoot growth and dry matter yield of the crop genotypes studied as the levels of soil compaction increased. Whilst each of the crop varieties has its genetic maximum height, the magnitude of height reduction, representing growth rate, was greater under decreasing soil compaction. The height attained at the end of the experiment was greater at 1.1 to 1.5 Mg m^{-3} than at the 1.7 and 1.9 Mg m^{-3} bulk densities. Cultivation of the soil for better soybean and maize production should therefore aim at dry bulk density of 1.1 to 1.5 Mg m^{-3} at which air-filled porosity ranged from 17 to 27 percent which exceeds the 10 percent critical value for adequate root growth (Gupta and Allmaras, 1987).

The restricted root growth under the severely compacted soil at the 1.7 and 1.9 Mg m^{-3} bulk densities, with aeration porosity $\leq$ 5 percent may have constrained adequate aeration and oxygen diffusion rate as well as moisture availability, which is needed for the requisite plant turgor for cell enlargement and shoot elongation. Hakansson *et al.* (1987) and Wolfe *et al.* (1995) found that restricted root distribution in compacted soils can lead to reductions in shoot growth and yield due to limiting water and nutrient uptake. Thus, in evaluating the effect of subsoil compaction on the growth of maize, Gediga (1991) and Lowery and Schular (1991) found significant reductions in plant height, dry matter and grain yield.

The influence of soil compaction manifests itself in several ways through soil-water-air-plant relationships. The final result of this interaction is an overall slowing of the metabolic processes of plant growth. The reduction in growth can be attributed, among other factors, to one or a combination of root impedance, lack of oxygen, accumulation of carbon dioxide, poor water utilization and nutrient uptake (Flocker *et al.,* 1959). The adverse effect of these factors at the 1.7 and 1.9 Mg m^{-3} bulk densities on the root growth of soybean and maize could be the cause of the reduction in the shoot dry mass recorded in this study.

The respective reduction in shoot fresh and dry masses of soybean as bulk density increased from 1.3 to 1.5, 1.7 and 1.9 Mg m^{-3} were 6.4, 50 and 63 percent and 7.8, 53 and 65 percent. The corresponding figures for maize were 11.2, 19.4 and 33.5 percent and 17, 32 and 48 percent. Marschner (1995) pointed out that as a result of a feedback regulation mechanism due to root-shoot growth relationship, shoot growth is retarded when roots are exposed to soil compaction, poor soil aeration or drought stress.

Several authors have reported reductions in shoot dry matter yield in crops due to soil compaction (Gediga, 1991; Lowery and Schular, 1991; Hakansson *et al.,* 1987; Wolfe *et al.,* 1995; Asady *et al.,* 1985). Bertrand and Kohnke (1957) reported reductions in the growth of corn, soybean and cotton due to soil compaction. Increased penetration resistance resulting from increased soil compaction was found to reduce soybean parameters of plant height, dry matter mass, number of pods and seed mass (Beutler and Centurion, 2004). However, the magnitude of the impact was reduced by soil fertilization, implying that fertilization could increase soybean tolerance to soil compaction.

Seedlings that are robust and capable of tolerating soil compaction would therefore be more preferable when aiming at early establishment of the requisite plant stand for optimum yield in a cropping system. Accordingly the main effects of the soybean and maize varieties, which give the average performance of each variety over the range of bulk densities studied, were examined.

The main effect of soybean varieties showed both fresh and dry masses of Anidaso to be significantly ($P<0.05$) greater than Nangbaar and Ahoto. Anidaso seedlings were about 20 percent more robust, in terms of shoot dry mass, than Nangbaar and Ahoto. However, the relative magnitude of shoot dry matter yield of each variety depended on its interaction with the level of bulk density. This is implicit in the bulk density × soybean variety interaction means. The interaction means showed the shoot dry mass of the soybean varieties to differ significantly ($P<0.05$) at each level of bulk density. In all cases Anidaso significantly ($P<0.05$) outyielded Ahoto and Nangbaar. However, between the latter two varieties, Nangbaar was more tolerant to the 1.9 Mg m^{-3} bulk density than Ahoto.

The differences between the shoot dry mass of each variety at the different levels of bulk density were also significant ($P<0.05$). At the base values at the 1.3 Mg m^{-3} shoot dry masses of Ahoto, Anidaso and Nangbaar were reduced by 12, 27 and 7 percent at the 1.5 Mg m^{-3} bulk density; 57, 51 and 47 percent at the 1.7 Mg m^{-3}; and 71, 61 and 57 percent at the 1.9 Mg m^{-3} bulk density. The reduction in shoot dry mass by 47.11 percent at the 1.7 and 1.9 Mg m^{-3} bulk densities makes these levels of soil compaction unfavourable for shoot growth. At these levels of compaction, the tolerance level of the varieties ranked as Nangbaar>Anidaso>Ahoto.

Indications are that shoot dry matter yield of all the varieties is significantly reduced when soil compaction exceeds a bulk density of 1.5 Mg m^{-3} which therefore appear to be the limit for adequate seedling growth of soybean. Based on the parameters studied, 1.3 Mg m^{-3} appear to be the optimum level of dry bulk density for the shoot yield of soybean. This accords with the observation of Beutler and Centurion (2004) that soybean yield started to decline beyond a bulk density of 1.36 Mg m^{-3} on soils without mineral fertilization and 1.48 Mg m^{-3} on soils that received fertilizer.

The maize varietal effect also showed no significant differences in their shoot fresh and dry masses. Similarly, the bulk density × maize variety interaction means showed no significant differences in the varieties at each level of bulk density. The differences in the shoot dry mass of each variety at the different levels of soil compaction ranging from 1.1 to 1.5 Mg m^{-3} were not significant. However, the shoot dry masses of the varieties at the latter bulk densities were significantly greater than their counterparts at 1.7 and 1.9 Mg m^{-3}. The base values at 1.3 Mg m^{-3} showed that the shoot dry mass of Enibi, Mamaba and Obatanpa were reduced by 18, 18 and 17 percent respectively at the

1.5 Mg m^{-3} bulk density. The corresponding values were 35, 31 and 31 percent at the 1.7 Mg m^{-3} and 51, 54 and 51 percent at the 1.9 Mg m^{-3} bulk density. These figures show soil compaction beyond 1.5 Mg m^{-3} to significantly reduce maize seedling shoot growth as observed under soybean. Although maize is less sensitive to soil compaction than soybean, the tolerable range for adequate growth fall within the 1.1 to 1.5 Mg m^{-3} bulk density range with an optimum at 1.3 Mg m^{-3}. Obatanpa was also relatively more tolerant to soil compaction than the other two maize varieties.

5.4 Root : Shoot Ratio

There is limited information on the amount of dry matter incorporated in roots as compared with shoots, largely because of the difficulty of obtaining entire root systems. The results of the root:shoot ratios are a contribution to knowledge in filling this gap. The ratios of the soybean and maize varieties show how much dry matter is partitioned into the roots relative to the shoots. The generation of such information, although relevant for the accurate assessment of net productivity, is often neglected in most studies on crop productivity and may therefore mislead interpretation.

The implication of the root:shoot ratios recorded for the seedlings of the soybean and maize varieties is that the amount of dry matter incorporated in the roots per plant was 9.3, 11.4 and 11.8 percent for Anidaso, Nangbaar and Ahoto respectively. The respective values for Enibi, Mamaba and Obatanpa were 17.9, 20 and 18.9 percent.

Since roots depend on the shoots for the supply of carbohydrates, factors, such as soil compaction, which reduced shoot growth and dry matter yield in this study, also depressed root growth and dry mass. The magnitude of reduction in the growth of the shoots and roots revealed a variable response of shoot and root dry masses to increases in soil compaction.

For bulk densities ranging from 1.1 to 1.5 Mg m^{-3}, the root:shoot ratio tended to decrease as bulk density increased. However, beyond a bulk density of 1.5 Mg m^{-3}, the root:shoot ratio increased as bulk density increased to 1.7 and 1.9 Mg m^{-3}. These figures indicate that under favourable soil conditions for plant growth, dry matter yield was more depressed in roots than shoots. Thus, for a 13 percent increase in bulk density from 1.3 to 1.5 Mg m^{-3}, the reduction in soybean shoot and root dry mass was 8 and 20 percent respectively. The corresponding figures for maize were 17 and 25 percent. However, as bulk density increased from 1.5 to 1.7 and 1.9 Mg m^{-3}, shoot dry mass was reduced by 49 and 69 percent respectively. The reduction in root dry mass was 25 percent at both 1.7 and 1.9 Mg m^{-3}.

Implicitly, at the higher level of soil compaction, despite increasing soil strength and mechanical impedance, root growth is much less depressed than shoot growth, leading to the observed increase in root:shoot dry mass ratio from 0.169 at 1.5 Mg m^{-3}, through 0.172 at 1.7 Mg m^{-3} to 0.182 at 1.9 Mg m^{-3}. This observation accords with that of Masle and Passioura (1987) that in compacted soils, shoot growth is often more depressed than root growth, suggesting root-derived hormonal signals in response to soil compaction. Most likely, the root cap is the sensor of this stress factor (Marschner, 1995).

The root cap not only protects the root meristem and facilitates penetration of the root through pores (by secretion of mucilage as “lubricant”), it is also the site of perception of chemical and physical stress signals (Sievers and Hansel, 1991). It is well established that the accumulation of Abscicic acid (ABA), a typical stress hormone, in roots under drought stress and its transport to the shoots acts as a non-hydraulic root signal leading to inhibition in shoot and leaf elongation and a decrease in stomatal aperture. The restricted root distribution in the highly compacted soil and its adverse impact on water uptake (Wolfe *et al.,* 1995) may have induced conditions similar to those of drought stress with a resultant production of ABA which depressed shoot growth by inhibiting cell extension in shoot tissue and induced stomatal closure (Marschner, 1995).

5.5 Parameter Relationships

5.5.1 Bulk density vs Plant parameters

The regression analysis has amply shown the highly negative correlation between soil compaction, using bulk density as an index, and plant height, shoot and root dry matter, root length and root penetration ratio. An increase in soil compaction therefore results in a reduction in these plant parameters.

The intercept of the regression equations indicate the magnitude of reduction in the measured parameters due to a unit increase in the dry bulk density of the soil. In the case of soybean, a unit increase in bulk density reduced plant height by 12.9 cm, dry shoot and root masses by 0.43 g and 0.03 g respectively, root length by 80.61 cm and root penetration ratio by 1.18.

The figures for the dry shoot and root masses show that soil compaction reduces shoot dry matter yield more than root dry matter. The inferred impact of compaction in increasing abscicic acid (ABA) production in shoots and roots may be implicated in this observation. Marschner (1995) indicated that under such conditions, roots, as a rule continue to grow whilst shoot growth is depressed. This underscores and lends credence to the increases observed in the root:shoot ratios as bulk density increased. A similar trend was observed in the case of maize where a unit increase in bulk density reduced shoot and root dry masses by 0.51 g and 0.11 g respectively.

The reduction in plant height, root length and root penetration ratio as a result of a unit increase in bulk density was 6.67 cm, 114.55 cm and 0.84 respectively.

A comparison of the values for soybean and maize shows the former to be more sensitive to increases in soil compaction in relation to the magnitude of reduction in plant growth using height as an index and root penetration ratio. The high coefficient of determination of the regression equations make them suitable for predictive purposes, given that the interpretation is done within the limits of parameter values and the empirical nature of the equations.

5.5.2 Total and Aeration porosity Vs Plant parameters

Reduced aeration in the root medium is often a limiting factor for root growth and functioning as well as the general growth of the plant. Total and aeration porosities are therefore important soil parameters as they relate to the extent of soil air renewal, water storage and movement, root growth and extension and nutrient uptake. Despite these important functions, soil compaction tends to reduce the volume and continuity of the larger pores with adverse impacts of plant growth (Ball *et al.,* 1998).

The results showed a positive correlation between both total and aeration porosities and the plant parameters measured. The implication is that plant height, shoot and root dry matter, root length and root penetration ratio increase as total porosity and aeration porosities increase. The magnitude of the impact of porosity on the plant parameters can be quantitatively assessed by the value of the intercept of the regression equations relating the plant parameters to total and aeration porosities.

A unit increase in total porosity increased plant height, root dry mass, shoot dry mass, root length and root penetration ratio of soybean seedlings by 0.3438 cm, 0.0008 g, 0.0113 g, 2.144 cm, 0.0312, respectively. The corresponding values for maize seedlings were 0.1774 cm, 0.003 g, 0.013 g, 3.04 cm and 0.0223. The values of the intercept for aeration porosity were not significantly different from those of total porosity. The regression equations were also satisfactory for predictive purposes due to high R^2 recorded.

5.6 Effect of Bulk Density on Root Structure and Anatomy of Soybean and Maize

The importance of the impact of soil compaction on the anatomical tissues of the roots of soybean and maize has to be viewed in the context of the role of these tissues in the proper growth of the crops as presented by Pandey and Chadha (2008). The epidermis, the outermost layer of the root, protects the inner tissues from desiccation, excessive heat and from microbial attack. It gives rise to root hairs which absorb water and minerals from the soil. The cortex, which lies below the epidermis, generally stores food materials in the form of starch grains. It participates in metabolic activities and also gives mechanical support to some extent. The innermost layer of the cortex, endodermis, acts as a water tight jacket between the xylem and cortex, prevents diffusion of air into the xylem, which would otherwise get clogged, protective cover, regulates and maintains root pressure, provides regulated and systematized flow of water through its passage cells.

The xylem transports water and solutes from roots to stem and leaves whilst the phloem translocates prepared food materials downward to storage organs and upward to the growing region mainly in the form of sucrose.

The damage caused by soil compaction to these tissues adversely affects their functioning. These include reduced water and nutrients uptake and availability for various metabolic activities and proper growth of the plants as reported by Walch-Lui *et al.* (2006). It is therefore not surprising that the 1.7 and 1.9 Mg m^{-3} bulk densities recorded the least values for the growth parameters measured including shoot and root dry masses, root penetration ratio and root length.

CHAPTER SIX

6.0 CONCLUSIONS AND RECOMMENDATIONS

The study has amply shown the impact of soil compaction, crop variety and their interactions on some soil and plant parameters. Increasing soil compaction, results in increased soil bulk density, reduced total and aeration porosities, saturated hydraulic conductivity and soil moisture content at field capacity.

Soil compaction reduces dry root and shoot masses, root length and root penetration ratio of maize and soybean seedlings. The differences in these parameters at the lower (1.1 – 1.5 Mg m^{-3}) bulk densities and higher (1.7 – 1.9 Mg m^{-3}) bulk densities were not significant. However significant differences were recorded between the lower and higher bulk densities. Subsoil compaction induces 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. Consequently root proliferation and accumulation beyond the compacted zone decreases as soil compaction increases.

Dry shoot mass and root penetration ratio differed significantly among the soybean varieties in the order of Anidaso>Nangbaar>Ahoto. In maize varietal differences in all the plant parameters measured were not significant.

The bulk density × crop variety interactions on the measured parameters were significant ($P<0.05$). The magnitude of the effects of each factor on the parameters depends on the level of each other factor.

Whilst the main effect of crop variety recorded no significant differences, the interactions revealed the levels of the factors at which the effects differed significantly. Such information is confounded when only the main effects are examined.

Parameter relationships through regression analysis showed soil compaction to be negatively correlated with the measured plant parameters. Increases in soil compaction therefore reduce plant height, dry shoot and root mass, root length and root penetration ratio. Total and air-filled porosity, on the other hand, were positively correlated with the measured plant parameters. The high coefficient of determination of the regression equations ($R^2 = 0.8 - 0.96$) make the equations satisfactory for predictive purposes.

The intercept values of the equations have produced quantitative values for the change in the measured parameters due to a unit change in bulk density or porosity.

These values have shown that:

i. soybean roots are more sensitive to soil compaction than maize roots;

ii. soil compaction reduces shoot dry matter more than root dry matter; and

iii. root:shoot ratio therefore increases with increasing soil compaction.

Increasing soil compaction, beyond 1.5 Mg m^{-3}, adversely affects root structure and anatomical features consisting of epidermis, cortex, endodermis and vascular bundles (xylem and phloem). The study showed the ideal bulk density for maize and soybean seedling growth and dry matter yield to be in the range of 1.1 to 1.5 Mg m^{-3} with 1.3 Mg m^{-3} being the most preferable.

The soil core seedling test could be used to screen crop genotypes for tolerance to soil compaction to enable breeders select crops that could be adapted to soil compaction. This could be a useful test to be included in crop breeding programmes.

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APPENDICES

APPENDIX 1: Mean separation of soil compaction and soybean varietal interactions for plant height

	Bd1V2	Bd1V3	Bd2V1	Bd2V2	Bd2V3	Bd3V1	Bd3V2	Bd3V3	Bd4V1	Bd4V2	Bd4V3	Bd5V1	Bd5V2	Bd5V3
Bd1V1	1.53	1.27	0.77	0.93	0.74	1.9	0.06	2.57	6.5*	4.97*	6.4*	10.67*	8.67*	10.44*
Bd1V2		2.8	2.3	0.6	2.27	3.43*	1.47	4.1*	8.03*	6.5*	7.93*	12.2*	10.2*	11.97*
Bd1V3			0.5	2.2	0.53	0.63	1.33	1.3	5.23*	3.7*	5.13*	9.4*	7.4*	9.17*
Bd2V1				1.7	0.03	1.13	0.83	1.8	5.73*	4.2*	5.63*	9.9*	7.9*	9.67*
Bd2V2					1.67	2.83	0.87	3.5*	7.43*	5.9*	7.33*	11.6*	9.6*	11.37*
Bd2V3						1.16	0.8	1.83	5.76*	4.23*	5.66*	9.93*	7.93*	9.7*
Bd3V1							1.96	0.67	4.6*	3.07*	4.58*	8.77*	6.77*	8.54*
Bd3V2								2.63	6.56*	5.03*	6.46*	10.73*	8.73*	10.5*
Bd3V3									3.93*	2.4	3.83*	8.1*	6.1*	7.87*
Bd4V1										1.53	0.1	4.17*	2.17*	3.94*
Bd4V2											1.43	5.7*	3.7*	5.47*
Bd4V3												4.27*	2.27	4.04*
Bd5V1													2	0.23
Bd5V2														1.77
													LSD	**3.05**

APPENDIX 2: Mean separation of soil compaction and soybean varietal interactions for fresh shoot mass

	Bd1V2	Bd1V3	Bd2V1	Bd2V2	Bd2V3	Bd3V1	Bd3V2	Bd3V3	Bd4V1	Bd4V2	Bd4V3	Bd5V1	Bd5V2	Bd5V3
Bd1V1	-0.39*	0.08	-0.08	-0.57*	0.16*	0.22*	-0.37*	0.2*	1.21*	0.97*	1.13*	1.48 *	1.29*	1.46*
Bd1V2		0.47*	0.31*	-0.18*	0.55*	0.61*	0.02	0.59*	1.6*	1.36*	1.52*	1.87*	1.68*	1.85*
Bd1V3			-0.16*	-0.65*	0.08	0.14*	-0.45*	0.12	1.13*	0.89*	1.05*	1.4*	1.21*	1.38*
Bd2V1				-0.49*	0.24*	0.3*	-0.29*	0.28*	1.29*	1.05*	1.21*	1.56*	1.37*	1.54*
Bd2V2					0.73*	0.79*	0.2*	0.77*	1.78*	1.54*	1.7*	2.05*	1.86*	2.03*
Bd2V3						0.06	- 0.53*	0.04	1.05*	0.81*	0.97*	1.32*	1.13*	1.3*
Bd3V1							- 0.59*	0.02	0.99*	0.75*	0.91*	1.26*	1.07*	1.24*
Bd3V2								0.57*	1.58*	1.34*	1.5*	1.85*	1.66*	1.83*
Bd3V3									1.01*	0.77*	0.93*	1.28*	1.09*	1.26*
Bd4V1										-0.24*	-0.08	0.27*	0.08	0.25*
Bd4V2											0.16*	0.51*	0.32*	0.49*
Bd4V3												0.35*	0.16*	0.33*
Bd5V1													-0.19*	0.02
Bd5V2														0.17*
													LSD	**0.13**

APPENDIX 3: Mean separation of soil compaction and soybean varietal interactions for dry shoot mass

	Bd1V2	Bd1V3	Bd2V1	Bd2V2	Bd2V3	Bd3V1	Bd3V2	Bd3V3	Bd4V1	Bd4V2	Bd4V3	Bd5V1	Bd5V2	Bd5V3
Bd1V1	-0.08*	-0.02	-0.06*	-0.16*	-0.01	0	-0.12*	0	0.22*	0.14*	0.2*	0.29*	0.2*	0.24*
Bd1V2		0.06*	0.02	0.08*	0.07*	0.08*	-0.04	0.08*	0.3*	0.22*	0.28*	0.37*	0.28*	0.32*
Bd1V3			0.04	-0.14*	0.01	0.02	-0.1*	0.02	0.24*	0.16*	0.22*	0.31*	0.22*	0.26*
Bd2V1				0.1	0.05*	-0.06*	0.05*	0.06*	0.28*	0.20*	0.26*	0.35*	0.26*	0.3*
Bd2V2					0.15*	0.16*	0.04	0.16*	0.38*	0.22*	0.36*	0.45*	0.36*	0.4*
Bd2V3						0.01	-0.11*	0.01	0.23*	0.15*	0.21*	0.3*	0.21*	0.25*
Bd3V1							-0.12*	0	0.22*	0.14*	0.2*	0.29*	0.2*	0.24*
Bd3V2								0.12	0.34*	0.26*	0.32*	0.41*	0.32*	0.36*
Bd3V3									0.22*	0.14*	0.2*	0.29*	0.2*	0.24*
Bd4V1										-0.08*	0.02	0.07*	-0.02*	0.02
Bd4V2											0.06*	0.15*	0.06*	0.1*
Bd4V3												0.09*	0	0.04
Bd5V1													-0.09*	-0.05*
Bd5V2														0.04
													LSD	**0.04**

APPENDIX 4: Mean separation of soil compaction and soybean varietal interactions for fresh root mass

	Bd1V2	Bd1V3	Bd2V1	Bd2V2	Bd2V3	Bd3V1	Bd3V2	Bd3V3	Bd4V1	Bd4V2	Bd4V3	Bd5V1	Bd5V2	Bd5V3
Bd1V1	-0.03	0	-0.01	-0.04	-0.01	0.04	0.02	0.03	0.15	0.11	0.12	0.16	0.15	0.15
Bd1V2		0.03	0.02	-0.01	0.02	0.07	0.05	0.06	0.18	0.14	0.15	0.19	0.18	0.18
Bd1V3			-0.01	-0.04	-0.01	0.04	0.02	0.03	0.15	0.11	0.12	0.16	0.15	0.15
Bd2V1				-0.03	0	0.05	0.03	0.04	0.16	0.12	0.13	0.17	0.16	0.16
Bd2V2					0.03	0.08	0.06	0.07	0.19	0.15	0.16	0.2	0.19	0.19
Bd2V3						0.05	0.03	0.04	0.16	0.12	0.16	0.17	0.16	0.16
Bd3V1							- 0.02	0.01	0.11	0.07	0.08	0.12	0.11	0.11
Bd3V2								0.01	0.13	0.09	0.1	0.14	0.13	0.13
Bd3V3									0.12	0.08	0.09	0.13	0.12	0.12
Bd4V1										-0.04	0.03	0.01	0	0
Bd4V2											0.01	0.05	0.04	0.04
Bd4V3												0.04	0.03	0.03
Bd5V1													- 0.01	-0.01
Bd5V2														0
													LSD	**0.21**

APPENDIX 5: Mean separation of soil compaction and soybean varietal interactions for dry root mass

	Bd1V2	Bd1V3	Bd2V1	Bd2V2	Bd2V3	Bd3V1	Bd3V2	Bd3V3	Bd4V1	Bd4V2	Bd4V3	Bd5V1	Bd5V2	Bd5V3
Bd1V1	0	0	0	0	0	0.01	0.01	0.01	0.02	0.02	0.02	0.02	0.02	0.02
Bd1V2		0	0	0	0	0.01	0.01	0.01	0.02	0.02	0.02	0.02	0.02	0.02
Bd1V3			0	0	0	0.01	0.01	0.01	0.01	0.02	0.02	0.02	0.02	0.02
Bd2V1				0	0	0.01	0.01	0.01	0.02	0.02	0.02	0.02	0.02	0.02
Bd2V2					0	0.01	0.01	0.01	0.02	0.02	0.02	0.02	0.02	0.02
Bd2V3						0.01	0.01	0.01	0.02	0.02	0.02	0.02	0.02	0.02
Bd3V1							0	0	0.01	0.01	0.01	0.01	0.01	0.01
Bd3V2								0	0.01	0.01	0.01	0.01	0.01	0.01
Bd3V3									0.01	0.01	0.01	0.01	0.01	0.01
Bd4V1										0	0	0	0	0
Bd4V2											0	0	0	0
Bd4V3												0	0	0
Bd5V1													0	0
Bd5V2														0
													LSD	**0.02**

APPENDIX 6: Mean separation of soil compaction and soybean varietal interactions for root penetration ratio

	Bd1V2	Bd1V3	Bd2V1	Bd2V2	Bd2V3	Bd3V1	Bd3V2	Bd3V3	Bd4V1	Bd4V2	Bd4V3	Bd5V1	Bd5V2	Bd5V3
Bd1V1	-0.02	-	-0.01	-0.02	-	0.26*	0.22 *	0.28*	0.87 *	0.43*	0.58*	0.87*	0.87*	0.82
Bd1V2		0.02	0.01	-	0.02	0.28*	0.24*	0.3*	0.87*	0.45*	0.6*	0.89*	0.89*	0.84
Bd1V3			-0.01	-0.02	-	0.26*	0.22*	0.28*	0.87*	0.43*	0.58*	0.87*	0.87*	0.82
Bd2V1				-0.01	0.01	0.27*	0.23*	0.29*	0.88*	0.44*	0.59*	0.88v	0.88v	0.83
Bd2V2					0.02	0.28*	0.24*	0.3*	0.87*	0.45*	0.6*	0.89*	0.89*	0.84
Bd2V3						0.26*	0.22*	0.28*	0.87*	0.43*	0.58*	0.87*	0.87*	0.82
Bd3V1							-0.04	0.02	0.61*	0.17*	0.32*	0.61*	0.61*	0.56
Bd3V2								0.06	0.65*	0.21*	0.36*	0.65*	0.65*	0.6
Bd3V3									0.59*	0.15*	0.3*	0.59*	0.59*	0.54
Bd4V1										-0.44*	-0.29*	-	-	-0.05
Bd4V2											0.15*	0.44*	0.44*	0.39
Bd4V3												0.29*	0.29*	0.24
Bd5V1													-	-0.05
Bd5V2														-0.05
													LSD	**0.11**

APPENDIX 7: Mean separation of soil compaction and soybean varietal interactions for root length

	Bd1V2	**Bd1V3**	**Bd2V1**	**Bd2V2**	**Bd2V3**	**Bd3V1**	**Bd3V2**	**Bd3V3**	**Bd4V1**	**Bd4V2**	**Bd4V3**	**Bd5V1**	**Bd5V2**	**Bd5V3**
Bd1V1	-1.82	-1.04	-6.02	-6.28	-3.93	17.81 *	7.6	9.17	47.14 *	40.86*	43.74*	59.19 *	52.64 *	53.17*
Bd1V2		0.78	-4.2	-4.46	-2.11	19.63*	9.42	10.99*	48.96*	42.68	45.56*	61.01*	54.46*	54.99*
Bd1V3			-4.98	-5.24	-2.89	18.85*	8.64	10.21	48.18*	41.9	44.78*	60.23 *	53.68*	54.21*
Bd2V1				-0.26	2.09	23.83*	13.62*	15.19*	53.16*	46.88	49.76*	65.21*	58.66*	59.19*
Bd2V2					2.35	24.09*	13.88*	15.45*	43.42*	47.14	50.02 *	65.47*	58.92*	59.45*
Bd2V3						21.74*	11.53*	13.1*	51.07*	44.79	47.67*	63.12*	56.57*	57.1*
Bd3V1							-10.21	-8.64	29.33*	23.05	25.93*	41.38*	34.83*	35.36*
Bd3V2								1.57	39.54*	33.26	36.14*	51.59*	45.05*	45.57*
Bd3V3									37.97*	31.69	34.57*	50.02*	43.47*	44.0*
Bd4V1										6.28	-3.4	12.05*	5.5	6.03
Bd4V2											2.88	18.33*	11.78	12.31*
Bd4V3												15.45*	8.9	9.43
Bd5V1													-6.55	-6.02
Bd5V2														0.53
													LSD	**10.6**

APPENDIX 8: Mean separation of soil compaction and maize varietal interactions for plant height

	Bd1V2	Bd1V3	Bd2V1	Bd2V2	Bd2V3	Bd3V1	Bd3V2	Bd3V3	Bd4V1	Bd4V2	Bd4V3	Bd5V1	Bd5V2	Bd5V3
Bd1V1	0.56	-0.94	-1.3	-0.44	-1.6	0.73	0.7	0.36	3*	2.03	1.9	4.96*	6.33*	3.2*
Bd1V2		-1.5	-1.86	-1	-2.16	0.17	0.14	-0.2	2.44	1.47	1.34	4.4*	5.77*	2.64*
Bd1V3			-0.36	0.5	-0.66	1.67	1.64	1.3	3.94*	2.97*	2.84	5.9*	7.27*	4.14*
Bd2V1				0.86	-0.3	2.03	2	1.66	4.3*	3.33*	3.2*	6.26*	7.63*	4.5*
Bd2V2					-1.16	1.17	1.14	0.8	3.44*	2.47	2.34	5.4*	6.77*	3.64*
Bd2V3						2.33	2.3	1.96	4.6*	3.63*	3.5*	6.56*	7.93*	4.8*
Bd3V1							-0.03	-0.37	2.27	1.3	1.17	4.23*	5.6*	2.47
Bd3V2								-0.34	2.3	1.33	1.2	4.26*	5.63*	2.5
Bd3V3									2.64	1.67	1.54	4.6*	5.97*	2.84
Bd4V1										-0.97	-1.1	1.96*	3.33*	0.2
Bd4V2											-0.13	2.93*	4.3*	1.17
Bd4V3												3.06*	4.43*	1.3
Bd5V1													1.37	-1.76
Bd5V2														-3.13*
													LSD	**2.84**

APPENDIX 9: Mean separation of soil compaction and maize varietal interactions for fresh shoot mass

	Bd1V2	Bd1V3	Bd2V1	Bd2V2	Bd2V3	Bd3V1	Bd3V2	Bd3V3	Bd4V1	Bd4V2	Bd4V3	Bd5V1	Bd5V2	Bd5V3
Bd1V1	0.17	-0.36	-0.49*	-0.28	-0.71*	0.5*	0.55*	0.3	1.47*	0.94*	0.99*	2.52*	3*	1.4*
Bd1V2		-0.53*	-0.66*	-0.45*	-0.88*	0.33	0.38	0.13	1.3*	0.77*	0.82*	2.35*	2.83*	1.23*
Bd1V3			-0.13	0.08	-0.35	0.86*	0.91*	0.66*	1.83*	1.3*	1.35*	2.88*	3.36*	1.76*
Bd2V1				0.21	-0.22	0.99*	1.04*	0.79*	1.96*	1.43*	1.48*	3.01*	3.49*	1.89*
Bd2V2					-0.43*	0.78*	0.83*	0.58*	1.75*	1.22	1.27*	2.8*	3.28*	1.68*
Bd2V3						1.21*	1.26*	1.01*	2.18*	1.65*	1.7*	3.23*	3.71*	2.11*
Bd3V1							0.05	-0.2	0.97*	0.44*	0.49*	2.02*	2.5*	0.9*
Bd3V2								-0.25	0.92*	0.39	0.44*	1.97*	2.45*	0.85*
Bd3V3									1.17*	0.64*	0.69*	2.22*	2.7*	1.1*
Bd4V1										-0.53*	-0.48*	1.05*	1.53*	-0.07
Bd4V2											0.05	1.58*	2.06*	0.47*
Bd4V3												1.53*	2.01*	0.41
Bd5V1													0.48*	-1.12*
Bd5V2														-1.6*
													LSD	**0.41**

APPENDIX 10: Mean separation of soil compaction and maize varietal interactions for dry shoot mass

	Bd1V2	Bd1V3	Bd2V1	Bd2V2	Bd2V3	Bd3V1	Bd3V2	Bd3V3	Bd4V1	Bd4V2	Bd4V3	Bd5V1	Bd5V2	Bd5V3
Bd1V1	0.04	-0.02	-0.03	-	-0.08	0.12	0.15	0.07	0.27*	0.25*	0.2	0.4*	0.44*	0.3*
Bd1V2		-0.06	-0.07	-0.04	-0.12	0.08	0.11	0.03	0.23*	0.21	0.16	0.36*	0.4*	0.26*
Bd1V3			-0.01	0.02	-0.06	0.14	0.17	0.09	0.29*	0.27*	0.22*	0.42*	0.46*	0.32*
Bd2V1				0.03	-0.05	0.15	0.18	0.1	0.33*	0.28*	0.23*	0.43*	0.47*	0.33*
Bd2V2					-0.08	0.12	0.15	0.07	0.27*	0.25*	0.2	0.4*	0.44*	0.3*
Bd2V3						0.2	0.23*	0.15	0.35*	0.33*	0.28*	0.48*	0.52v	0.38*
Bd3V1							0.03	-0.05	0.15	0.13	0.08	0.28*	0.32*	0.18
Bd3V2								-0.08	0.12	0.1	0.05	0.25*	0.29*	0.15
Bd3V3									0.2	0.18	0.13	0.33*	0.37*	0.23*
Bd4V1										-0.02	-0.07	0.13	0.17	0.03
Bd4V2											-0.05	0.15	0.19	0.05
Bd4V3												0.2	0.24*	0.1
Bd5V1													0.04	-0.1
Bd5V2														-0.14
													LSD	**0.21**

APPENDIX 11: Mean separation of soil compaction and maize varietal interactions for fresh root mass

	Bd1V2	Bd1V3	Bd2V1	Bd2V2	Bd2V3	Bd3V1	Bd3V2	Bd3V3	Bd4V1	Bd4V2	Bd4V3	Bd5V1	Bd5V2	Bd5V3
Bd1V1	-0.06	-0.32	-	-0.03	-0.24	0.48*	0.38	0.13	0.66*	0.56*	0.82*	1.02*	0.96*	0.88*
Bd1V2		-0.26	0.06	0.03	-0.18	0.54*	0.44*	0.19	0.72*	0.62*	0.88*	1.08*	1.02*	0.94*
Bd1V3			0.32	0.29	-0.02	0.8	0.7	0.45*	0.98*	0.88*	1.14*	1.34*	1.28*	1.2*
Bd2V1				-0.03	-0.24	0.48*	0.38	0.13	0.66*	0.56*	0.82*	1.02*	0.96*	0.88*
Bd2V2					-0.21	0.51*	0.41	0.16	0.69*	0.59*	0.85*	1.05*	0.99*	0.91*
Bd2V3						0.72*	0.62*	0.37	0.99*	0.8*	1.06*	1.26*	1.2*	1.12*
Bd3V1							-0.1	-0.35	0.18	0.08	0.34	0.54*	0.48*	0.4
Bd3V2								-0.25	0.28	0.18	0.44*	0.64*	0.58*	0.5*
Bd3V3									0.53*	0.43*	0.69*	0.89*	0.83*	0.75*
Bd4V1										-0.1	0.16	0.36	0.3	0.22
Bd4V2											0.26	0.46*	0.4	0.32
Bd4V3												0.2	0.14	0.06
Bd5V1													-0.06	-0.14
Bd5V2														-0.08
													LSD	**0.42**

APPENDIX 12: Mean separation of soil compaction and maize varietal interactions for dry root mass

	Bd1V2	Bd1V3	Bd2V1	Bd2V2	Bd2V3	Bd3V1	Bd3V2	Bd3V3	Bd4V1	Bd4V2	Bd4V3	Bd5V1	Bd5V2	Bd5V3
Bd1V1	-0.01	-0.02	-	-0.01	-0.02	0.04	0.03	0.01	0.05	0.04	0.04	0.08	0.07	0.07
Bd1V2		-0.01	0.01	-	-0.01	0.05	0.04	0.02	0.06	0.05	0.05	0.09*	0.08	0.08
Bd1V3			0.02	0.01	-	0.06	0.05	0.03	0.07	0.06	0.06	0.1*	0.09*	0.09*
Bd2V1				-0.01	-0.02	0.04	0.03	0.01	0.05	0.04	0.04	0.08	0.07	0.07
Bd2V2					-0.01	0.05	0.04	0.02	0.06	0.05	0.05	0.09*	0.08	0.08
Bd2V3						0.06	0.05	0.03	0.07	0.06	0.06	0.07	0.09*	0.09*
Bd3V1							-0.01	-0.03	0.01	-	-	0.04	0.03	0.03
Bd3V2								-0.02	0.02	0.01	0.01	0.05	0.04	0.04
Bd3V3									0.04	0.03	0.03	0.07	0.06	0.06
Bd4V1										-0.01	-0.01	0.03	0.02	0.02
Bd4V2											-	0.04	0.03	0.03
Bd4V3												0.04	0.03	0.03
Bd5V1													-0.01	-0.01
Bd5V2														-
													LSD	**0.08**

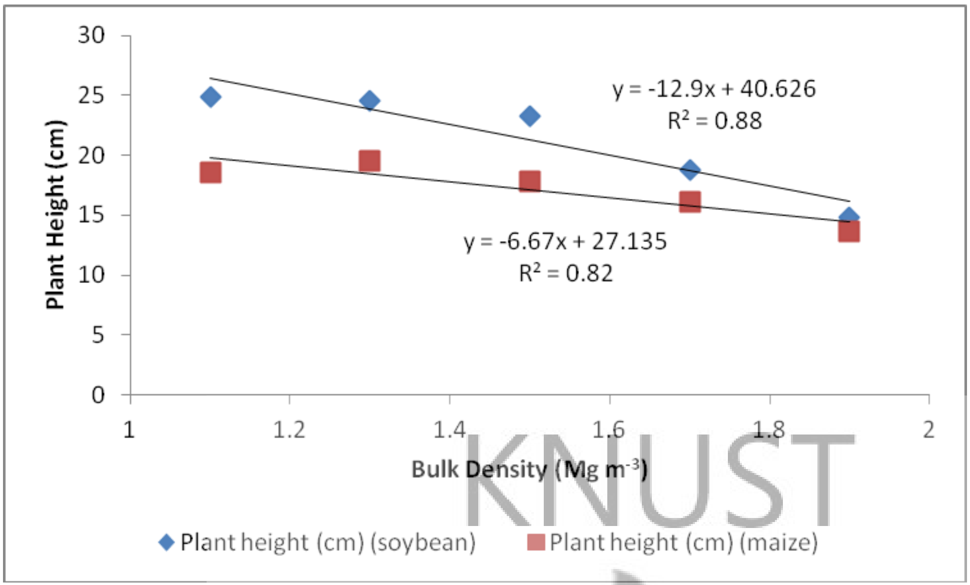
APPENDIX 13: Mean separation of soil compaction and maize varietal interactions for root penetration ratio

	Bd1V2	Bd1V3	Bd2V1	Bd2V2	Bd2V3	Bd3V1	Bd3V2	Bd3V3	Bd4V1	Bd4V2	Bd4V3	Bd5V1	Bd5V2	Bd5V3
Bd1V1	0.02	-0.04	0.03	-0.04	-0.02	0.17*	0.15*	0.1	0.36*	0.38*	0.44*	0.69*	0.62*	0.59*
Bd1V2		-0.06	0.01	-0.06	-0.04	0.15*	0.13*	0.08	0.34*	0.36*	0.42*	0.67*	0.6*	0.57*
Bd1V3			0.07	-	0.02	0.21*	0.19*	0.14*	0.4*	0.42*	0.48*	0.73*	0.66*	0.63*
Bd2V1				-0.07	-0.05	0.14*	0.12*	0.07	0.33*	0.35*	0.41*	0.66*	0.59*	0.56*
Bd2V2					0.02	0.21*	0.19*	0.14*	0.4*	0.42*	0.48*	0.73*	0.66*	0.63*
Bd2V3						0.19*	0.17*	0.12*	0.38*	0.4*	0.46*	0.71*	0.64*	0.61*
Bd3V1							-0.02	-0.08	0.19*	0.21*	0.27*	0.52*	0.45*	0.42*
Bd3V2								-0.05	0.21*	0.23*	0.29*	0.54*	0.47*	0.44*
Bd3V3									0.26*	0.28*	0.34*	0.59*	0.52*	0.49*
Bd4V1										0.02	0.08	0.33*	0.26*	0.23*
Bd4V2											0.06	0.31*	0.24*	0.21*
Bd4V3												0.25*	0.18*	0.15*
Bd5V1													-0.07	-0.1
Bd5V2														-0.03
													LSD	**0.10**

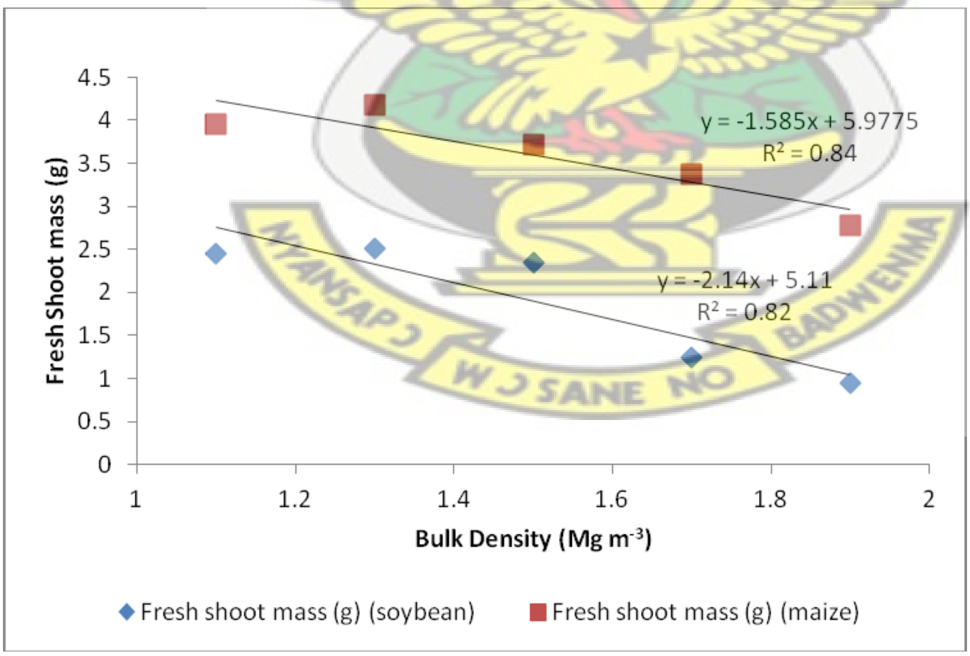
APPENDIX 14: Mean separation of soil compaction and maize varietal interactions for root length

	Bd1V2	Bd1V3	Bd2V1	Bd2V2	Bd2V3	Bd3V1	Bd3V2	Bd3V3	Bd4V1	Bd4V2	Bd4V3	Bd5V1	Bd5V2	Bd5V3
Bd1V1	2.09	-9.43	-12.31	-14.67	103.06*	21.47	31.16*	18.59	65.26*	65.21*	56.31*	74.64*	73.85*	69.4*
Bd1V2		-11.52	-14.4	16.76	100.97*	19.38	29.07	16.5	63.17*	63.12*	54.22*	72.55*	71.76*	67.31*
Bd1V3			-2.88	-5.24	112.49*	30.9*	40.59*	28.02	74.69*	74.64*	65.74*	84.07*	83.28*	78.83*
Bd2V1				-2.36	115.37*	33.78*	43.47*	30.9*	77.57*	77.82*	68.62*	86.95*	86.16*	81.71*
Bd2V2					117.73*	36.14*	45.83*	33.26*	79.93*	79.88*	70.98*	89.31*	88.52*	84.07*
Bd2V3						-81.59*	-71.9*	-84.47*	-37.8*	-37.85*	-46.75*	-28.42	-29.21*	-33.66*
Bd3V1							9.69	-2.88	43.79*	43.74*	34.84*	53.17*	52.38*	47.93*
Bd3V2								-12.57	34.1*	34.05*	26.15	43.48*	42.69*	38.24*
Bd3V3									46.67*	46.62*	37.72*	56.05*	55.26*	50.81*
Bd4V1										-0.05	-8.95	9.38	8.59	4.14
Bd4V2											-8.9	9.43	8.64	4.19
Bd4V3												18.33	17.54	13.09
Bd5V1													-0.79	-5.24
Bd5V2														-4.45
													LSD	**29.15**

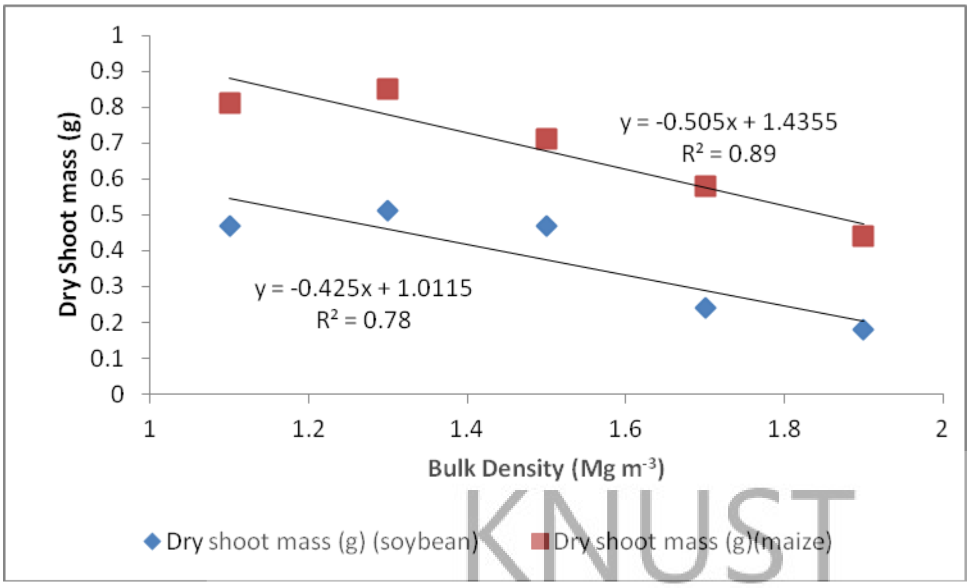
Appendix 15: The relationship between soil bulk density and plant parameters



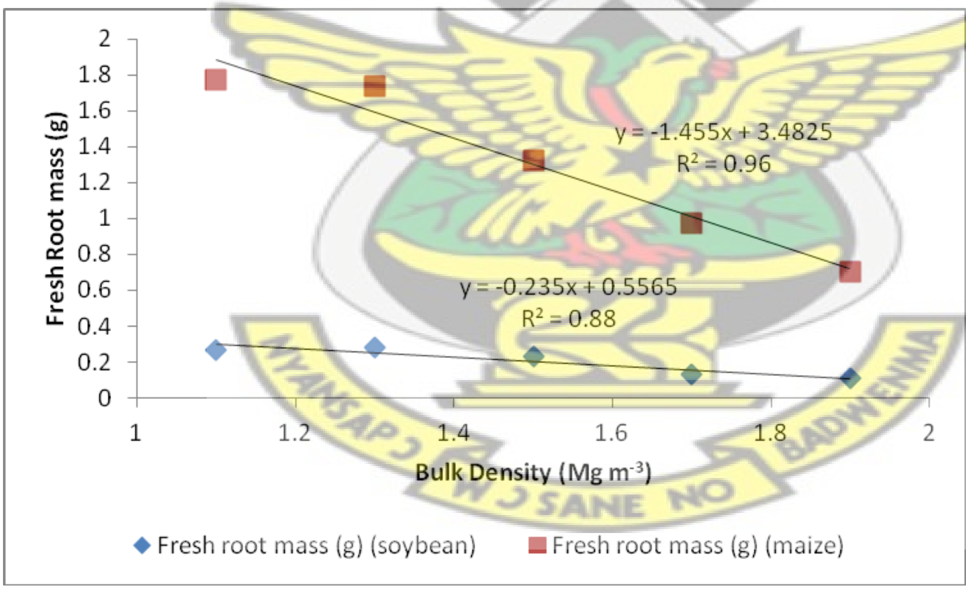
Appendix 15a: Relationship between soil bulk density and soybean - maize plant height at 15 and 21 DAP



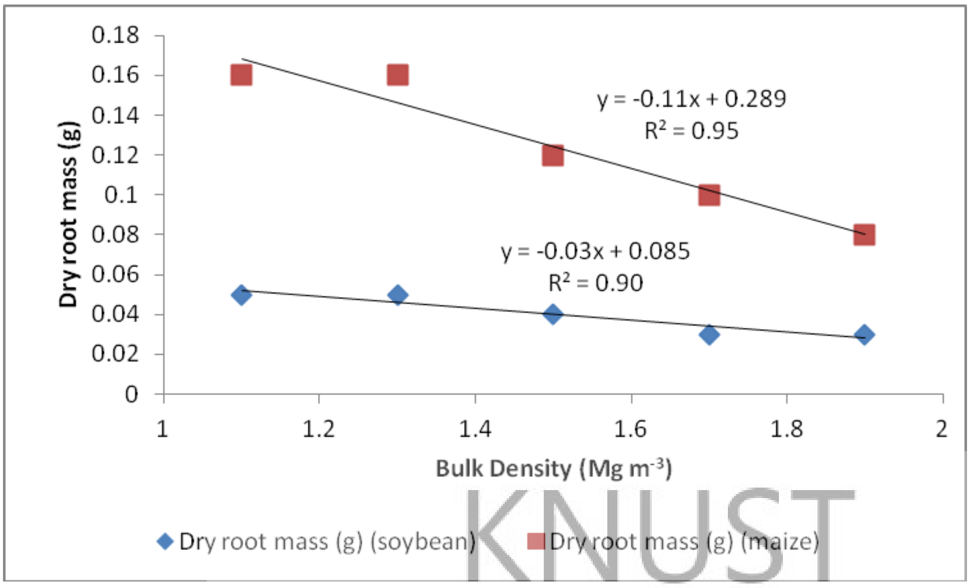
Appendix 15b: Relationship between soil bulk density and soybean - maize fresh shoot mass at 15 and 21 DAP



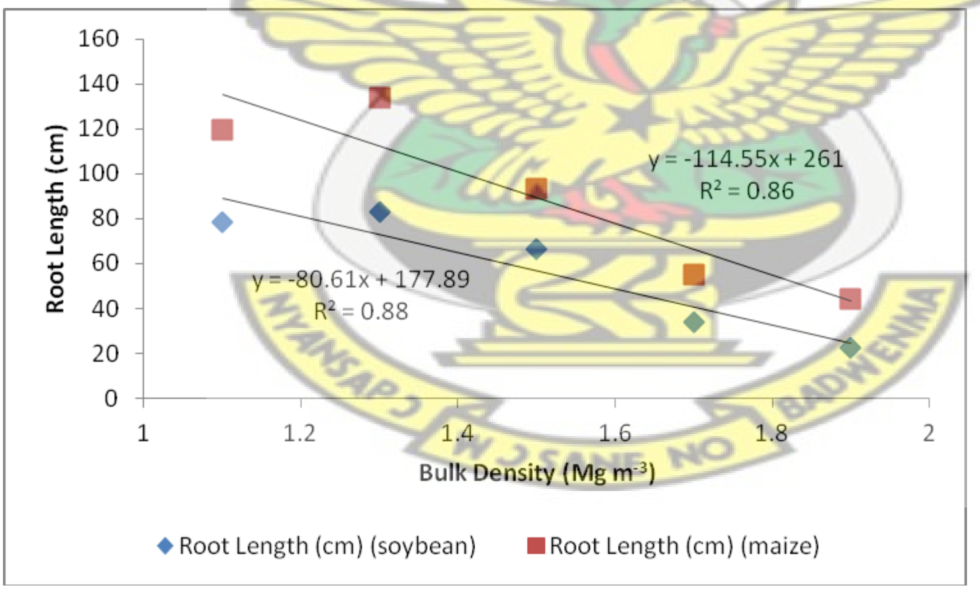
Appendix 15c: Relationship between soil bulk density and soybean - maize dry shoot mass at 15 and 21 DAP



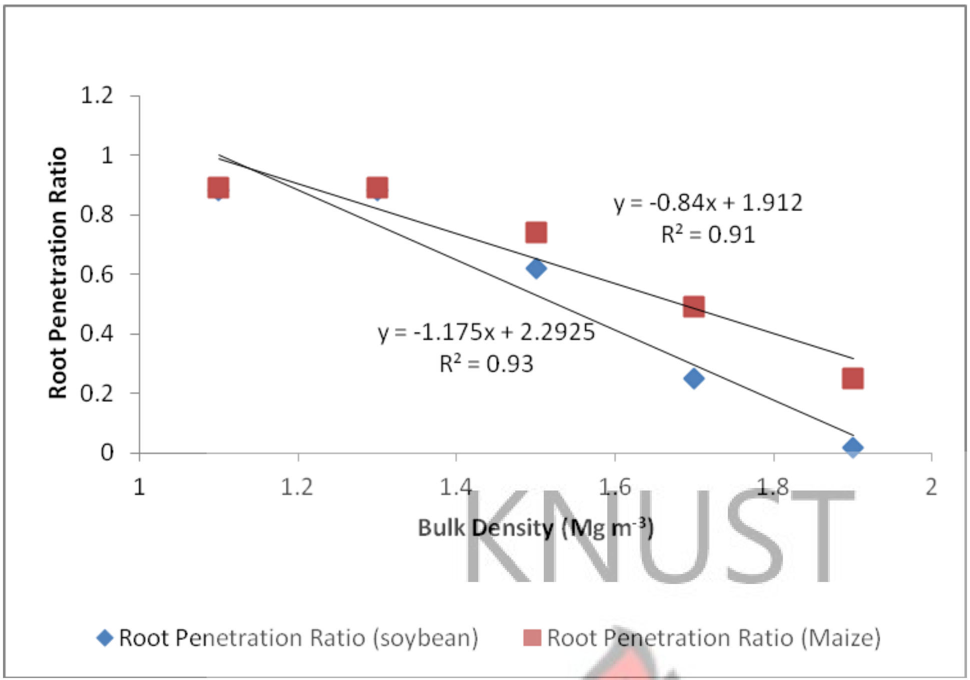
Appendix 15d: Relationship between soil bulk density and soybean - maize fresh root mass at 15 and 21 DAP



Appendix 15e: Relationship between soil bulk density and soybean - maize dry root mass at 15 and 21 DAP

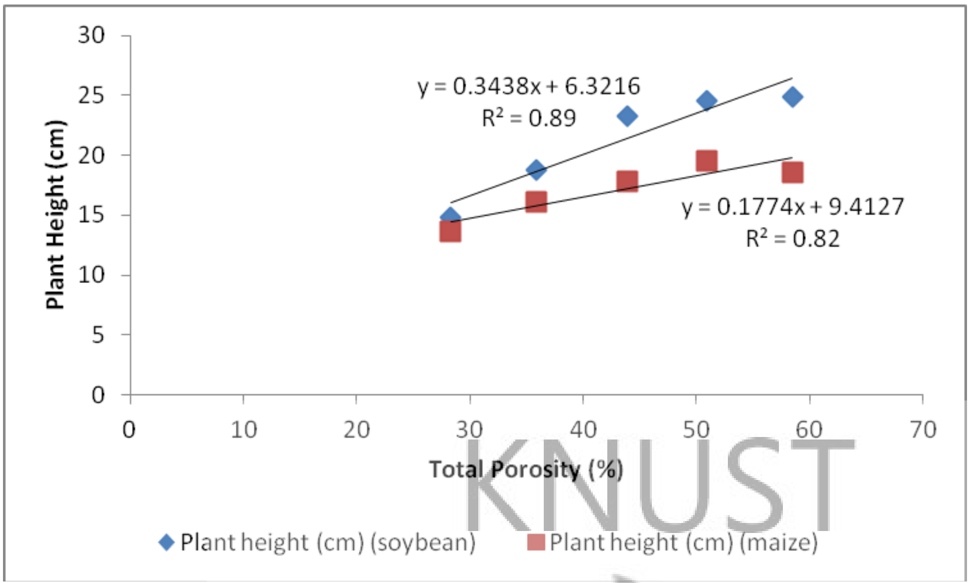


Appendix 15f: Relationship between soil bulk density and soybean - maize root length at 15 and 21 DAP

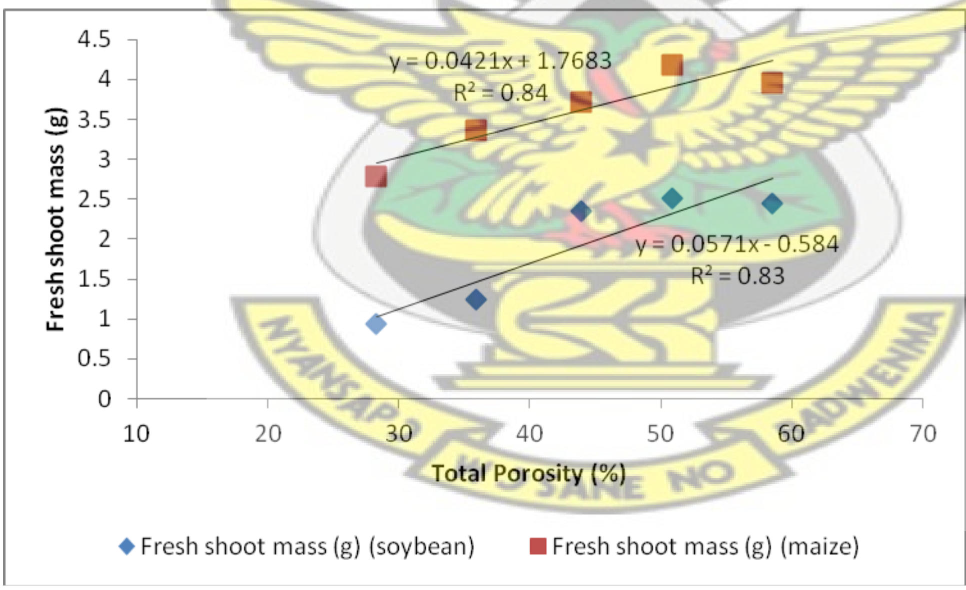


Appendix 15g: Relationship between soil bulk density and soybean - maize root penetration ratio at 15 and 21 DAP

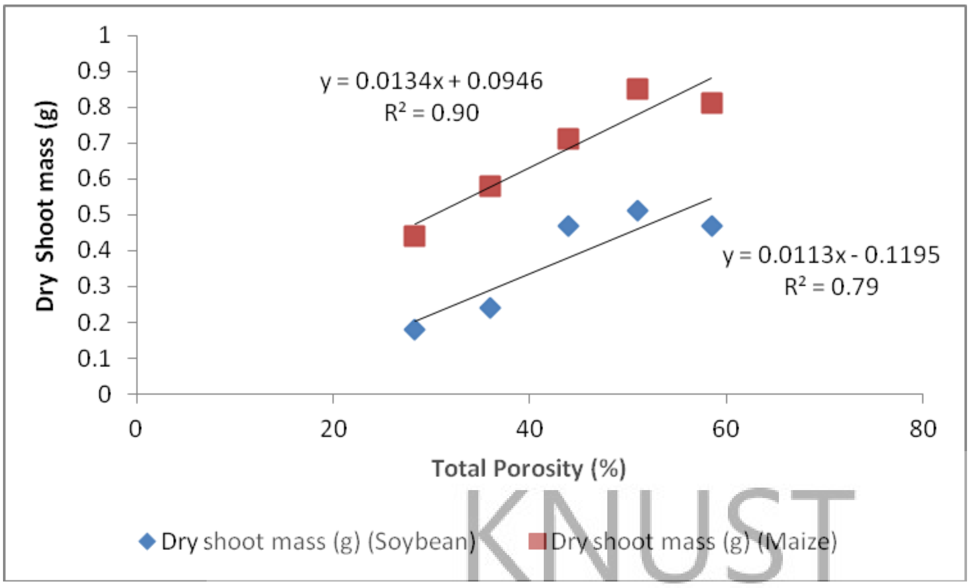
Appendix 16: The relationship between total porosity and plant parameters



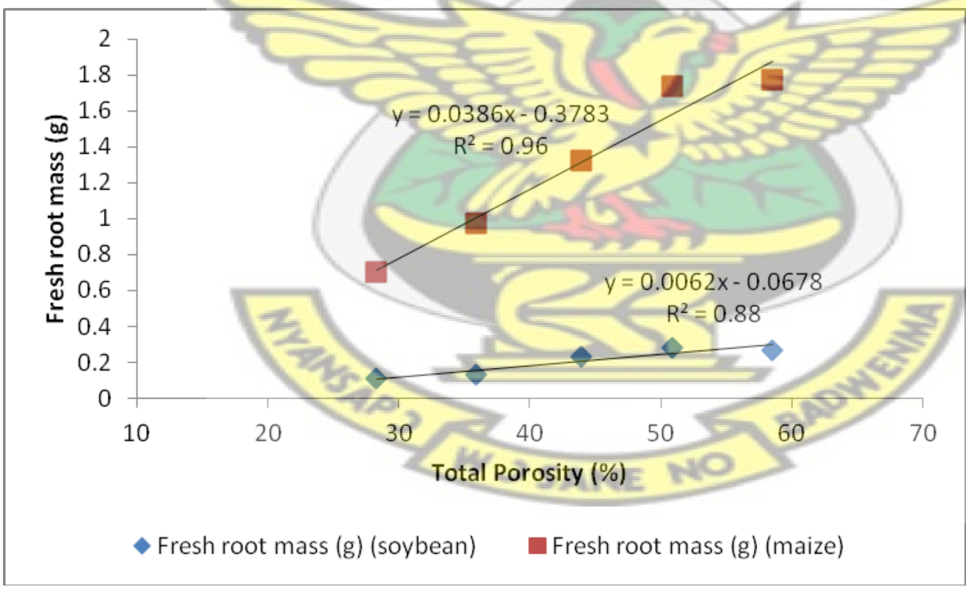
Appendix 16a: Relationship between total porosity and soybean - maize plant height at 15 and 21 DAP



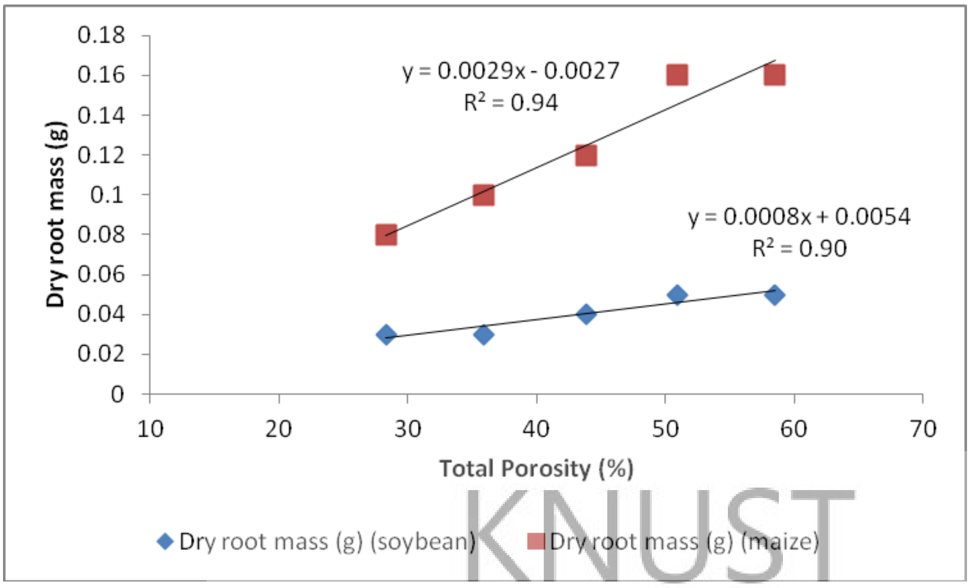
Appendix 16b: Relationship between total porosity and soybean - maize fresh shoot mass at 15 and 21 DAP



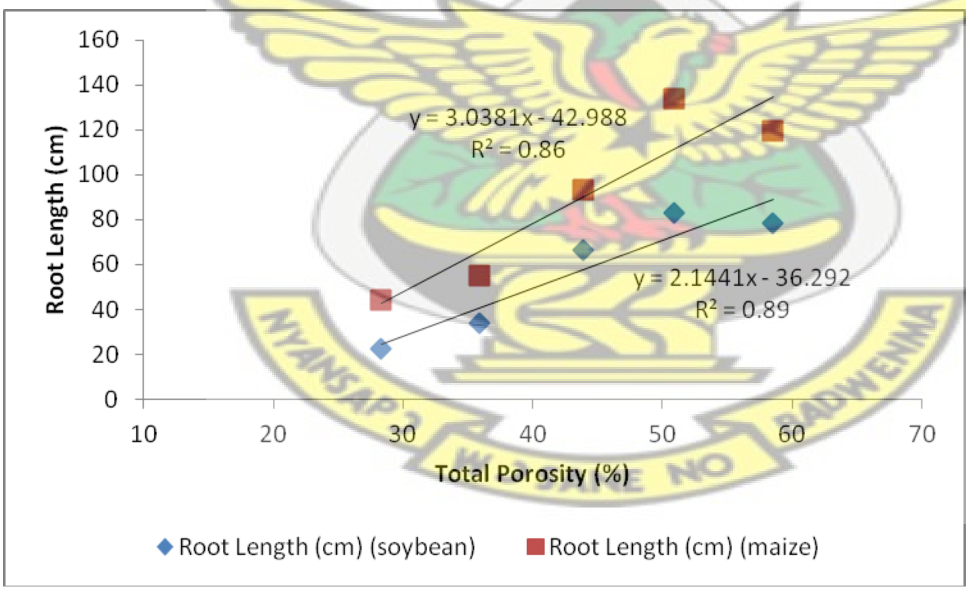
Appendix 16c: Relationship between total porosity and soybean - maize dry shoot mass at 15 and 21 DAP



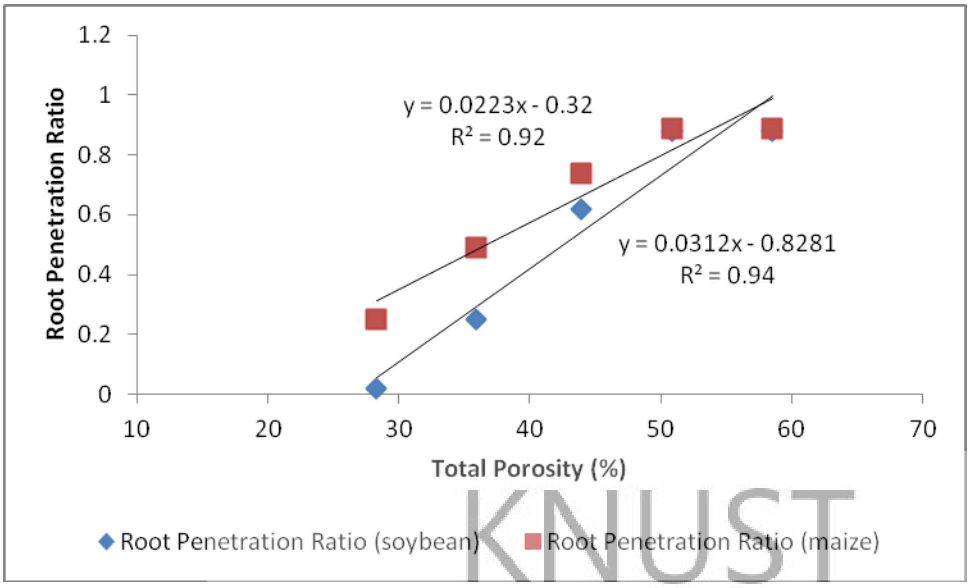
Appendix 16d: Relationship between total porosity and soybean - maize fresh root mass at 15 and 21 DAP



Appendix 16e: Relationship between total porosity and soybean - maize dry root mass at 15 and 21 DAP

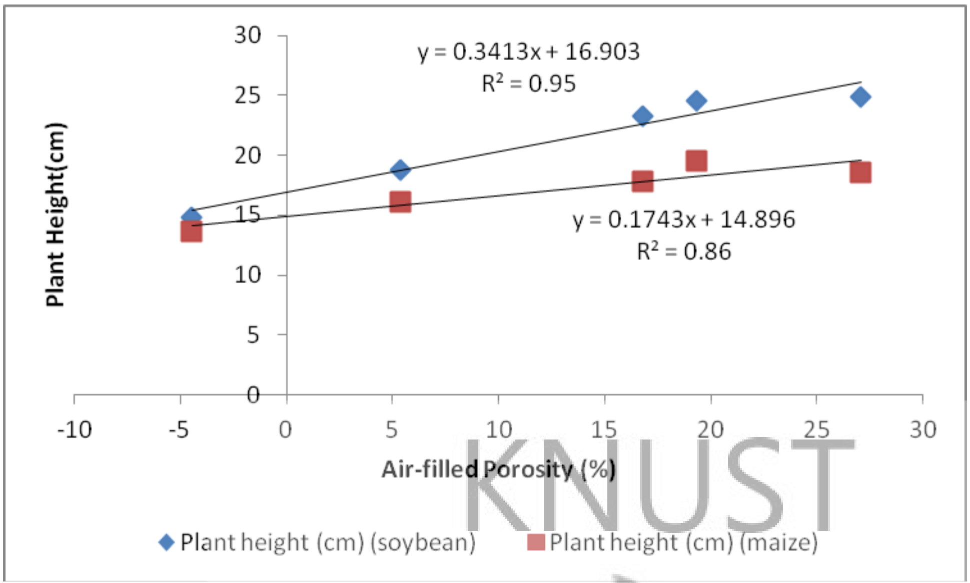


Appendix 16f: Relationship between total porosity and soybean - maize root length at 15 and 21 DAP

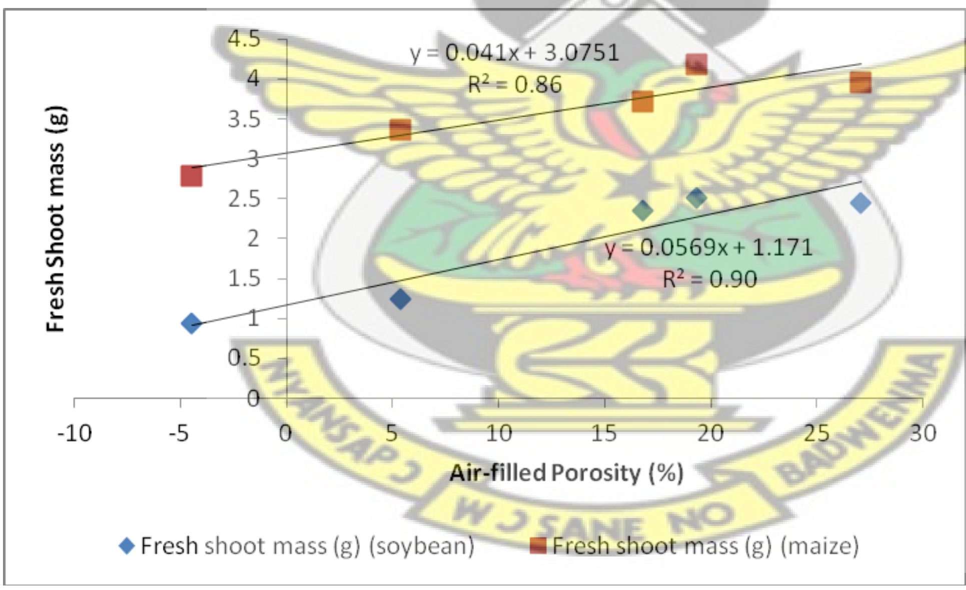


Appendix 16g: Relationship between total porosity and soybean - maize root penetration ratio at 15 and 21 DAP

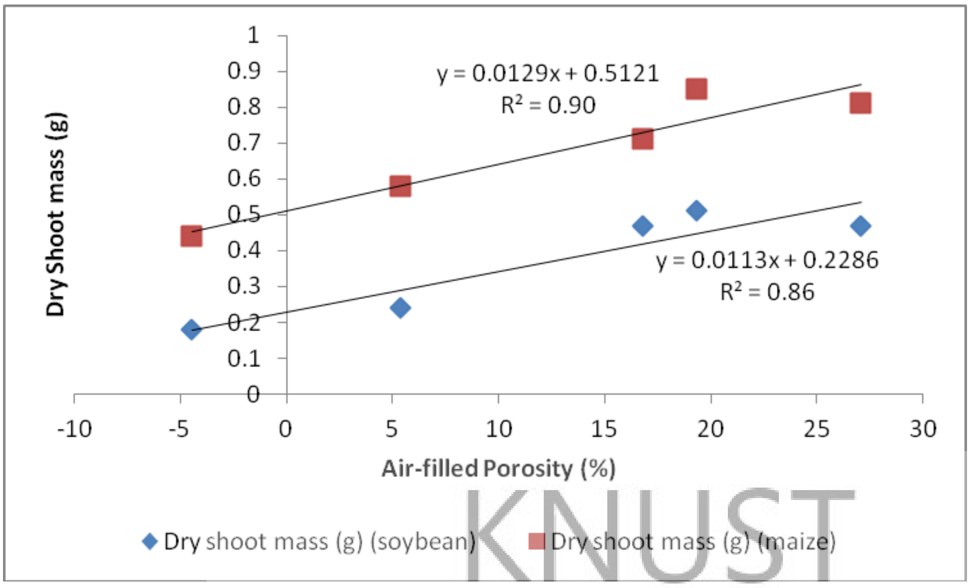
Appendix 17: The relationship between air-filled porosity and plant parameters



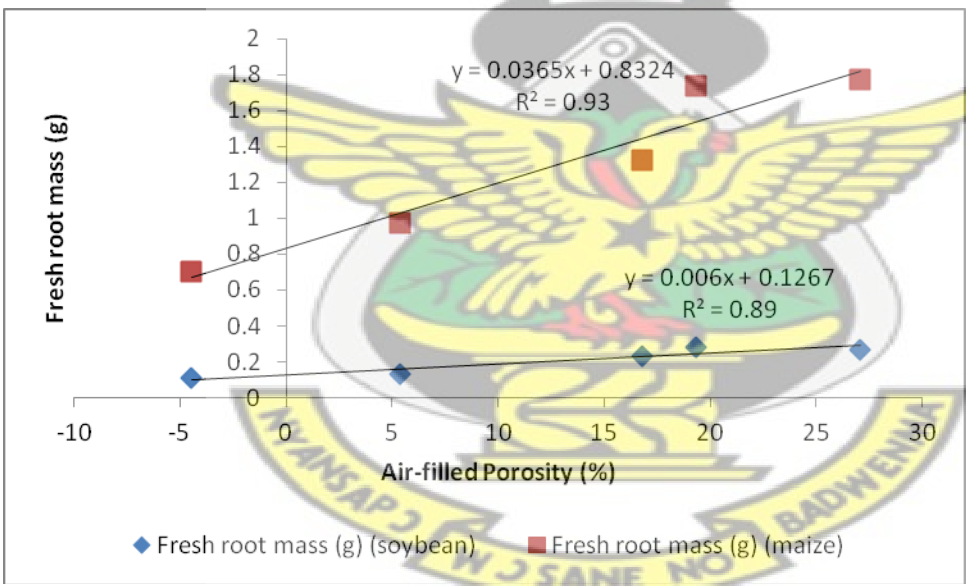
Appendix 17a: Relationship between air-filled porosity and soybean - maize plant height at 15 and 21 DAP



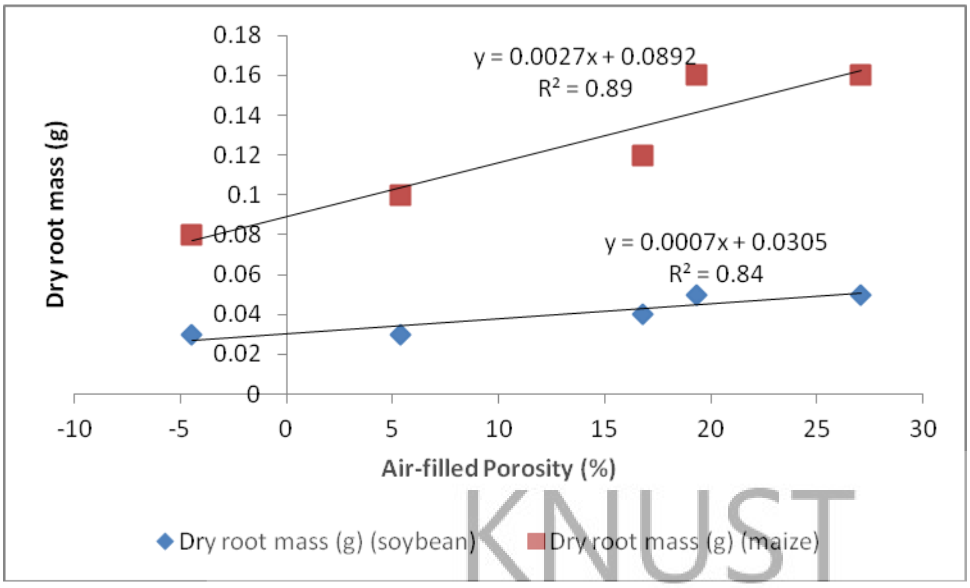
Appendix 17b: Relationship between air-filled porosity and soybean - maize fresh shoot mass at 15 and 21 DAP



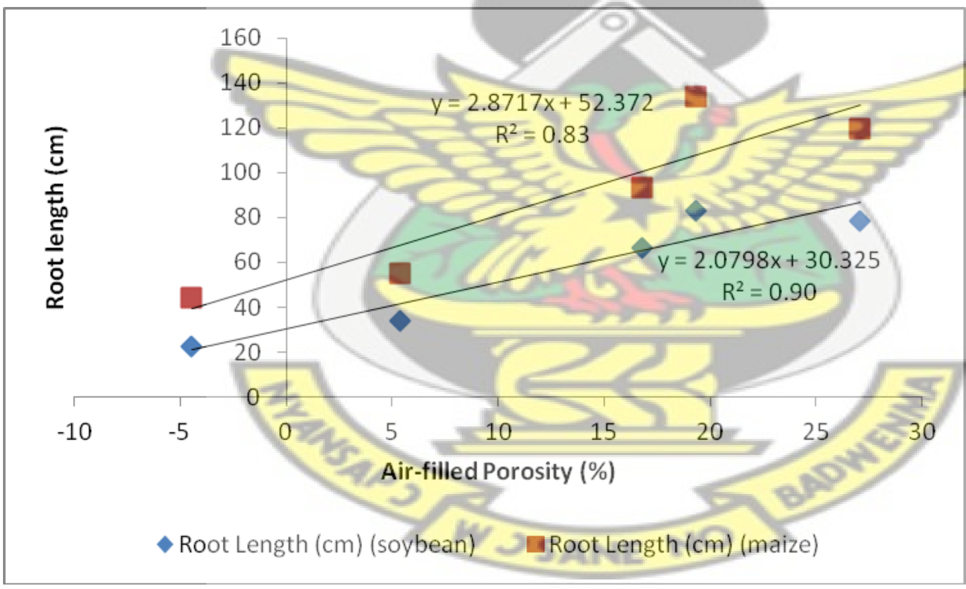
Appendix 17c: Relationship between air-filled porosity and soybean - maize dry shoot mass at 15 and 21 DAP



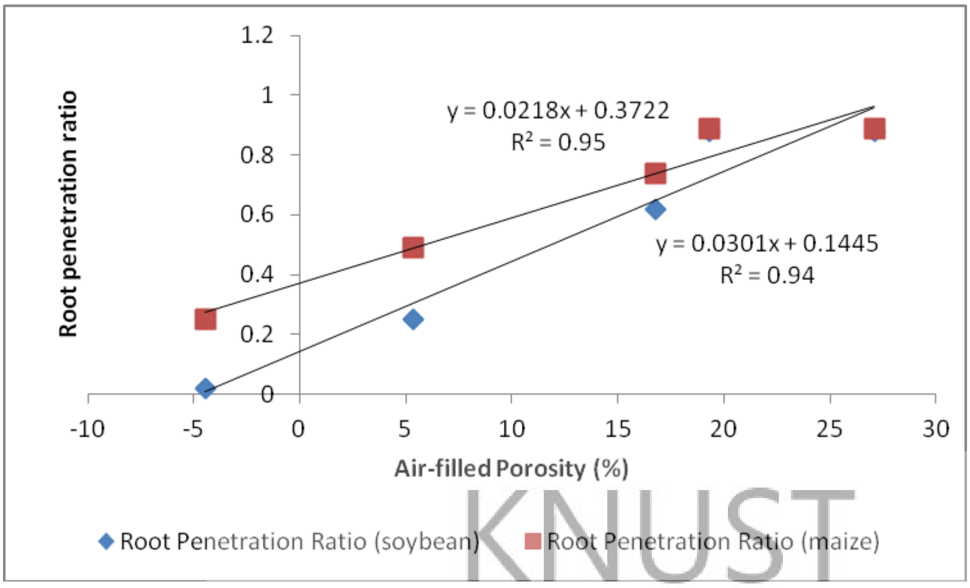
Appendix 17d: Relationship between air-filled porosity and soybean - maize fresh root mass at 15 and 21 DAP



Appendix 17e: Relationship between air-filled porosity and soybean - maize dry root mass at 15 and 21 DAP

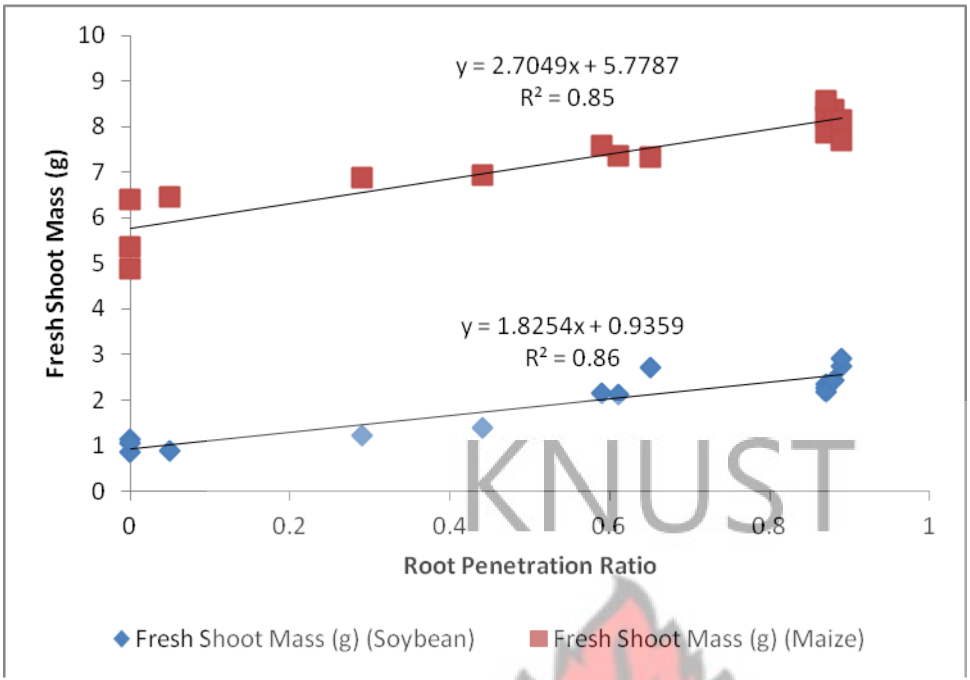


Appendix 17f: Relationship between air-filled porosity and soybean - maize root length at 15 and 21 DAP

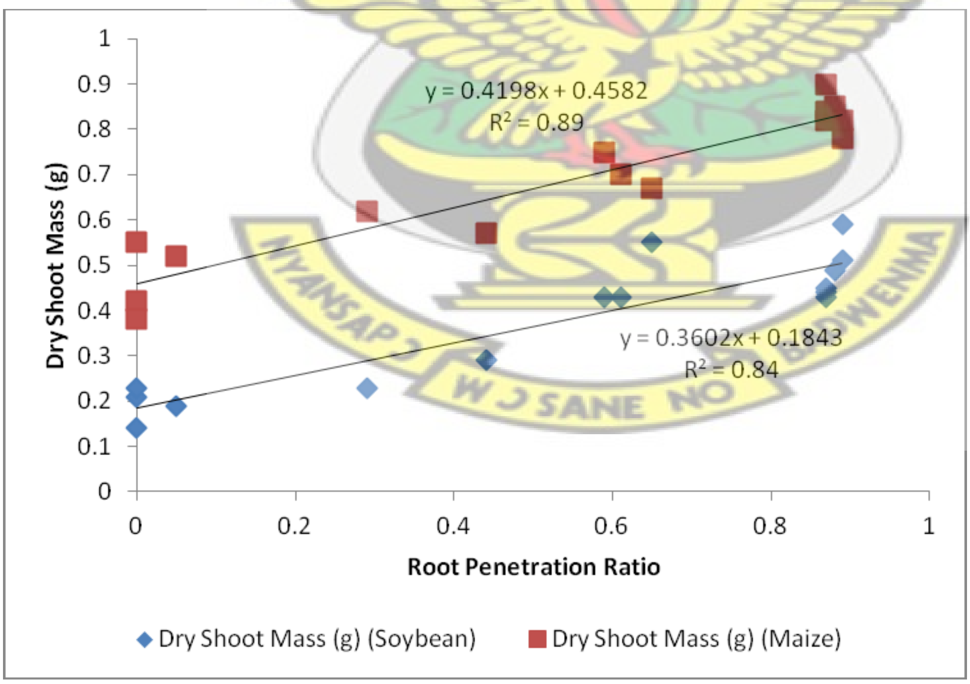


Appendix 17g: Relationship between air-filled porosity and soybean - maize root penetration ratio at 15 and 21 DAP

Appendix 18: Relationship between root penetration ratio and plant parameters



Appendix 18a: Relationship between soybean root penetration ratio and fresh shoot mass for soybean and maize



Appendix 18b: Relationship between soybean root penetration ratio and dry shoot mass for soybean and maize