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The Hydraulic Conductivity of Soils under Continuous Maize (Zea May) Cultivation

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Abstract

The severity and scope of our modern day practices in the last few centuries on the hydraulic conductivity of soil has affected its ability to control water infiltration and surface runoff. Soils exposed to human impact are often stripped of the organic-rich upper horizons, thereby increasing bulk density and reducing soil porosity. The study saw to determine the effects of continuous cultivation on the hydraulic conductivity, bulk density and porosity of soil. The hydraulic conductivity was measured with ring infiltrometer. Hydraulic conductivity was observed to decrease with increasing years of soils cultivation indicating a high impact of land use on this soil property. Hydraulic conductivity (K_s) values of 0.189±0.020cmh^{-1}, 0.162±0.023cmh^{-1}, 0.097±0.011cmh^{-1}, and 0.078±0.028cmh^{-1} were respectively recorded for undisturbed forest, one year cultivated soil, two years cultivated soil and three years cultivated soil. The dry bulk densities obtained in forested soils, one year cultivated soil, two years continuous cultivated soils and three years continuously cultivate soil were 0.991±0.047gcm^{-3}, 1.025±0.031gcm^{-3}, 1.215±0.102gcm^{-3}, and 1.332±0.074gcm^{-3} respectively with the least occurring on forest soils owing to high organic matter content and abundant burrowing fauna. To conclude, the study revealed that soil hydraulic conductivity, bulk density and porosity are time-variant and this fact should not be neglected in soil water flow modeling.

Keywords: Hydraulic conductivity, bulk density, porosity and continuous cultivation

1. Introduction

Hydraulic conductivity (K_s) is defined as “the metres per day of water seeping into the soil under the pull of gravity or under a unit hydraulic gradient” (Kirkham, 2005). Hydraulic conductivity is one of the most important soil physical properties for determining infiltration rate, irrigation, drainage practices, and other hydrological processes (Gulser and Candemir, 2008). When coupled with other physical soil properties such as the intrinsic permeability (soil or fractures), the degree of saturation, the type of soil, bulk density, total porosity and the configuration of the soil pores, it can be used to evaluate the potential use of soil for many agricultural and non-agricultural uses (Chakravorty *et al.,* 1998). With respect to agricultural soils, it is also useful in controlling water infiltration and surface runoff, leaching of pesticides from agricultural lands and migration of pollutants from contaminated sites to the groundwater (Bagarello and Sgroi, 2004). The understanding of these physical properties of soil and the management of agricultural practices requires assessment of the hydraulic properties of soil, such as infiltration and conductivity (Green *et al*., 2003).

In Ghana, soils exposed to human impact (such as construction, farming etc.) are often stripped of organic-rich upper horizons or compacted by heavy equipment or livestock during its preparation, thereby increasing bulk density and reducing infiltration rates (Li and Shao, 2006). Such disturbances, generally, outweigh the genoform traits (e.g. those inherited from parent material, topographic setting) in determining soil water movement (Schwartz *et al.,* 2003). Therefore these lands impacted by land use activities may have marked disparities from the original forested soil which may result in bad land formation and reduced crop growth, irrigation problems and poor root development resulting in lateral root growth of plant species. Knowledge of soil hydraulic conductivity will assist in defining the best strategies for sustainable soil management through the provision of information for estimating the soils susceptibility to erosion, hydrological modeling and efficient planning of irrigation projects. Studies investigating soil hydrologic response to temporal land-use changes have heavily emphasized comparison of cultivated cropland soils versus soils underlying native forest because subjecting a land to continuous cropping over a long period adversely affect soil physical properties. This research therefore seeks to examine the hydraulic conductivity of soils under three types of cropping periods to provide data for use to estimate the hydrologic responses to land use changes in the study area.

1.1 Research Objectives

The main objective of this study is to assess the hydraulic properties of soil under three different continuous cultivation periods.

The specific objectives are:

To determine the effect of continuous cultivation on soil hydraulic conductivity

To determine the effect of continuous cultivation on soil bulk density and porosity

2.0 Study Area

The study was carried out on an experimental plot at Kwadaso, North West of Kumasi on Longitude 6^0 40’ 35.9”N and Latitude 1^0 40’ 0.6”N at the Soil Research Institute. The site has an elevation of 262m above sea level with a Mean Annual Rainfall of 1500mm from June to August. It has an average monthly temperature ranging from 24^0C - 28^0C. All plots were subjected to the same land preparation activities.

2.1 Experimental Design and Data analysis

The study was conducted on three fields, namely; 1 year continuously cultivated land (Field A), 2 years continuously cultivated land with Maize Crop (Field B), and 3 years continuously cultivated land with Maize Crop (Field C). Additionally, an adjacent undisturbed forest (Field D) was selected and used as control experiment. The grid design sampling design was used in the study. Each of the selected sites ($16x16m^2$) was surveyed and demarcated into 16 grid cells each of size 4m × 4m (Fig. 1). Three subplots were randomly selected from each field. Thus a total of 12 subplots were used for the research. Within each subplot, three separate quadrants (Q1, Q2, and Q3) were constructed representing three replications (Fig.1). Double ring infiltrometer was mounted at these spots for hydraulic conductivity measurements. Soil samples were taken from the spots and analyzed for bulk density and porosity. One-way ANOVA was conducted to compare mean hydraulic conductivity, mean Bulk density, and mean bulk density of soils across the three different years of agricultural land use at α= 5% level of significance. Fisher’s LSD multiple comparisons tests was performed in situations where there was significant difference between the three different years of continuous cultivation of soils.

Hydraulic conductivity values were correlated to bulk density and soil porosity by the use of the following models;

Equation 1: $$K_s = mBD + c$$

where K_s is the hydraulic conductivity; BD is bulk density; m and c are coefficients;

Measurements of soil hydraulic conductivity (K_s) were correlated with soil total porosity to estimate the dependency of K_s variability on soil porosity using the simple exponential relationship:

Equation 2: $$K_s = ke^{mP}$$

where K_s is soil hydraulic conductivity (cmh^{-1}), P is soil porosity (cm^3/cm^3) at 5cm depth and k and m are coefficients.

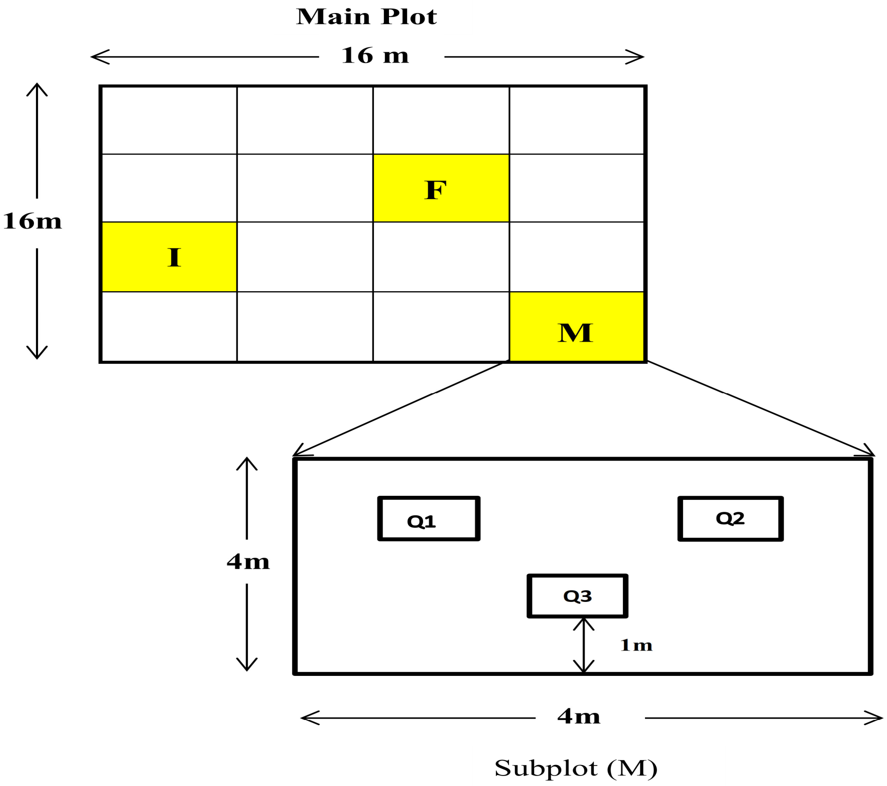

Fig. 1: Experimental plot layout

3.0 RESULTS AND DISCUSSION

3.1 Hydraulic Conductivity (K_s)

Table 1 shows the hydraulic conductivity of soil subjected to one, two, and three years of cultivation. It revealed a decreasing trend in hydraulic conductivity with increasing years of soil cultivation. Highest K_s was recorded at the undisturbed forest ($0.189 \pm 0.020 cmh^{-1}$). The three year old cultivated soil recorded the least mean K_s value of $0.078 \pm 0.028 cmh^{-1}$. K_s values for two years continuous cropping was $0.097 \pm 0.011 cmh^{-1}$ and $0.162 \pm 0.201 cmh^{-1}$ for one year continuous cropping (Table 1). There was significance ($p<0.05$) differences between the different years of soil cultivation. This observation could be due to soil compaction by machine as well as human traction which reduces significantly the hydraulic conductivity tendencies of soil. Again, the presence of more macropores, associated with the activity of fauna and roots in the undisturbed forest than in the arable cultivated soil may have also affected the hydraulic conductivity. This result implies that the movement of water (irrigation), chemicals and other liquids through the various soils under consideration will decrease as the number of years of cultivation increases. Therefore intensive irrigation activity on the three years old cultivated plot will cause significant problem as the water may fill the little remaining macropores (resulting from continuous cultivation) and starts flowing as runoff. Compared to the third year with the least hydraulic conductivity, the undisturbed forest which featured the highest Ks value will cause insignificant problems related to irrigation as the many macropores present in the soil can assist in water seepage. This goes to prove that soil hydraulic properties are time-variant, and this fact should not be neglected in soil water flow modeling. Compared with the bulk density, it means that insignificant increase in a bulk density can lead to a significant increase in hydraulic conductivity.

Table 1 Descriptive statistics of Hydraulic conductivity of soils under variable years of cultivation of maize

Treatment	**Hydraulic Conductivity (cmh^{-1})**			
	Mean	Stdev	Min	Max
1 year of Continuous Cropping of Maize	0.162^{b}	0.023	0.124	0.201
2 years of Continuous Cropping of Maize	0.097^{a}	0.011	0.084	0.121
3 years of Continuous Cropping of Maize	0.078^{a}	0.028	0.042	0.113
Undisturbed Forest (Control)	0.189^{c}	0.020	0.157	0.213
Total Mean (n = 36)	**0.131**	**0.021**	**0.102**	**0.162**
p-value (α = 0.05) = 1.19×10^{-10}				

Values with same alphabets are not significantly different from each other at $p<0.05$

These results confirm with the work Lampurlanés and Cantero ‑ Martínez (2005) that hydraulic conductivity can be influenced by seasonal changes. As the growing season progresses, hydraulic conductivity can decrease because of increased root growth clogging pores, soil slaking, and a breakdown of structure in tilled soils. McGarry *et al.,* (2000) also observed higher values of hydraulic conductivity (Ks) under undisturbed forests relative to tilled lands at the beginning of the growing season due to a greater number of macropores (Logsdon *et al.,* 1990), increased fauna activity and the litter of residues formed by accumulated organic matter (Logsdon and Kaspar, 1995). Such changes in topsoil hydraulic properties are very important not only for hydrological processes such as surface runoff but also groundwater and water quality. The hydraulic properties modify the hydrological response in terms of water balance components and their annual temporal variability (Fohrer *et al.*, 2005; Bormann *et al.*, 2007).

3.2 Bulk Density (BD)

Bulk density of soils under the various plots increased as the time with which the land has been submitted to cultivation increases. The mean bulk densities observed were $0.991 \pm 0.047 g/cm^3$, $1.025 \pm 1.02 g/cm^3$, $1.215 \pm 0.102 g/cm^3$ and $1.332 \pm 0.074 g/cm^3$ for undisturbed forest, 1 year, 2 years and 3 years continuously cultivated plots respectively. The undisturbed forest (UnF) plot recorded the least bulk density whereas the 3 year plots recorded the highest mean bulk density. Significant differences ($p<0.05$) were recorded for soils under the variable years of continuous cultivation (Table 2).

Table 2: Descriptive statistics of bulk desnity of soils under variable years of cultivation of maize

Treatment	**Bulk density (gcm^{-3})**			
	Mean	Stdev	Min	Max
1 year of Continuous Cropping of Maize	1.025^{a}	0.031	0.98	1.08
2 years of Continuous Cropping of Maize	1.215^{b}	0.102	1.11	1.37
3 years of Continuous Cropping of Maize	1.332^{c}	0.074	1.21	1.47
Undisturbed Forest (Control)	0.991^{a}	0.047	0.88	1.03
Total (n = 36)	**1.141**	**0.064**	**1.20**	**1.24**
P-value(α = 0.05) = 4.49×10^{-11}				

Values with same alphabets are not significantly different from each other at $p<0.05$

High bulk density is an indicator of low soil porosity and high soil compaction. The higher bulk density in the three years cultivated soil may cause restrictions to root growth as well as poor movement of air and water through the soil. Compaction can result in shallow plant rooting and poor plant growth, influencing crop yield and reducing vegetative cover available to protect soil from erosion. By reducing water infiltration into the soil, compaction can lead to increased runoff and erosion from sloping land or waterlogged soils on flat terrains. Soil compaction may restrict water movement through the soil profile and although it might be beneficial under arid conditions, it leads to a decrease in crop yield under humid conditions. Since the three year old continuously cultivated recorded the highest bulk density, it means compaction levels and its associated effects were bound to be high on the soil. Lal (1996) also reported an increase in dry bulk density when forest was replaced by cultivated lands, which is consistent with the findings of this study. The highest mean bulk density observed on the 3 years cultivated soil (1.433g/cm^{-3}) must have been caused by crop and land management practices that affect soil cover, organic matter, soil structure, and/or porosity as the years of soil cultivation increases. Cultivation destroys soil organic matter and weakens the natural stability of soil aggregates making them susceptible to damage caused by water and wind.

3.3 Porosity

General decrease in porosity was observed in sampled plots when the means were collated and plotted (Table 3). The decrease occurred in the order 0.6215 ± 0.018cm^{3}cm^{-3}, 0.612 ± 0.013cm^{3}cm^{-3}, 0.541 ± 0.039cm^{3}cm^{-3} and 0.496 ± 0.026cm^{3}cm^{-3} for plots under undisturbed forest (control), one year, two years and three years old cultivated soils respectively. The undisturbed forest (UnF) recorded the highest porosity and the 3 years plot recorded the least. The 1 year and 2 years continuously cultivated plots formed the intermediates. Significant differences were observed between the treatment means at 0.05 significant level (Table 3).

Table 3 Descriptive statistics of porosity of soils under variable years of cultivation of maize

Treatment	**Total Porosity (cm/cm^{-3})**			
	Mean	Stdev	Min	Max
1 year of Continuous Cropping of Maize	0.612 ^{c}	0.013	0.59	0.63
2 years of Continuous Cropping of Maize	0.541 ^{b}	0.039	0.48	0.58
3 years of Continuous Cropping of Maize	0.496 ^{a}	0.026	0.45	0.54
Undisturbed Forest (Control)	0.627 ^{c}	0.018	0.61	0.67
Total (n = 36)	**0.569**	**0.024**	**0.53**	**0.61**

p-value ($\alpha = 0.05$) = 7.27×10^{-11}

Porosity, according to the results indicated an inverse relationship with the treatment. As the number of years of continuous cultivation increases, the porosity of the soil becomes lesser. The mean bulk densities obtained for undisturbed forest (UnF), one year, two years and three years continuously cultivated soil were 63%, 61%, 54%, and 50% respectively. The decrease could be attributed to the fact that soil pores continuity are converted to "dead end" pores when the land was subjected to continuous cultivation. Thus the pore spaces between the soils under the undisturbed forest (control) had a relatively continuous pore than when the land was cultivated for one year, two years and three years. The continuous macropores (water-conducting macropores) will contribute to fast water flow since the ratio of the volume of these pores to the total soil volume is high. In light of the above, Luxmoore *et al.,* (1990) asserts in his research that soil pores are not only important because of their role in moisture retention, root growth and aeration, but also for their hydrological importance.

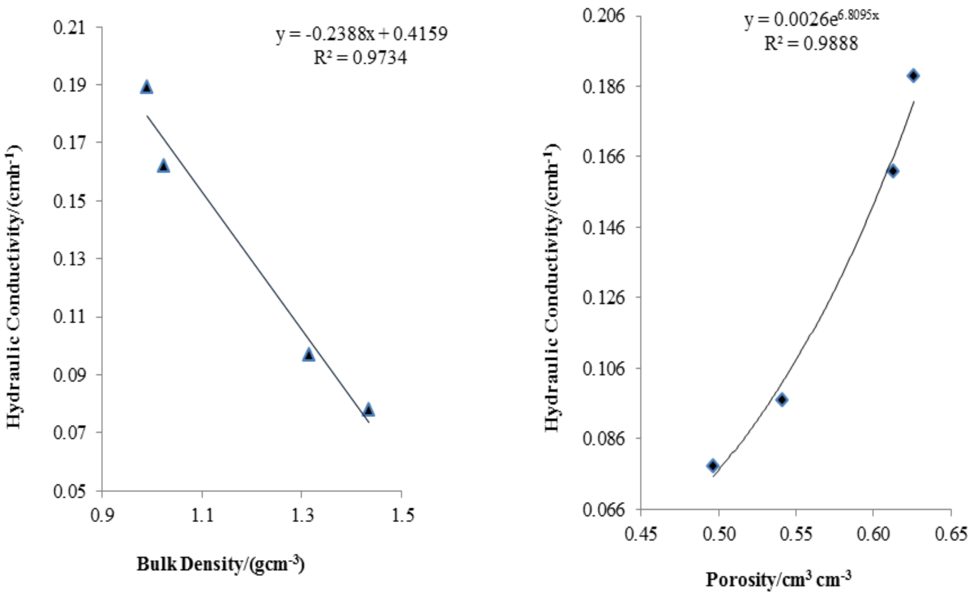

Figure 1: A scatter plot of Ks and bulk density (a), Ks and porosity (b)

Figure 1 presents the scatter diagram showing the negative correlation between hydraulic conductivity and Bulk density. This indicates that as the hydraulic conductivity increases, bulk density decreases and vice versa. Ks = -0.2388BD + 0.4159 equation will assist in hydrologic modeling especially those soils from the site i.e. hydraulic conductivity at the near surface (more specifically within 0 - 10cm range) can be calculated by taking samples from the field and analyzing them for the bulk density, after which the BD values can be substituted to determine the hydraulic conductivity without necessarily using the double rings. The correlation of determination between hydraulic conductivity and bulk density suggest that weak and no useful relationship exists between the two parameters. R^2 implies that the 97.34% of the changes in hydraulic conductivity can be explained by the changes in bulk density. Again, the regression equation of $Y = 0.0026e^{6.9X}$ was obtained for the relationship between hydraulic conductivity and porosity (Figure 1b). It can therefore be deduced that $Ks = 0.0026e^{6.9P}$. The square of Pearson product moment (R^2) between the hydraulic conductivity is 98.89%. This suggests that a useful relationship exist between the two parameters which imply that 98.89% of the variation of hydraulic conductivity can be explained by the changes of pore structure of soils.

4.0 CONCLUSION

The results presented in this paper show that soil hydraulic conductivity, bulk density and porosity of small cultivated lands are time variant. Ks value obtained for the various continuously cultivated lands were 0.189±0.020cmh^{-1}, 0.162±0.023cmh^{-1}, 0.097±0.011cmh^{-1} and 0.078±0.028cmh^{-1}. The results show a decrease in hydraulic conductivity from undisturbed forest (UnF) to one year, two years and three years cultivated soils. Porosity, according to the results, indicated an inverse relationship with the different continuously cultivated soils. Thus, as the number of years of soil cultivation increased, the porosity of the soil decreased. The decrease occurred in the order 0.6215±0.018cm^{3}cm^{-3}, 0.612±0.013cm^{3}cm^{-3}, 0.54±0.039cm^{3}cm^{-3} and 0.496±0.026cm^{3}cm^{-3} for plots under undisturbed forest (control), one year, two years and three years old cultivated soils respectively. Monitoring of hydraulic conductivity, soil bulk density and porosity provided information on the long term impact of agricultural land use on soil hydraulic properties. The study revealed a significant impact of agricultural land use on dry bulk density and porosity, as well as on hydraulic conductivity. These results show the importance of soil hydraulic conductivity and so must be taken into account in the mapping of soil hydraulic properties for hydrological modeling.

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