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Effects of Soil Compaction on Soil Physical Properties.

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Abstract: - A 15x51m² field was manually cleared with cutlass and divided into three blocks of four plots each. The soil was compacted using a 35.5KN wheel tractor. The treatment consisted of 0, 1, 5, and 10 passes (wheel to wheel) of the tractor and were replicated three times. Soil physical properties were analyzed from core samples taken from each plot. This experiment was conducted on the Owerri soil precisely Uratta. This was done between the months of May and June 2018. Soil physical properties analyzed are the grain size analysis, cone index, dry bulk density, moisture content, soil porosity, water holding capacity, hydraulic conductivity and soil air. The results got showed that compaction affects the soil physical properties in so many ways. It results in poor nutrient and water uptake by plants and soil structure degradation which are reflected in the changes in soil physical properties. It also lowers the production potentials of the soil by exposing the soil to physio-chemical damages with a resultant poor nutrient uptake and poor growth and crop yield.

Keyword: Soil compaction, tractor passes, soil physical properties, soil physio-chemical damages.

INTRODUCTION

Soil compaction is the process of applying pressure to the agricultural soil thereby disturbing the soil texture and structure and thereby compressing the soil.

The compaction of soil can also be defined as an increase in its dry density, and the closer packing of solid particles or reduction in porosity. Modern cropping systems are based on agricultural machinery and this machinery is responsible for most of the soil compaction.

Vehicular traffic on agricultural mechanization i.e. a process by which any or all of the usual operations involved in agricultural production are carried out with mechanical assistance using either manually operated machinery or motorized and/or automated machine units. The mechanization of crop production is increasing in most parts of the world. In many countries this trend is viewed with concern because of the compaction which results when wheels pass over soils used as a growing medium for crops (Soane, 1970; Barnes *et al.*, 1971; Eriksson *et al.*, 1974; Chancellor, 1976; Osuji, 1988; Ohu *et al.*, 1991).

Among the numerous studies carried out to determine the effects of wheel traffic on soils, parameters such as bulk density, soil strength, total porosity and hydraulic conductivity have been used as indicators of soil compaction (Gameda *et al.*, 1988), with bulk density being the most used (Raghavan *et al.*, 1978; De Knipe *et al.*, 1981; Voorhess *et al.*, 1986; Cupta and Almares, 1987).

Soil compaction is important in Agriculture as it reduces runoffs. The use of tractors in Agriculture makes agricultural practice less stressful etc. The mutual interaction between these parameters are affected by soil moisture content. As soil moisture content increases, the soil strength (cone index) decreases and dry bulk density increases (Taylor *et al.*, 1981). However, at a fixed moisture content a soil will have a higher strength at larger densities, which reflects the closer packing of solid particles. This compaction also alters the water content and movement in soils by modifying the void size distribution (Warkentin, 1971).

This tends to reduce both the amount of water which is retained at low water suction pressure in the macropores, and the saturated hydraulic conductivity of the soil. Ide *et al.* (1984) found that the reduction in total porosity resulting from compaction would lead to a shortage of oxygen for plant roots while the reduction in pore diameter would prevent the entrance of root tips and easy flow of gravitational water.

From the above review, it may be summarized that tractor passes on the soil result in:

- Poor nutrient and water uptake by plants
- Soil structure degradation which are reflected in changes in soil physical properties such as dry bulk density, soil strength, soil porosity, permeability etc. With soil structure degradation, soil compaction due to traffic lowers the production potentials of the soil

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by exposing the soil to physio-chemical damages with a resultant poor nutrient uptake and poor growth and yield of crops.

Although compaction is detrimental to plant growth, but it can be ameliorated (Mckyes, 1985) by any or all of the following:

- Avoid high machinery contact pressure especially during repeated passes in fields.
- Avoid moving on fields with machines when the top soil is moist, close to the "optimum" moisture content for compaction.
- Avoid excessive slipping of tractor lives during field operations, which could double soil density changes under the same weight.
- Manage cultural programs that leave healthy system of roots, and sufficient organic matter in the top soil. So in this work, it is intended to assess the interactions of soil properties as they are affected by tractor wheel traffic.

LITERATURE REVIEW

Soil compaction had been a very sensitive problem to agricultural production because it involves poor soil and water conservation and thus reduced crop growth and yield. In developing countries like Nigeria, mechanization is increasing and, although the vehicles used may be light, the low structural stability of many tropical soils combined with the high erosivity of rainfall together increase the chances of serious soil degradation by field traffic. Compaction from field traffic may occur in virtually all types of crop production (Soane and Van Ouiverkerk, 1981).

It modifies the pore volume and pore structure of the soil with changes in void ratio, total porosity, specific volume and dry bulk density. Changes in bulk volumetric properties may not be as important to plant growth as the associated increased strength and reduction of conductivity, permeability and diffusivity of water and air through the soil pore system (Soane, 1985; Boone *et al.*, 1987; Guerif, 1988).

The soil properties to measure in compaction studies must be chosen by the researcher. The properties must strongly influence the way in which the soil responds to applied loads and the likely importance of the measured changes in subsequent crop growth. Bulk density had found application for comparing growth of different varieties of crops (Hakansson, 1973, Raghavan *et al.*, 1976) and for the comparison of the compacting effects of different wheel treatments over a range of soil types (Ljungara, 1977; Lamers *et al.*, 1986).

Changes in pore size distribution during compaction are important particularly with respect to large air-filled pores. Porosity and void ratio changes in a wide range of agricultural soils resulting from an applied mechanical stress have been reported by Larson *et al.* (1980) and Voinvail and Flocker (1991). Compaction reduces the diameter and continuity of pores and thus reduces the permeability and diffusion of gases and liquids in the soil (Grabble, 1971; Ball, 1979).

The cone resistance that measures soil strength is an important parameter affected by compaction. Compaction increases soil strength which not only increases soil cutting forces and energy required but will also impede the growth of plant roots (Mckyes, 1985; Taylor *et al.*, 1981).

All these soil properties mentioned above are usually affected by both soil type and soil moisture content (Mulqueen *et al.*, 1980).

It is widely thought that second subsequent passes a wheel produce less compaction than that caused by the first pass. This depends on the initial soil strength and its distribution with depth (Soane *et al.*, 1981). Modern systems of crop production are trending to increase both the number of passes and the loads carried on the wheels of agricultural vehicles especially in seed bed preparation, spraying and harvesting operations (Soane *et al.*, 1982).

During fertilizer distribution, secondary cultivation and sowing, soil strength is generally low as a result of the loosening during primary cultivation and the soil is usually moist making tractor to cause appreciable compaction. Ljungars (1977) found that the soil moisture content and the number of wheel passes were the factors primarily responsible for the compaction resulting from seedbed traffic.

Compaction by wheel traffic was found by Raghavan *et al.* (1979) to delay germination and early growth of maize silage. Root distribution of maize has been found to be closely associated with both the number of passes and the contact pressure of types running over the soil either before or after seedling (Raghavan and Mckyes, 1978).

Many researches have used several numbers of wheel passes in their work. Bonsu (1991) used 0, 2, 8 and 14 passes; Osuji (1988) used 0, 2, 5, 10 and 15 passes; and Raghavan *et al.* (1976) used 1, 5, 10 and 15 passes. Canarache *et al.* (1988) used 0, 1, 3, 5, 10, 20 and 30 passes; and Daniel *et al.* (1988) used 0, 1, 3, 5 and 10 passes. In view of the fact that mechanization sequence is different in South Eastern Nigeria, 0, 1, 5 and 10 passes of the tractor wheel were used in this work.

MATERIALS AND METHODS

In the analysis a 4-cylinder Steyr 768 tractor, hand operated auger, cutlasses, metre rule vibratory sieve materials and other relevant experimental apparatus as the affect different analysis were employed.

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A piece of land at Umunahu, Uratta in Owerri was manually cleared using cutlass and piled. The soil was leveled by the use of rake and measured in three blocks of four plots each. The field measured 15x 51m².

The field was divided into three blocks, leaving a head land of 3m wide between blocks. Each plot measured 1x10m².

Before and after each treatment, a hand operated anger of core size 7.6 x 7.40m² was used to excavate the soil at different depths of 0-50cm, 5-100cm and 10-15cm for soil analysis and for the determination of soil physical properties.

A 4-cylinder Steyr 768 tractor having two rear tires inflation pressure of 40psi with a weight of 35.5KN and tire size of 16.9/14-30 (6 ply rating) and this very tractor was to make passes on the field leaving a portion as control. The number of passes were 0, 1, 5 and 10 replicated three times and the mean value recorded.

Samples of soil were taken in straight lines with the aid of the auger. Moisture content, Cone index etc were tested. The particles size distribution was done using vibratory sieve method. With mesh sizes 4.75mm, 2.36mm, 1.18mm, 950mm, 425mm, 212mm, 200mm, 150mm and 75mm arranged accordingly. Three samples were taken per plot.

The following soil physical properties were determined using standard laboratory methods on the soil core samples. Soil analyses were performed on the different soil physical properties as seen below:

Shear strength: Shear strength measurement was done using the following – Soil samples, shear box, successive loads etc. Collected soil sample was prepared in a direct shear box, with load applied. The box was split into two parts, the lower part was fixed and the upper part was given a gentle increasing force. The soil specimen was removed for the shear box. This was repeated with different specimen. This was repeated in all the different plots.

Hydraulic conductivity (constant head method): Constant head was maintained by having a tap of water flowing constantly into the both. It was also constantly discharged so that the height was maintained constant. The time within which discharge was collected was recorded.

Porosity: Soil sample was collected into a funnel which was placed in a graced cylinder. The soil was put on top of cotton wool to act as sieve and water was poured into the cylinder through the funnel and the time taken for the water to drain and the amount of water drained and retained were recorded.

Cone Index (Penetration Resistance): This was done at 60⁰ tip cone penetration having a base area of $5x10^{-4}m^2$. Soil was put into a container and the cone allowed to touch it. The screw of this penetrometer was turned causing pressure on the tin and dial gauge's reading was recorded.

Bulk Density: A core sample of soil was got by driving the sample into the soil to a desired depth and then removed. Having known the volume of the sample, the mass, the dry bulk density was easily calculated.

Moisture Content: The hand operated anger was used to excavated the soil to collect a soil sample. This natural soil was weighted and recorded. The soil was dried in an oven at the temp of 105⁰ for 24 hours and was allowed to cool and it was re-weighted. The moisture content was calculated. This was replicated three times. It was allowed to cool before reviewing again to allow it to assume its normal weight because the soil is hydroscopic.

Soil Air: A milk tin was opened at one end and a volume was estimated by filling it with water and then pouring the water into a graduated cylinder. The empty tin was turned upside down and the open end was pressed firmly into the ground until the tin was filled with soil. It was later turned back and the soil was level to the brim of the tin with a ruler. 2300m³ of water was poured into a 500cm³ graduated cylinder. The soil was scrapped in the tin. Bubbles of air started escaping till no more air escaped.

Grain size analysis: This was done by weighing and noting the weights of the meshes and arranged in descending order of sizes. A known weight of dried soil sample was placed inside the mechanical shaker and timed for 2 mines. The meshes weighed again to know the amount of soil retained in each mesh.

Hydraulic Conductivity: An undisturbed packed soil sample was placed on the cylindrical container with enough space below and above the soil pack. The cross-sectional area of soil pack or core A and the length L of the soil column was measured. One side of the soil column was sealed with paraffin wax to prevent passage of water down the sides of the soil column. A known volume of water for a measured time was passed three the soil. The difference in head between two levels after the same measured time was measured.

Dry bulk (Core Technique Method): A sampler is known volume was used to collect a core sampler of known volume was used to collect a core sample of soil by driving it into the soil to depths of 0-5cm, 5-10cm and 10-15cm respectively at different times and then removed. After the sample was removed from the soil, the core was placed in a paraffin point-sized cream container and sealed. The core sample dimension was noted to be 7.6 x 7.4cm² taken layer by layer along three profile pits due to the site. The soil was weighted wet and

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result noted as x gm. It was later over dried at 105^0C for 24 hours and allowed to cool, and was weighted dry, y gm.

N. OWERRI
MCC/URATTA, RD, OWERRI
IHITTA OGADA – EMEKUKU
EMII
ROAD SAFTETY
EGBU
AWAKA
NAZE
ABA RD
PROJECT SITE AT UMUNAHU-URATTA, IN OWERRI NORTH LGA OF IMO STATE NIGERIA.

OWALLA OWAELU
ORJI
OKIGWE RD
EKEMEGBUOHA MKT SQ – URATTA
URATTA
ORJI URATTA
OKIGWE RD
TORONTO R/ABOUT URATTA
UZOAGBA
IKEDURU

RESULTS AND DISCUSSION

Table 1: Result of Sieve Analysis of Soil from The Experimental Plot.

Sieve Diameter	0-5cm % finner	5-10cm % finner	10-15cm % finner
4.75 mm	100	100	100
2.36 mm	99.95	99.95	99.99
1.18 mm	99.70	99.80	98.24
850 mm	96.65	98.10	94.91
425 mm	54.55	63.00	51.3
212 mm	43.35	41.05	40.36
200 mm	3.85	4.85	5.10
150 mm	0.15	1.91	2.07
75 mm	0.12	0.05	0.6
P an	0	0	0

Table 2: Effect of traffic density on cone index (penetration resistance) (kg/cm 2) Penetration Resistance

Depth(cm)	T=0	T=1	T=5	T=10
0-5	0.35	0.89	2.55	7.45
5-10	0.77	1.12	2.93	8.23
10-15	1.16	1.81	5.45	8.96

From Table 2 it could be said that the cone index was increasing with both traffic density and soil depth. The values for the 10-15 cm and 5-10 cm depth were closer to each other while that of the 0-5 cm depth deviated a bit.

We therefore, conclude that compaction increases soil strength which also increase soil cutting force and energy required and as such impede plant root growth. This is in consonance with the previous research work (Mckyes, 1985; Taylor *et al.*, 1981).

Dry Bulk Density: The traffic density has a significant effect on the Dry Bulk Density of a soil sample. It has found application for comparing growth of different varieties of crops (Hakansson 1973, Bagharan *et al.*, 1976) and for the comparison of the compacting effects of different wheel treatment over a range of soil types. Increase in traffic intensity, increases the pressure and thereby reducing the volume of the pores resulting in increased density at constant soil mass (Table 3). The lowest value of Dry Bulk Density (1.05 g/cm^3) was found from the 0 treatment and the highest value (1.33 g/cm^3) was found in the 10 passes pattern while that of 5-10 cm soil depth deviated. The deviation could be due to certain experimental errors.

Generally, those results agree with Osuji (1988) and are a bit different from those of D. Han and van der Valk (1970). This is so because Osuji (1988) carried out his research on a tropical alfisoil while unlike that of van der Valk (1970).

Table 3: Effect of traffic density on dry density (g/cm 3) G= 2.65g/cm 3

Depth (cm)	T=0	T=1	T=5	T=10
0-5	1.05	1.20	1.20	1.21
5-10	1.05	1.10	1.17	1.21
10-15	1.15	1.17	1.20	1.33

Hydraulic Conductivity (Permeability): Permeability decreased with traffic density and increased with soil depth according to Bonsu (1991). Soil permeability was highest (0.44 m/s) at 10-15 cm soil depth and 0 pass treatment, and lowest (0.045 m/s) at 0-5 cm soil depth and 10 pass treatment (Table 4).

Soil Porosity and Water Holding Capacity: It is evident from Table 5 that porosity decreased as the soil depth increased. This observation is consistent with Larson *et al.* (1980) and Voinvail and Flocker (1961).

Moisture Content: From Table 6, it can be said that increased traffic density resulted in increased moisture content, and this moisture content increased with soil depth. According to Ljungars (1977), soil moisture content and the number of traffic passes were factors responsible for the compaction resulting from seed bed traffic. From Table 6 again, moisture content was lowest (7.03%) at 0-5 cm soil depth with 0 pass treatment, and highest (15.96%) at 5-10 cm soil depth with 10 passes treatment.

Table 4: Effect of traffic density on Hydraulic Conductivity (m/s)

Depth (cm)	T=0	T=1	T=5	T=10	
0-5	0.124	0.070	0.056	0.045	
5-10	0.340	0.340	0.285	0.141	0.116
10-15	0.440	0.440	0.353	0.230	0.126

Table 5: Effect of traffic density on soil porosity

Depth of soil (cm)	T=O	T=1	T=5	T=10
0-5	1.9	1.70	1.63	1.17
5-10	1.9	1.70	1.10	1.0
10-15	1.30	1.30	0.93	0.83

Table 6: Effect of traffic density on moisture content

Depth of soil (cm)	T=0	T=1	T=5	T=10
0-5	7.03	7.95	8.90	9.03
5-10	9.34	9.3	12.32	15.96
10-15	10.90	11.64	13.45	14.9

Relationships Between Different Soil Parameters

- **Dry Bulk Density and Moisture Content:** The Dry Bulk Density and Moisture Content are two important parameters in this research work. Different results for different traffic intensities are shown in the same table. The values increased until the optimum moisture content of each was reached, then the values started to fall; i.e., at the dry side of optimum, the Dry Bulk Density was rising steadily with the moisture content and falling with increased moisture content at the wet side of optimum.

  The Dry Bulk Density is maximum (1.35 g/cm³) in the 10 passes treatment at moisture content 10%, and lowest (1.05 g/cm³) at moisture content 13.5%. This is true with Bonsu (1991) and similar to Asoegwu (1987).

- **Cone Index and Dry Bulk Density:** The Cone Index and Dry Bulk Density have the same pattern of growth under axle wheels (Table 2 and Table 3). From these tables, we observed that the Cone Index increased with increased Dry Bulk Density at different soil depths. From this, we could confirm that compaction governs both Cone Index and Dry Bulk Density of a soil. This result is similar to Bonsu (1991) and Asoegwu (1987).

- **Cone Penetration and Moisture Content:** The Cone Penetration increased as the Moisture Content increased. The relationship between Cone Penetration and Moisture Content is linear (Tables 4.2 and 4.6).

  At 13% moisture content, which is about the optimum moisture content, the Cone Penetration was 20 mm. From this result, we could believe traffic density affects both Cone Penetration and Moisture Content as discussed by Mulqueen, Stafford, and Tanner (1977).

- **Proving Ring and Strain:** The result on Proving Ring Dial and Strain has a direct relationship with each other. The values have the same pattern but different values of Proving Ring Dials for different traffic densities at the same strain (Table 7). From this table, we observe that the Proving Ring Dial was lowest (6 mm) at 3.6% strain in the 10 passes treatment.

  It was observed that at 2.8% strain, the different Proving Ring values for different traffic intensities became almost steady. This is so because the soil is plastic and obeys Hook's law. This result agrees with Campbell, Stafford, and Blackwell (1980).

- **Pressure Applied and Depth of Penetration:** We found that the applied pressure was highest (235 kN/m²) at 9 cm depth of penetration in the 10 passes treatment. For the 5 passes treatment, the highest value was 140 kN/m² at 9 cm depth of penetration.

Table 7: Effect of traffic intensity on soil strength

Strain 6	Proving ring dial (cm)			
	0	1	5	10
0.4	6.0	8.5	16.5	28
0.8	14	16	27	39
1.2	20.5	22.5	34.9	46.8
1.6	25.3	27.5	39.9	52.3
2.0	29.0	31.3	45	56.6
2.4	30.8	33.4	46	59.7
2.8	30.5	33.4	47.6	61.7
3.2	30.5	33.4	47.6	62.7
3.6	30.5	33.4	47.6	62.7

Table 8: Normal stress against shear stress at failure.

Normal Stress (kN/m²)	Shear Stress at Failure, τ (kN/m²)
0	50
100	193
200	139
300	160
4	222

Normal Stress, 6 (kN/m²). The highest for 0-pass treatment was 110 kN/m² at 9 cm depth of penetration. From the results, we conclude that an increase in traffic density results in an increased depth of penetration. This agrees with the research of McKyes (1985) and Taylor *et al.* (1981).

Shear Stress and Normal Stress: The result of the shear and normal stress formed a linear curve, originating at 50 kN/m², indicating that the soil sample was a cohesive soil (sandy loam). At normal stress 0 kN/m², the shear stress was 50 kN/m², and at the maximum normal stress of 400 kN/m², the shear stress was 222 kN/m² (Figure 9).

From this, we could conclude that traffic density governs the shear strength of a soil. This result agrees with the work of Campbell, Stafford, and Blackwell (1980).

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Conclusion and Recommendation

From the results so far gathered, it is found that soil compaction as a result of farm vehicular traffic significantly affects soil physical properties. It alters soil structure and stability, which in turn influences water retention, nutrient uptake, and root development.

A more concise and uniform result could have been obtained if a roller wheel had been used instead of the tire-type tractor. The roller wheel would have compacted a broader area of soil and increased the effective pressure or load of the tractor on the soil surface.

References

1. Asoegwu, S. N. (1987). Comparison of tillage systems for the production of egusi-melon (*Citrullus colocynthis* L.) and okra (*Abelmoschus esculentus* L. Meerch) in Eastern Nigeria. *Crop Research (Hertfordshire Research)*, 27(2), 77–90.
2. Bonsu, M. (1991). Three indices for assessing tillage-induced compaction in a shallow organic soil. *Proceedings of the 12th ISTRO Conference*, Ibadan, Nigeria, pp. 221–228.
3. (1987). The effect of growth of maize for tillage (2): Soil conditions and plant growth. *Netherlands Journal of Agricultural Science*, 35, 113–128.
4. Campbell, D. J., Stafford, J. V., & Blackwell, P. S. (1980). The plastic limit as determined by the drop-cone test in relation to the mechanical behavior of soil. *Journal of Soil Science*, 31, 11–24.
5. Canarache, A., Elibas, I., Celibas, M., Herebeanu, I., Simota, H., & Trandafirescu. (1988). New field experimental research concerning induced soil compaction in Romania. *Proceedings of the 11th International Conference of ISTRO*, Edinburgh, Scotland, pp. 215–220.
6. Chancellor, N. J. (1976). Compaction of soil by agricultural equipment.
7. Cupta, S. C., & Allmaras, R. R. (1987). Models to assess the susceptibility of soils to excessive compaction. *Advances in Soil Science*, 6, 65–100.
8. Grameda, S., Raghavan, C. S. V., Mokyes, E., Watsen, A., Mehuys, G., & Duval, J. (1988). Soil structure and crop response under heavy axle load compaction. *Proceedings of the 11th ISTRO Conference*, Edinburgh, Scotland, Vol. 1, pp. 203–268.
9. Guerif, J. (1988). Factors influencing soil strength increases induced by compaction. *Proceedings of the 11th ISTRO Conference*, Edinburgh, Scotland, pp. 269–274.
10. Hakansson, I. (1973). The sensitivity of different crops to soil compaction. *Proceedings of the 6th ISTRO Conference*, Wageningen, Paper 14, pp. 1–3.
11. Lamers, J. G., Perdek, U. D., Lumkes, L. M., & Klvester, J. J. (1986). Controlled traffic farming systems in the Netherlands. *Soil Tillage Research*, 8, 65–76.
12. Ljungars, A. (1977). Importance of different factors of soil compaction by tractors. *Measurements in 1974–1976*. Agricultural College Sweden, Department of Soil Science, Report 52, 43 pp.
13. Mokyes, E. (1985). *Soil cutting and tillage* (Developments in Agricultural Engineering, Vol. 7). Elsevier Science Publishers B.V., Amsterdam, The Netherlands.
14. Mulqueen, J., Stafford, J. V., & Tanner, D. W. (1977). Evaluation of penetrometers for measuring soil strength. *Journal of Terramechanics*, 14, 137–151.
15. Ohu, J. O., Folorunso, O. A., & Ekwue, E. I. (1991). The influence of tractor traffic on crop production in a semi-arid region of Nigeria. *Proceedings of the 12th International ISTRO Conference*, Ibadan, Nigeria, pp. 238–246.
16. Osuji, G. E. (1971). *Compaction of agricultural soils*. American Society of Agricultural Engineers (ASAE), St. Joseph, MI, 471 pp.
17. Osuji, G. E. (1988). The effects of vehicular traffic on the growth pattern of maize on a tropical Alfisol. *Proceedings of the 11th International ISTRO Conference*, Edinburgh, Scotland, pp. 311–331.
18. Raghavan, G. S. V., & Mokyes, E. (1978). Effect of vehicular traffic on soil moisture content in corn (maize) plots. *Journal of Agricultural Engineering Research*, 23, 429–439.
19. Raghavan, G. S. V., Mokyes, E., Chasse, M., & Merineau, F. (1976). Development of compaction patterns due to machinery operation in an orchard soil. *Canadian Journal of Plant Science*, 56, 505–507.
20. Raghavan, G. S. V., Mokyes, E., Gendren, G., Burglum, B. K., & Le, H. H. (1978a). Effects of contact pressure on corn yield. *Canadian Agricultural Engineering*, 20, 34–37.
21. Raghavan, G. S. V., Mokyes, E., & Baxter, R. (1979). Traffic-soil-plant (maize) relations. *Journal of Terramechanics*, 16, 181–189.
22. Soane, B. D. (1970). The effects of traffic and implements on soil compaction. *Journal of the Institution of Agricultural Engineers*, 25, 115–126.
23. Soane, B. D., & Van Ouwerkerk, C. (1981). The role of field traffic studies in soil tillage research. *Soil Tillage Research*, 1, 205–206.
24. Soane, B. D., Blackwell, P. S., Dickson, J. W., & Painter, D. J. (1981). Compaction by agricultural vehicles: A review. II. Compaction under tyres and other running gear. *Soil Tillage Research*, 1, 373–400.
25. Soane, B. D., Dickson, J. N., & Campbell, D. J. (1982). Compaction by agricultural vehicles: A review. III. Incidence and control of compaction in crop production. *Soil Tillage Research*, 2, 3–36.
26. Taylor, F., Vigier, B., Raghavan, G. S. V., & Mokyes, E. (1981). Effects of soil compaction generated by machinery traffic on production of

***Corresponding Author:** Chiagorom, V. C.

peas in Quebec. *Report to Quebec Ministry of Agriculture, Food and Fisheries*, Project No. MCA-80-850, 95 pp.

27. Voorhees, W. B., & Lindstrom, M. J. (1983). Soil compaction constraints and conservation tillage in the northern Corn Belt. *Journal of Soil and Water Conservation*, 34, 184–186.
28. Voorhees, W. B., Nelson, W. W., & Randall, G. W. (1986). Extent and persistence of subsoil compaction caused by heavy axle loads. *Soil Science Society of America Journal*, 50.
29. Warkentin, B. P. (1971). Effects of compaction on content and transmission of water in soils. In *Compaction of Agricultural Soils*. ASAE, St. Joseph, MI, pp. 126–153.

***Corresponding Author:** Chiagorom, V. C.