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Effect of Soil Compaction on the Growth and Nutrient Uptake of *Zea Mays* L.

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Abstract

Agricultural mechanization and open livestock grazing contribute to soil compaction and consequently on crop productivity. This study used a greenhouse experiment to identify the effects of soil compaction on the growth, productivity and nutrient uptake of maize plant seedlings grown at three bulk density (1.17, 1.37, and 1.45 g cm^{-3}) and three water contents (0.12, 0.18, and 0.30 g/g soil). Shoot elongation and leaf area decreased significantly by 27.1 and 67.8% respectively at high compaction ($P<0.05$). Fresh and dry root mass also decreased significantly at high compaction by 39.1 and 37.8% respectively. Increase in soil compaction also reduced the grain yield by 18.8%. The adverse soil conditions created by increasing soil compaction accounted for the reduction in nutrient uptake. Increase in penetration resistance of the soil reduced the plants ability to absorb nitrogen (13.5%), potassium (51.4%), magnesium (50.4%) and sodium (51.5%) whereas the concentration of calcium and phosphorous were higher when soil resistance varied between 3 and 4 MPa. The relationship between root production, shoot elongation, root biomass and soil strength shows that increase in soil strength/compaction was detrimental to maize production. High soil compaction negatively influenced plant ability to absorb minerals from the soil thus decreased the yield performance.

Keywords: soil compaction, bulk density, mechanical impedance, soil strength, *Zea mays L*.

1. Introduction

Soil compaction can be associated with majority of field operations that are performed in agriculture which include animal trampling and passage of heavy machinery and equipment which often cause damage to the soil structure. Soil structure is important because it determines the ability of a soil to hold and drain water, nutrients, and air required for plant root activities. Soil compaction occurs when soil particles are pressed together, reducing pore space between them, it changes pore space size and distribution (Keller *et al.*, 2013). Soil compaction can be divided into two categories, surface horizon compaction and subsoil compaction. Surface horizon compaction mostly occur due to wheel trafficking during field operations and surface crusting that occur due to impact of raindrops on weak soil aggregates. Subsoil compaction occur deeper in the soil profile, because the ground contact pressure or the axle load is very high that the effect attains greater depth (Etana *et al.*, 2013).

Water movement in soil is important in supporting plant growth. Plants require water, because it acts as a major metabolic agent for growth (Kuncuro *et al*., 2014). Compaction restricts plant ability to absorb water from the soil and this could reduce the yield. Large pores are more effective in soil water movement but compaction causes a reduction in pore space distribution which could result on reduced water infiltration rate and drainage.

Plant roots must exert greater force to penetrate the compacted layer because soil shear strength is higher in compacted soil. Change in bulk density, shear and penetration resistance are some factors caused by compaction which affects plants root growth (Taylor and Gardner, 1963; Grzesiak *et al*., 2013; Cambi *et al*., 2015). Soil compaction can influence the concentration and movement of water, oxygen and carbon dioxide which could result in a restricted root development root (Taylor and Brar, 1991; Jourgholami *et al*., 2016).

Guan *et al.* (2014) stated that one of the function of plant roots is to maintain the supply of nutrients and water to the plant while the yield is dependent on the root development in the soil profile which determines the capacity for nutrient uptake and water extraction by plants. The potential of plants to obtain water and mineral nutrients from the soil is related to their capacity to develop extensive roots, meanwhile compaction restricts deep root growth and consequently limits plant access to subsoil water and nutrients.

Several studies have investigated the effects of soil compaction on plant growth. A study by Beckett *et al*. (2017) shows that compaction at the optimum water content (5%) was the most dramatic for plant growth. However, plant growth was higher for compaction conditions which bestowed both a lower soil dry density and hydraulic conductivity.

Another study by Igoni and Ayotamuno (2016) in which maize was planted on five experimental plots with different bulk density (1.17, 1.20, 1.23, 1.28, 1.35 g cm^{-3}) to examine the yield response of maize under varying soil compaction conditions. The study showed that plots with lower bulk densities had higher percentage emergence than the ones with higher bulk densities. Higher maize yield was recorded in plots with lower bulk density. Igoni and Ayotamuno (2016) deduced that bulk density of 1.31 g cm^{-3} may be referred to as optimal for maize cultivation in a sandy-loam soil in a humid tropical environment.

Maize (*Zea Mays L*.) is a tropical crop largely grown in various parts of Nigeria and is one of the most widely consumed food and a basic raw material for feed mill and beverage industries. The sustainable production of maize promotes continuous food supply throughout the year, job opportunities for the population, and increased income. Various agro-based industries now depend on maize as raw material. This may be as result of to the growing demand of the product as a staple food in Nigeria (Igoni and Ayotamuno, 2016). Maize produces better in a well-drained fertile loamy soil and it grows best on sandy clay loams, loamy and silty clay soils, it is less adapted to compact clays and sandy soils (Igoni and Ayotamuno, 2016).

The aim of this paper was to evaluate the effect of soil compaction on the growth and productivity of maize plants. This work enabled us to (i) analyse the response of maize in relation to shoot elongation, leaf development, yield performance and root biomass to induced soil compaction, and (ii) to evaluate the variation in maize plant's ability to absorb nutrient from soil of various compaction. Compaction had a negative effect on shoot elongation, leaf area, grain yield and root mass.The relationship between root production, shoot elongation, root biomass and soil strength shows that increase in soil strength/compaction was detrimental to maize production. High soil compaction negatively influenced plant ability to absorb minerals from the soil thus decreased the yield performance.

2. Materials and Methods

2.1 Soil

Soil sample for this experiment was collected on May 21, 2018 from a 0 – 15 cm depth from the Agricultural and Environmental Engineering research farmland at the Federal University of Technology Akure, Ondo state, Nigeria (latitude 7° 5' N and longitude 5° 15' E of the Greenwich meridian). The soil was classified as sandy clay loam (64.8% sand, 23.2% clay and 13% silt). Soil sample was air dried, crushed and sieved through a 2 mm sieve. Only the fine soil particles were used in this experiment to avoid rocks in the growth medium. The properties of the soil are shown in Table 1.

Table 1. Characteristics of the experimental soil

Soil chemical properties								
pH (1:2) H_2O	Organic C (%)	Organic matter (%)	N (%)	P (mg kg^{-1})	K (Cmol kg^{-1})	Mg (Cmol kg^{-1})	Ca (Cmol kg^{-1})	Na (Cmol kg^{-1})
5.54	0.92	1.58	0.35	12.06	0.42	1.01	1.30	0.52

2.2 Soil Strength

An in-situ experiment was carried out to determine the strength of the soil at three levels of compaction and three levels of water contents by using a 60 ° cone penetrometer. Three repetitions of each treatment was used in the experiment. Soil was prepared on trial and error basis to simulate nine different conditions by combining three bulk densities (1.17, 1.37 and 1.45 g cm^{-3}) and three water contents (0.12, 0.18 and 0.30 g g^{-1} soil). Soil was collected from the surface horizon of 0-15 cmdepth.

Water was added to sub-samples of air-dried soil corresponding to 0.12, 0.18 and 0.30 g g^{-1} soil before compaction. Soil was compacted by hitting the soil in the cylindrical core compaction ram (2.55 kg). A compaction piston was used to ensure that compaction was uniformly distributed throughout the core.

2.3 Greenhouse Experiment

The experiment was laid out in a 3 ×3 factorial experiment in a randomized complete block with nine treatments with three repetitions. Treatments consisted of three bulk densities (low, medium and high) and three water contents (dry, moist and wet). The pots used for the experiment were 25 cm high with a 19 cm diameter. Soil compaction levels were denoted as low, medium and high corresponding to bulk density of 1.17, 1.37 and 1.45 g cm^{-3} respectively. The low compaction treatment was obtained by hand compacting which served as control. In order to have an equally distributed compaction throughout the soil, medium compaction treatment was obtained by adding a fraction of soil to form a single 10 cm layer in the pots, the compaction piston was placed on the soil and the compaction ram (2.55 kg) was dropped five times from a height of 40 cm on the piton's top plate. This procedure was repeated three times until the pot was full. Similar procedure was used for the high compaction treatment using ten blows. Soil water content was maintained by weighing each of the pots every two days and adding water to each pot to reach the appropriate weight.

All the pots were placed in a greenhouse located at the Agricultural and Environmental Engineering research farmland at the Federal University of Technology Akure, Ondo state, Nigeria. The greenhouse condition had no control over the relative humidity, temperature, gas present and the amount of light the plants were exposed to during this experiment.

The pots were randomly rotated every two weeks to level out the effects of different environmental conditions found in different areas of the greenhouse. Maize seedlings were grown for 12 weeks. At the end of the experiment, the shoots were cut out and the roots were also removed from the soil cores.

2.3.1 Growth Measurement

Weekly measurement of the length and central width of the shoot(±0.01 cm) and leaves were taken using a meter rule and a Vernier calliper. Leaf area was calculated by multiplying the leaf length and the leaf central width by a coefficient (0.835) (Miralles and Slafer, 1991).

$$\boldsymbol{A = LW\ 0.835}$$

Where A, L and W represents area, length and width respectively.

2.3.2 Root Measurements

After 3 months, there was a plant in each of the twenty seven pots, which was harvested and the roots were carefully extracted from the pots and washed free of sand. The roots were separated from the shoots and placed on the weighing scale to measure the fresh mass. The roots were placed in a laboratory oven at 70 ℃ for five days to obtain the dry mass.

2.3.3 Yield Measurements

During the harvest period for the early maturing maize on the third month, the yield from each plants in relation to the mass of the grains on each plants were obtained and recorded.

2.3.4 Shoot Chemical Analysis

In order to compare the extent to which compaction affect nutrient uptake by plants, shoots harvested on the third month were oven dried at 70 ℃ for 48 h and analysed for total nitrogen, total phosphorus, total potassium, total magnesium, total sodium and total calcium as described by Guo *et al.* (2014).

2.4 Statistical Analysis

All statistical analysis was performed using Microsoft Excel 16.00 (Microsoft Inc., USA) software package for windows. Analysis of variance (ANOVA) was computed for each variable to obtain the relationship between soil compaction (soil penetration resistance) and other plant parameters such as shoot length, leaf area, average weight of grains, root mass and nutrient concentration in the shoots.

3. Result and Discussion

3.1 Soil Strength

Soil penetration resistance as measured with a 60 ° cone penetrometer was affected by bulk density and water content (Figure 1). The effects of compaction on the soil were more severe when the soils were dry (0.14 cm^3 cm^{-3}). The greatest soil penetration resistance (5.2 MPa) was obtained at the highest bulk density (1.45 g cm^{-3}) and the lowest volumetric water content (0.14 cm^3 cm^{-3}) while the lowest soil penetration resistance was obtained at the lowest bulk density (1.17 g cm^{-3}) and the highest volumetric water content (0.36 cm^3 cm^{-3}). This was similarly reported by Bulinski and Sergiel (2014) and Cambi *et al*. (2015).

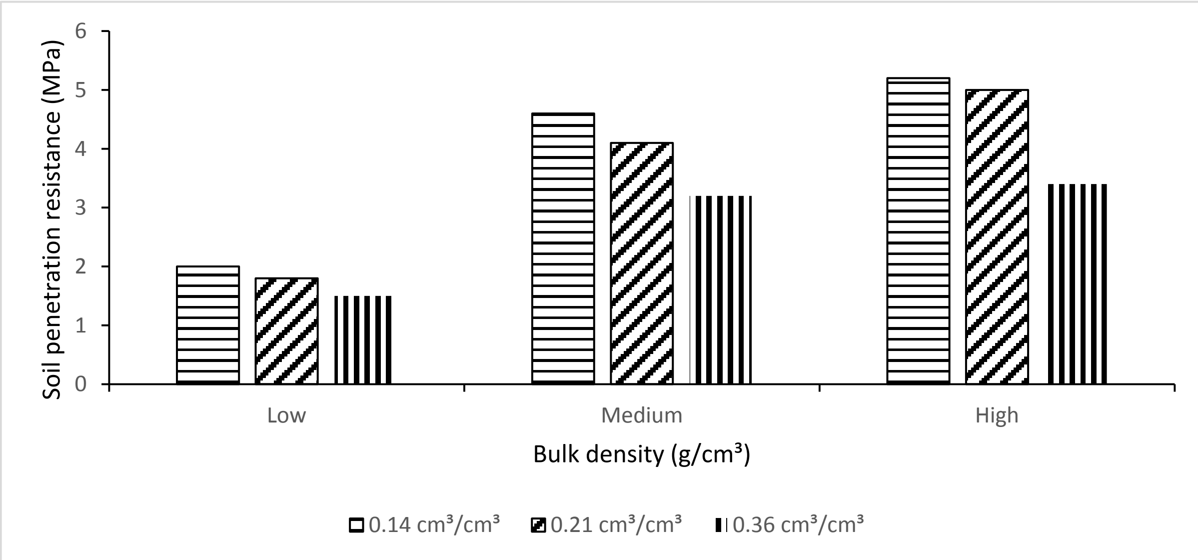


Figure 1. The soil strength value of the soil at three bulk densities and three volumetric water content.

3.2 Growth Rate

The growth rate of the plant was evaluated in relation to the shoot height in weeks after planting (7 days) and the leaf area in months after planting (30 days). The plant height varied between 85.6 and 131.8 cm and the leaf area between 0.150 and 0.592 m^2 (Figure 2 and 3). Plant height and leaf area were significantly lower in treatments with higher level of soil compaction (2.0, 3.2, 3.4, 4.1, 4.6, 5.0 and 5.2 MPa) when compared to the plant height on soil 1.8 MPa penetration resistance. Treatment with soil penetration resistance of 1.8 MPa produced the highest plant height (131.8 cm) while treatment with penetration resistance of 5.2 MPa produced the lowest plant height (85.6 cm). Highest value for leaf area was recorded in the 1.5 MPa treatment while the lowest value was recorded in the 5.2 MPa treatment. Similar observation has been reported by Igoni and Ayotamuno (2016). The magnitude of the shoot response, however seem to be influenced by the stage of growth. The reduction in shoot length enhanced by increasing soil compaction level might be attributed to one or a combination of the limiting conditions that were created in the growing environment as reported by Berisso *et al.* (2012). In this study, increase in soil compaction increased soil bulk density, reduced total and aeration porosity. The implication of these conditions include increased impedance to root growth, that consequently reduces water requirement and nutrient uptake for better root and shoot growth. The reduced aeration porosity and its negative impact on gaseous exchange resulting in reduced oxygen supply accumulation of carbon dioxide could adversely affect root growth and indirectly affect shoot growth (Patrick Jr and Henderson, 2017). Efforts can be made in order to reduce the alteration of these soil properties and sustain crop growth on compacted soils including tillage, biological drilling and suppressing the negative impact of compaction through the application of mineral and organic sources of nutrients to enhance vigorous root growth (Keller *et al.*, 2013; Kuncoro *et al.*, 2014; Salem *et al.*, 2015).

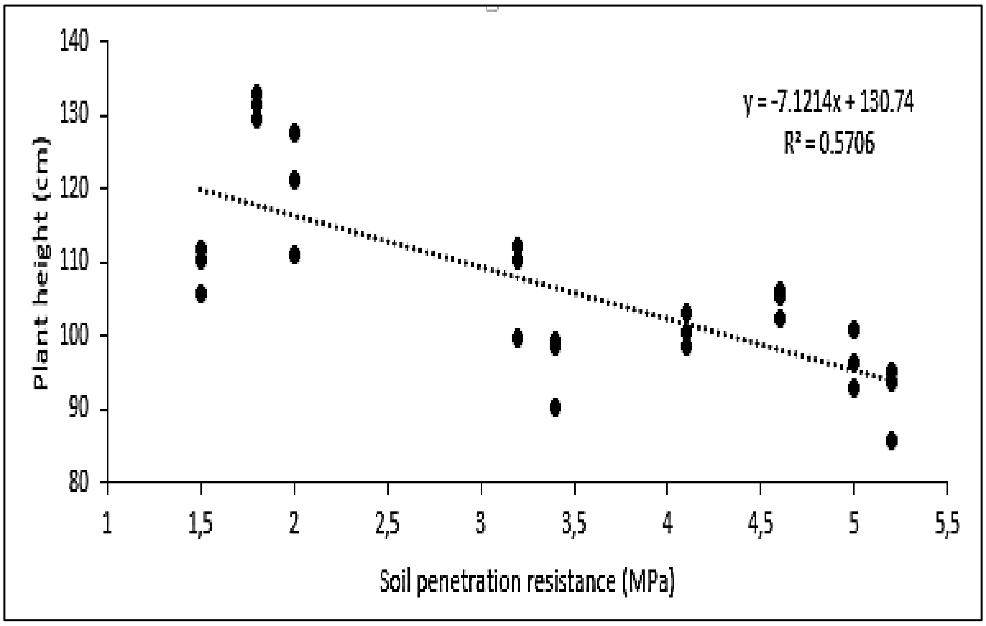


Figure 2. The effects of soil penetration resistance on the shoot height before harvest (30 days after planting)

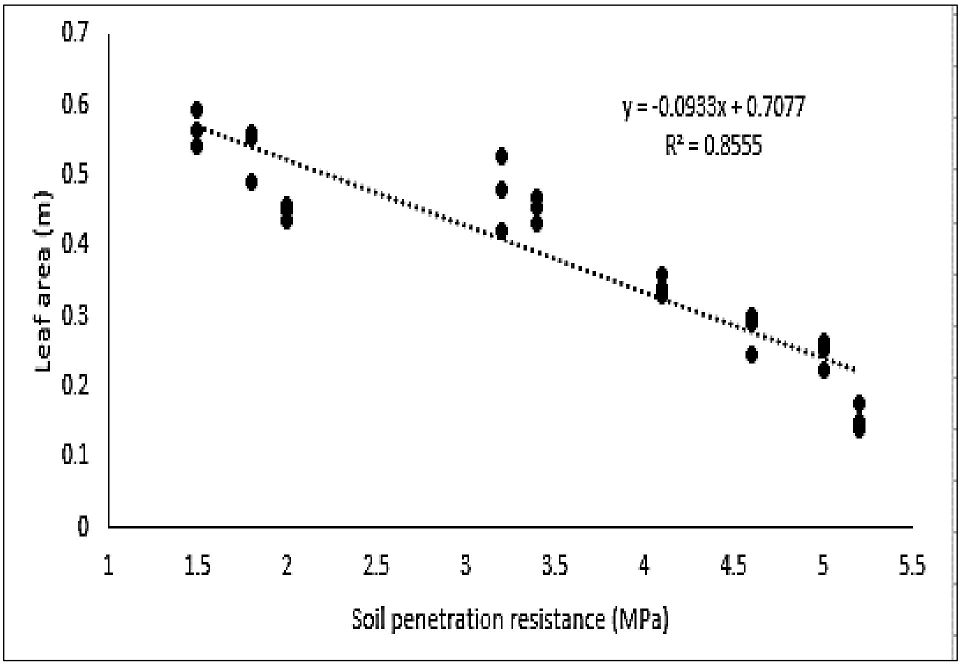


Figure 3. The effects of soil penetration resistance on leaf development (leaf area) before harvest

3.3Yield

Figure 4 shows the relationship between of the average yield per plant and the soil penetration resistance. Treatment with 4.1 MPa had the highest average grain yield (33.5 g) while treatment with 3.2 MPa had the lowest average grain yield (8.2 g). Negative effect of soil compaction on grain yield has been previously reported by Salem *et al.* (2015) and Zuo *et al*. (2017). The noticeable higher performance in terms of grain yield of some plants grown medium soil penetration resistance shows that soil compaction does not always decrease crop yields in agreement with Igoni and Ayotamuno (2016). The maize yield reductions under higher degree of subsoil compaction might be attributed to restricted root growth, limited oxygen and nutrient supply (Zuo *et al*., 2017).

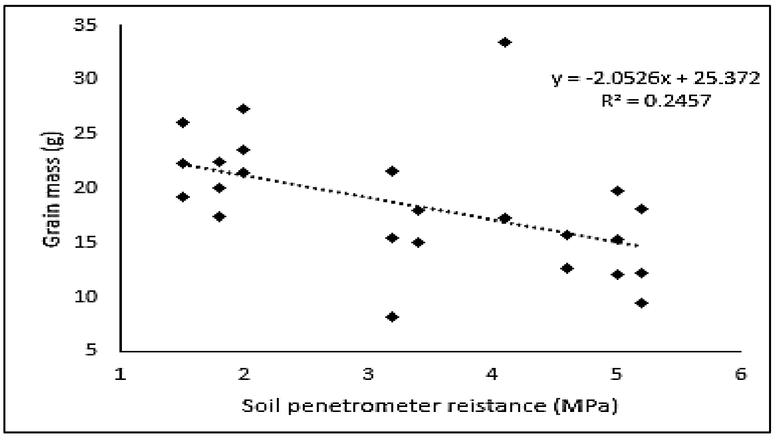


Figure 4. The effects of soil penetration resistance on average grain yield harvested

3.4 Root Biomass

The roots of each plants were separated from the shot after harvest and the wet and dry mass was obtained. Figure 5 shows the relationship between root mass (wet and dry) and soil penetration resistance. Wet root mass varied between 7.5 and 15.7 g and dry root between 5.9 and 13.6 g. Highest value for wet and dry root mass (15.7 and 13.6 g respectively) was recorded in the 2.0 MPa treatment while the lowest values (7.5 and 5.9 respectively) were recorded in the 5.2 MPa. The observed higher root biomass in the un-compacted soil was regarded as a compensatory response to the increased mechanical impedance and reduced total porosity and aeration porosity associated with compaction of the soil core as previously reported by Chen *et al*. (2014).The development of extensive root system promotes plants to take up nutrients and water from the soil. The ability of plant to readily take up nutrients in treatments with low compaction favoured root development and vigour for effective nutrient and water uptake from the soil. This pattern of root biomass distribution is ascribed mainly to the magnitude of mechanical impedance in the soil. When soil are compacted, the bulk density is increased and the pore spaces reduces, therefore plant roots have to develop a higher force necessary to displace the compacted soil particles which consequently limits root growth. The negative impact of soil compaction on root growth observed in this study can be due to limited availability of water and nutrients for satisfactory plant growth and yield (Chen *et al.*, 2014 and Jourgholami *et al.*, 2016).

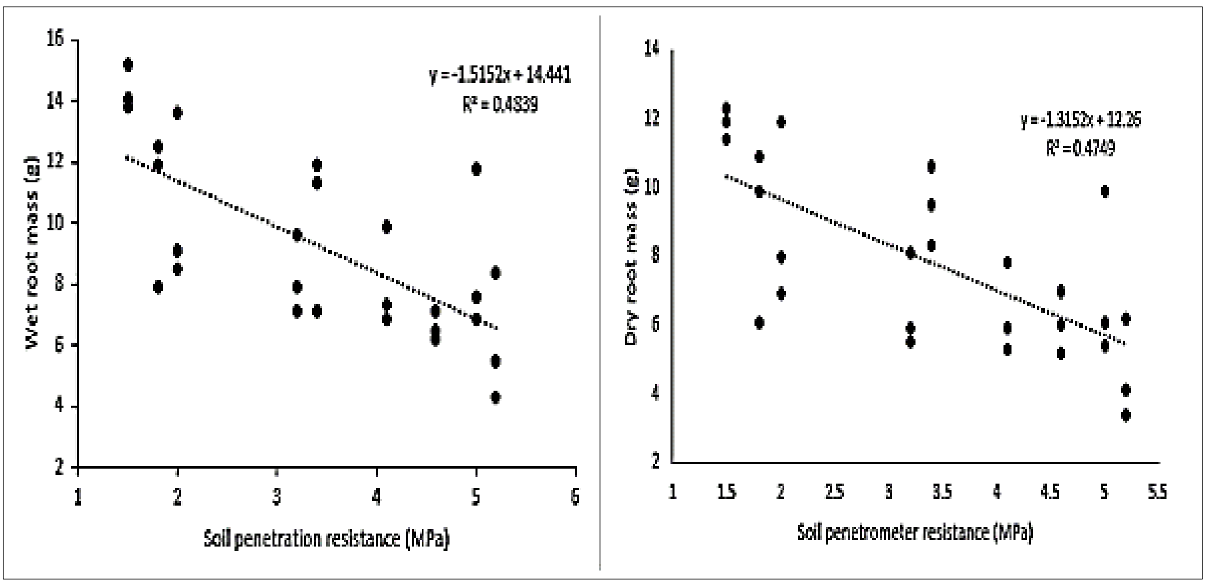
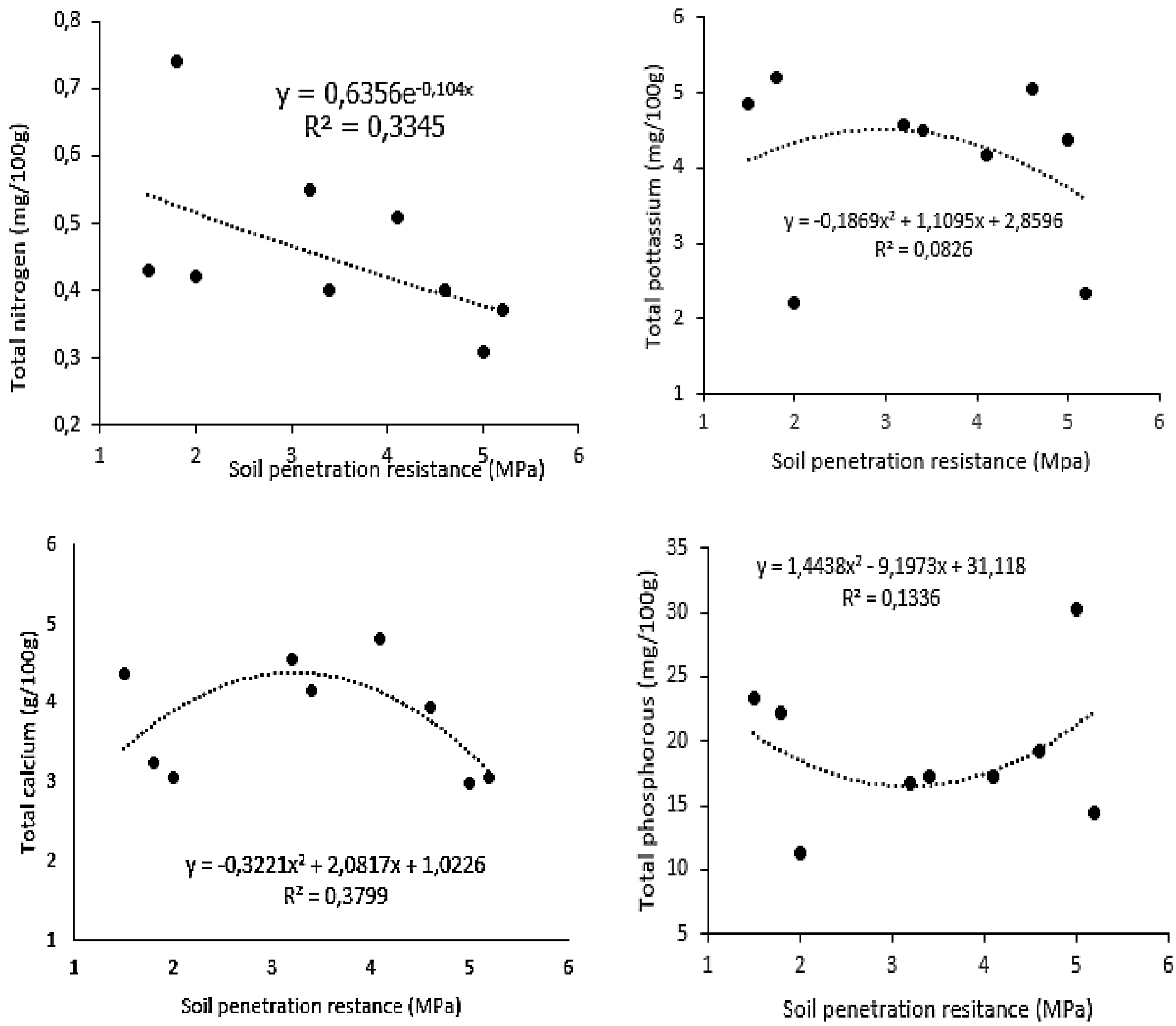


Figure 5. The effects of soil penetration resistance on wet root mass and dry root mass

3.5Nutrient Concentration in Shoot

The shoots of each plants after harvest was tested in the laboratory for total N, P, K, Mg, Ca and Na. The result of the analysis is summarized is Figure 6. Nutrient concentration was higher in treatment with low compaction for all elements except calcium and phosphorous. Increase in penetration resistance from 1.5 to 5.2 MPa reduced the concentration of nitrogen (13.5%), potassium (51.4%), magnesium (50.4%) and sodium (51.5%), whereas the concentration of calcium and phosphorous were higher when soil resistance varied between 3 and 4 MPa. Mixed nutrient concentration obtained could be as a result of external factors such as change temperature and humidity. In agreement with Guan *et al*. (2014), the result shows that the uptake of nutrients in some treatment decreased with increasing soil penetration resistance and weather condition was also a contributing factors to the changes on nutrient concentration across treatments. Mineral nutrients are important for effective plant growth and development. Enhancement in crop yield have been related with the availability of adequate amounts of nutrients. The unfavourable soil conditions created by increasing soil compaction (soil penetration resistance) observed in this study could account for the recorded reduction in mineral uptake. The ability of plants to absorb nutrients from the soil is essentially related to their ability to develop extensive roots systems (Jourgholami *et al.*, 2016).



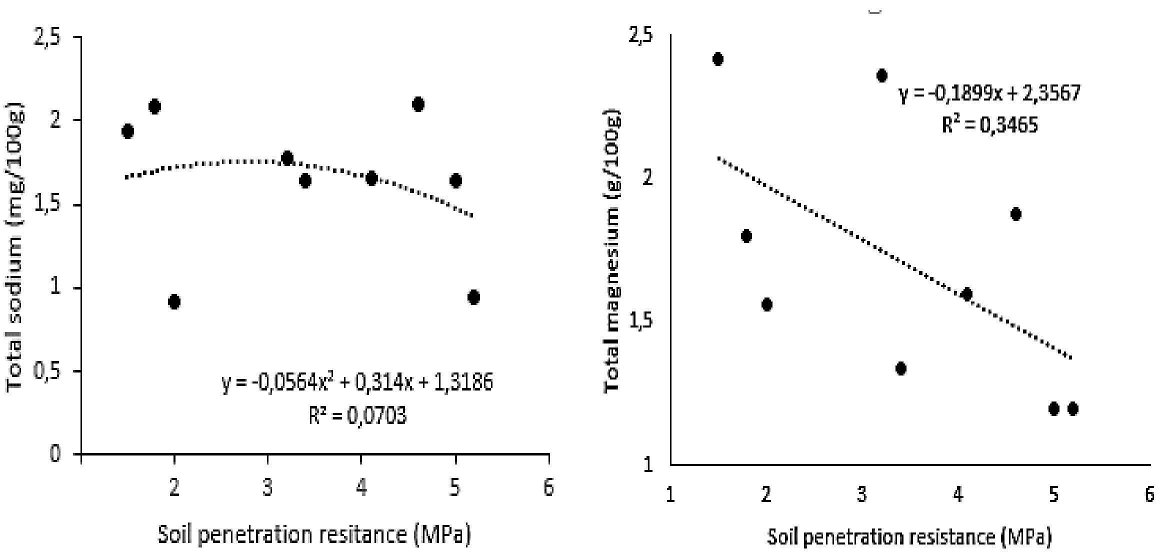


Figure 6. The effects of soil penetration resistance on the concentration of nitrogen, potassium, phosphorous, magnesium, sodium, and calcium in the shoots

4. Conclusion

This study offers a brief glance how maize plants respond to compacted soil under relatively constant environmental conditions. High soil strength reduced yield production, although the undesirable effect of compaction on the yield appeared to be moderated by an abundant water supply, while the yield level of some lower soil strengths treatments were further reduced by water stress. Increase in soil compaction negatively influenced plant nutrient uptake. From this study, it could be concluded that maize plant should not be grown on soil with penetration resistance higher than 2.0 MPa otherwise methods such as tillage and biological drilling could be used to reduce compaction in soils before cultivation.

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