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PORE SIZE DISTRIBUTION AND SOIL HYDRO PHYSICAL PROPERTIES UNDER DIFFERENT TILLAGE PRACTICES AND COVER CROPS IN A TYPIC HAPLUSULT IN NORTHERN NIGERIA[†]

[DISTRIBUCIÓN DE TAMAÑO DE PORO Y PROPIEDADES HIDRO FÍSICAS DEL SUELO BAJO DIFERENTES PRÁCTICAS DE LABRANZA Y CULTIVOS DE COBERTURA EN UN HAPLUSULT TÍPICO EN EL NORTE NIGERIA]

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SUMMARY

Tillage practices influence soil physical, chemical and biological qualities which in-turn alters plant growth and crop yield. In the Northern Guinea Savanna (NGS) ecological zone of Nigeria, agricultural production is mainly constrained by low soil nutrient and water holding capacity, it is therefore, imperative to develop appropriate management practices that will give optimal soil hydro-physical properties for proper plant growth, effective soil and water management and environmental conservation. This study investigated the effect of three tillage practices (no till, reduced till and conventional till) and four cover crops (*Centrosema pascuorum*, *Macrotyloma uniflorum*, *Cucurbita maxima* and *Glyine max*) and a bare/control (no cover crop) on some soil physical properties of a Typic Haplusult during the rainy seasons of 2011, 2012 and 2013 in Samaru, NGS ecological zone of Nigeria. The field trials were laid out in a split plot arrangement with tillage practices in the main plots and cover crops in the subplots, all treatments were replicated three times. Auger and core soil samples were collected at the end of each cropping season each year in three replicates from each treatment plot at four depths (0-5, 5-10, 10-15 and 15-20 cm). Particle size distribution, bulk density, total pore volume and water retention at various soil matric potentials were determined using standard methods. Data obtained were compared with optimum values and fitted into a RETC computer code for quantifying soil hydraulic behavior and physical quality. Results showed that different tillage practices had varied effect on soil physical properties. No-till had the highest water holding capacity at most suction points evaluated, it had 4.3 % and 12.9 % more soil moisture than the reduced till and conventionally tilled systems across all matric potentials while *Centrosema pascuorum* (3.1%) and *Cucurbita maxima* (5.5%) were best among evaluated cover crops in retaining soil moisture content compared to the bare plots at -33kPa matric potential. Generally the Dexter S value used as an index for soil physical quality ranged within the limits of very good to good soil physical quality irrespective of the tillage practice, cover crops grown or depth of soil sampling. However the conventional tillage practice and soil under no cover crop had adverse effect on soil structural stability, placing them at a high risk of soil degradation. Indicators like Macro porosity, Air capacity, relative field capacity and Plant available water capacity were all within the optimal range for normal plant growth. The RETC computer code well described soil hydraulic parameter regardless of the treatments imposed on the soil.

Keywords: tillage; cover crop; soil physical properties; optimal values; soil pore volumes; RETC code

RESUMEN

Las prácticas de labranza influyen en las cualidades físicas, químicas y biológicas del suelo, que a su vez alteran el crecimiento de las plantas y el rendimiento de los cultivos. En la zona ecológica de la sabana de guinea al norte (NGS) de Nigeria, la producción agrícola está limitada principalmente por la baja capacidad de retención de nutrientes y agua del suelo, por lo que es imperativo desarrollar prácticas de manejo adecuadas que proporcionen propiedades hidrofísicas del suelo óptimas para un crecimiento adecuado de las plantas, gestión eficaz del suelo y del agua y la conservación del medio ambiente. Se investigó el efecto de tres prácticas de labranza (sin labranza, labranza reducida y convencional) y cuatro cultivos de cobertura (*Centrosema pascuorum*, *Macrotyloma uniflorum*,

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Cucurbita maxima y *Glyine max*) y un control sin cobertura, sobre algunas propiedades del suelo de un Haplusult típico durante las estaciones lluviosas de 2011, 2012 y 2013 en Samaru, zona ecológica NGS de Nigeria. Los ensayos de campo se presentaron en un arreglo de parcelas divididas con prácticas de labranza como parcelas principales y cultivos de cobertura en las subparcelas, todos los tratamientos se replicaron tres veces. Cada año se recolectaron las muestras de barrena y núcleo de suelo al final de cada temporada de cultivo en tres repeticiones de cada parcela por tratamiento a cuatro profundidades (0-5, 5-10, 10-15 y 15-20 cm). La distribución del tamaño de partícula, la densidad aparente, el volumen total de poros y la retención de agua en diversos potenciales matriciales del suelo se determinaron usando métodos estándar. Los datos obtenidos se compararon con valores óptimos y se ajustaron a un código informático RETC para cuantificar el comportamiento hidráulico del suelo y la calidad física. Los resultados mostraron que diferentes prácticas de labranza habían variado efecto en las propiedades físicas del suelo. La siembra directa tuvo la mayor capacidad de retención de agua en la mayoría de los puntos de succión evaluados, tuvo un 4.3% y un 12.9% más de humedad del suelo que el sistema de labranza reducido y convencionalmente cultivado en todos los potenciales matriciales, mientras que *Centrosema pascuorum* (3.1%) y *Cucurbita maxima* (5.5%) fueron mejores entre los cultivos de cobertura evaluados en retener humedad del suelo en comparación con las parcelas desnudas a -33 kPa de potencial matricial. En general, el valor de Dexter S utilizado como índice de calidad física del suelo variaba dentro de los límites de calidad física del suelo muy buena a buena, independientemente de la práctica de labranza, cultivos de cobertura o profundidad del muestreo del suelo. Sin embargo, la práctica de labranza convencional y el suelo sin cultivos de cobertura tuvieron efectos adversos sobre la estabilidad estructural del suelo, colocándolos en un alto riesgo de degradación del suelo. Indicadores como la macroporosidad, la capacidad de aire, la capacidad de campo relativa y la capacidad de agua disponible para la planta estaban dentro del rango óptimo para el crecimiento normal. El código informático RETC describe bien el parámetro hidráulico del suelo independientemente de los tratamientos impuestos al suelo.

Palabras clave: labranza; cultivo de cobertura; Propiedades físicas del suelo; Valores óptimos; Volúmenes de poros del suelo; Código RETC.

INTRODUCTION

Soil physical quality is a central concept for quantifying land degradation and developing appropriate management land use practices. The physical quality of agricultural soil refers primarily to the soil’s strength, fluid transmission and storage characteristics in the crop root zone, which should be good enough to permit the correct proportions of water, dissolved nutrients, and air for both maximum crop performance and minimum environmental degradation (Topp *et al*., 1997). Furthermore, soil should be firm enough to maintain good structure, crop anchorage, and resist erosion and compaction; but loose enough to allow unrestricted root growth and proliferation of soil flora and fauna, so as to sustain optimal crop production.

A soil with excellent physical quality should have indicator values which fall within the optimal ranges, or at least not beyond the critical limits, for maximized crop performance, and minimized soil and environmental degradation (Carter, 1988; Drewry *et al*., 2001, 2008; Arshad and Martin, 2002; Dexter, 2004 a,b,c; Reynolds *et al*., 2007, 2008; Mueller *et al*., 2008). However, critical soil parameters such as bulk density, hydraulic conductivity, relative field capacity, plant-available water capacity, air capacity, macro porosity, organic carbon content and structural stability index that quantify the level or degree of quality as well as the nature and influence of these physical properties on soil-plant atmosphere had been reported (Reynolds *et al*., 2008; 2009). These parameters directly or indirectly quantify the soil's strength and its ability to store and provide crop-essential water, air and nutrients (Topp *et al*., 1997; Reynolds *et al*., 2007).

Additionally, soil organic carbon content is known to be a critical parameter affecting virtually all aspects of soil physical qualities (Gregorich *et al*., 1997; Shukla *et al*., 2006).

Optimal crop root growth and function requires adequate soil air and water storage capacities, in addition to appropriate soil strength or density (Reynolds *et al*., 2009), substantial work over the last 40 years suggests that near-surface air-filled soil pore space (i.e. air capacity) should be at least 0.10–0.15 m^3 m^{-3} (Grable and Siemer, 1968; Cockroft and Olsson, 1997), while plant-available water capacity should be > 0.20 m^3 m^{-3} (Cockroft and Olsson, 1997), or within the range of 0.15–0.25 m^3 m^{-3} (Craul, 1999). Furthermore, Dexter (2004a,b,c) proposed the “S-value” indicator of soil physical/structural quality, which has been related to many important soil properties or conditions including hydraulic conductivity, compaction, optimal soil water content for tillage, penetration resistance, plant-available soil water, root growth, and soil structural stability (Gate *et al*., 2006; Dexter and Czyz, 2007; Dexter and Richard, 2009). A common feature among the aforementioned indicators is that they are all direct or indirect expressions of the volume of soil pore spaces. Sanchez (1940) reported that soil cultivation warrants deterioration of many soil physical properties, thus rendering the soil less permeable to water and air and therefore more susceptible to runoff and erosion losses. Aside environmental factors, inappropriate tillage practices aggravate soil erosion and structural deterioration this is particularly true in Northern Guinea Savanna of Nigeria (Lawal *et al*., 2009). In this region, the rain fall pattern is erratic and since most grown crops in this area are rain-fed, hence they are constrained by the ability of the underlying soils to retain moisture and supply same appropriately, due to the conventional tillage system that is widely adopted without proper residue management such that farmlands are left bare generally for substantial part of the year and in particular in early part of cropping season before the crop attains full canopy.

The conventional tillage practice used in crop production in this region involves ploughing harrowing and ridging prior to seed sowing, In addition, the soil is typically bare. These intensive and continuous soil cultivation practices have contributed to an exacerbation of soil organic carbon, water and nutrient losses and have resulted in degraded soils with low organic matter contents and a fragile physical structure (Lawal *et al*., 2009), which are aggravated by drought and soil erosion.

Tillage operations can modify the geometry of the pore spaces which consequently lead to temporal variation in the fragile nature of soil surface macropores, their ventedness and connectedness as well as the hydraulic character of tilled soil (Carter, 1988; Ogden *et al*., 1999). The estimation of soil hydraulic properties is a fundamental step for quantifying water and solute movement in the vadose zone (Ventrella *et al*., 2005). Hydraulic properties are the key parameters in any quantitative description of water flow into and through the unsaturated soil zones (van Genuchten *et al*., 1992). These properties are determined by the geometry of soil pore space. Understanding changes of soil hydraulic properties arising from land use, as well as adopting conservation tillage practices and cover crop type(s) that best sustain soil physical quality is important for applications in hydrology, soil water management and environmental conservation. However, most previous studies focused on the effects of land use on soil structural quality, but there exist a dearth of knowledge and literatures on the effect of tillage on soil pore size distribution and the appropriate type of cover crops that best suit soil hydraulic properties in Northern Guinea Savanna agro ecological zone of Nigeria.

The objectives of this study are therefore: (i) to investigate the applicability of RETC computer code for evaluating the effect of tillage and cover crops on soil hydraulic behavior and physical quality, (ii) to measure and compare selected soil physical quality parameters among the three tillage practices evaluated and selected cover crops. (iii) To compare some of the measured soil quality parameters with the optimal values.

MATERIALS AND METHODS

Experimental Site

The trials was conducted for three rainy seasons (2011 – 2013) and sited at the horticultural garden of the Institute for Agricultural Research Samaru, (11º10.416'N, 07º37.812'E, 700m above sea level) in the Northern Guinea Savanna agro-ecological zone of Nigeria. The soil type is Typic haplusult derived from pre-Cambrian crystalline basement complex rocks with some quaternary aeolian deposits (Shobayo *et al.*, 2015). Samaru is characterized by a mono modal rainfall pattern with a long term mean annual rainfall of about 1011 ± 16 1mm, which spreads from March/April to October with the highest concentration in the three months of July to September. Samaru has long-term mean minimum and maximum temperatures of 21.1^0C and 33.5^0C respectively and relative humidity of 55.23% (Oluwasemire and Alabi, 2004).

Treatments and Experimental Design

The treatments consisted of three (3) tillage practices namely; No - tillage (NT), this involved no soil disturbance except dibbling or drilling for sowing holes; Reduced tillage (RT), here field was harrowed once and crops planted, and the Conventional tillage (CT), which involved ploughing, harrowing and ridging. Four (4) cover crops namely: *Centrosema pascuorum, Macrotyloma uniflorum, Glycine max, Cucurbita maxima* and no cover crop (bare) as control/ check. The trial was laid out in a split plot design and replicated three times; tillage practices and cover crops were allocated to the main and subplots respectively. Tillage operations were carried out using a tractor-drawn disc plough, disc harrow and disc ridger as per treatment.

Soil sampling and analysis

Disturbed augered and undisturbed core cylinders (98.125 cm^3 volume) soil samples were collected at depth 0-15 cm prior to trial establishment from each of the 45 treatment plots for characterization of soils the study area. The disturbed augered samples, after air drying and passing through 2 mm sieve, were used for determination of particle size distribution by the

Bouyoucos hydrometer (Gee and Orr, 2002), soil reaction (pH) in water and $CaCl_2$ (Rhoades, 1982), organic carbon by the dichromate wet oxidation method, (Nelson and Sommers, 1982), total nitrogen by the Kjeldahl digestion method (Bremner, 1982) available P by Bray No. 1 acid fluoride method (Bray and Kurtz, 1945) and exchangeable bases (Anderson and Ingram, 1993). Bulk density was determined by the core method (Grossman and Reinsch, 2002).

Undisturbed cylindrical core (height = 5 cm and diameter = 5 cm and volume = 98.125 cm^3) soil samples were collected from the three replicates of each treatment plot at four depths (0-5 cm, 5-10 cm, 10-15cm and 15-20 c m) at the end of each cropping season making a total number of 180 samples at the end of each year's trials. These samples were taken at maize maturity but prior to its harvest in September 25th 23rd and 27th of 2011, 2012 and 2013 respectively and were used to determine the following soil hydro physical properties.

Total pore volume

Total pore volume of the soil samples was determined as the volume of the total pores holding water at saturation (0 kPa) thus;

Total pore volume = $\frac{(Ms-Md)}{Md}\ x\ (\frac{BD}{ew})$

Where: Ms = mass of soil at saturation, Md = mass of oven dry soil, BD = bulk density and ew =0.998 g cm^{-3}density of water at 20ºC

Soil moisture retention and soil physical quality indicators

Soil moisture retention characteristics were determined on the core soil samples using a pressure plate membrane. Volumetric soil moisture content at suctions point of 0, -10, -33, -100, -500,-1000 and -1500 kPa, which represents saturation, near field capacity (NFC), field capacity (FC), above field capacity (AFC), far near permanent wilting point (FNPWP), near permanent wilting point (NPWP) and permanent wilting point (PWP). The RETC (retention curve version 6.02) computer code developed by van Genuchten *et al*. (2005-2009) for quantifying hydraulic functions of unsaturated soil was used to fit the data obtained to solve van Genuchten's (1980) water retention model presented in the two equations below (for water content and slope of the water retention curves at the inflection point).

Rosetta program, was used to obtain the closed form expressions of van Genuchten parameters (θs, θr, α and n) from the values of particle size distribution, soil bulk density and volumetric soil water contents at -33 and -1500 kPa (Schaap *et al*., 1998). Output data of Rosetta program were used in RETC as input data alongside the determined values of soil water retention. Output file of RETC run, which include measured and fitted relationships among pF matric potential (hPa) and soil water content (m^3 m^{-3}) was converted to ''Excel'' file (Microsoft Office Excel, 2007) for statistical analysis.

Water content at the inflection point (θINFL)

It was calculated from the parameters of the fitted van Genuchten equation using the equation of Dexter and Bird (2001):

$$\theta\mathrm{INFL} = (\theta\mathrm{s} - \theta\mathrm{r})\left[1+\frac{1}{\mathrm{m}}\right]^{-\mathrm{m}} + \theta\mathrm{r}$$

where: θs = saturated soil water content, θr = residual soil water content and m = 1- (1/n)

Slope of the water retention curves at the inflection point

The slope of the water retention curves at the inflection point, (S) considered as soil physical quality index, was calculated according to Dexter (2004a,b,c) "S-value", represents the magnitude of the slope of the soil water release or desorption curve at the inflection point when the curve is expressed as gravimetric water content, θg (kg kg^{-1}), versus natural logarithm of pore water tension head, ln(hi) (hPa, h≥0).

$$\boldsymbol{s} = \frac{\boldsymbol{d}(\boldsymbol{\theta}\mathbf{gi})}{\boldsymbol{d}(\boldsymbol{lnhi})} = -n(\theta\mathrm{gs} - \theta\mathrm{gr})\left[1+\frac{1}{\mathrm{m}}\right]^{\mathbf{(-m+1)}}$$

Where: θg (kg kg^{-1}) is gravimetric water content, θgs (kg kg^{-1}) is the saturated gravimetric water content, θgr (kg kg^{-1}) is the residual gravimetric water content, n (−) and m (−) are empirical curve-fitting parameters, with m =1- (1/n) in the above equation to release curve data using nonlinear least squares optimization (RETC, 2008).
Also Where:

$$\theta\mathrm{gi} = (\theta\mathrm{gs} - \theta\mathrm{gr})\left[1+\frac{1}{\mathrm{m}}\right]^{\mathbf{(-m+1)}}$$

and $hi = \frac{\boldsymbol{1}}{\boldsymbol{\alpha}}(\frac{1}{\mathrm{m}})^{\frac{1}{\mathrm{n}}}$

are the gravimetric water content and tension head, respectively, at the inflection point. The S, θgi and hi values for a measured water release curve are consequently provided after n, m, α, θgs and θgr are determined by fitting the release curve data (Dexter 2004b).

For both temperate and tropical soils, an S value ≥ 0.050 indicates "very good" soil physical or structural quality, while $0.035 \leq S < 0.050$ is "good physical quality", $0.020 \leq S < 0.035$ is "poor physical quality", and $S < 0.020$ is "very poor" or "degraded" physical quality (Dexter, 2004c; Dexter and Czyz, 2007; Tormena *et al*., 2008). The theoretical limits of S are $0 \leq S < \infty$, however, agricultural soils tend to fall within the range $0.007 \leq S \leq 0.14$ (Dexter and Czyz, 2007).

Air capacity

Air capacity, AC (m^3m^{-3}), of undisturbed field soil was calculated as (White, 2006):

$$AC = \theta S(\Psi = 0) - \theta FC\ (\Psi = -1m); \quad 0 \leq AC \leq \theta S$$

Where:
θS (m^3m^{-3}) is the saturated soil water content, θFC (m^3m^{-3}) is the field capacity (gravity drained) water content, and $\Psi(m)$ is pore water pressure head.

Plant-available water capacity

Plant-available water capacity, PAWC (m^3m^{-3}), indicates the soil's ability to store and provide water that is available to plant roots (White, 2006). Plant available water was calculated as the difference in moisture content between field capacity and permanent wilting point thus;

$$PAWC = \theta FC\ (\Psi = -1m) - \theta PWP\ (\Psi = -150m); \quad 0 \leq PAWC \leq \theta FC$$

Where:
θPWP (m^3m^{-3}) is the water content at permanent wilting point.

Relative field capacity

Relative field capacity, RFC (dimensionless), is defined by (Reynolds *et al*., 2008):

$$RFC = \left(\frac{\theta FC}{\theta S}\right) = \left[1 - \left(\frac{AC}{\theta S}\right)\right]: \quad 0 \leq RFC \leq 1$$

and it indicates the soil's ability to store water and air relative to the soil's total pore volume (θS). For rain-fed agriculture on mineral soils, the optimal balance between root-zone soil water capacity and soil air capacity occurs when $0.6 \leq RFC \leq 0.7$, as this range maximizes microbial production of nitrate which is usually the limiting nutrient for crop growth and yield (Doran *et al*., 1990) especially in tropical soils (Jones and Wild, 1975).

Macro porosity

Macro porosity, PMAC (m^3m^{-3}), was determined as defined by Jarvis *et al*. (2002); Dexter and Czyz (2007); Reynolds *et al*. (2008) and Dexter *et al*. (2008):

$$PMAC = \theta S(\Psi = 0) - \theta m(\Psi = -0.1m); \quad 0 \leq PMAC \leq \theta S$$

Where:
θm (m^3m^{-3}) is the "saturated" volumetric water content of the soil matrix. The PMAC parameter gives the volume of large (macro) pores (i.e.>0.3 mm equivalent pore diameter), which indirectly indicates the soil's ability to quickly drain excess water and facilitate root proliferation (Reynolds *et al.*, 2009).

PMAC ≥ 0.05–0.10 m^3m^{-3} is considered optimal, while PMAC ≤ 0.04 m^3m^{-3} has been found in soils degraded by compaction (Carter, 1988; Drewry *et al*., 2001; Drewry and Parton, 2005). However, PMAC ≥ 0.07 m^3m^{-3} and PMAC = 0.04 m^3m^{-3} represent the "optimal range" and "lower critical limit", respectively (Reynolds *et al.*, 2009).

Structural stability index (SI)

It is an index for assessing the risk of structural degradation in cultivated soils (Pieri, 1992)

$$SI(\%) = \frac{1.724OC}{(silt + clay)}\ x\ 100; \quad 0 \leq SI < \infty$$

Where:
OC (wt. %) is soil organic carbon content and (Silt + Clay) (wt. %) is the soil's combined silt and clay content.

An SI >9% indicates stable structure, 7%<SI≤9% indicates low risk of structural degradation, 5% SI≤7% indicates high risk of degradation, and SI≤5% indicates structurally degraded soil (Reynolds *et al.*, 2009).

Soil pore size distribution

Soil pore size distribution data was obtained from the predicted soil water retention data using the theoretical relation between soil water characteristic and distribution of pore sizes (Vomocil, 1965). It was determined for matric potential ranges of -0.0075 to -6.3 kPa defining range of distribution of pores draining quickly permeating gravitational water; -6.3 to -33 kPa, being range of matric potential where pores draining slowly permeating gravitational water as well as water in the large capillaries occur; -33 to -100 kPa, as range of distribution of pores draining capillary water easily accessible for plants exist; -100 to -1500 kPa considered as range of distribution of pores draining capillary water accessible to plants with difficulty and above -1500 kPa being range of distribution of pores draining water not useful for plants.

Equivalent pore diameter (EPD) of a given matric potentials was determined using the capillary rise equation (Warrick, 2002) according to the following expression that relates the suction applied to a water column as a function of the capillary radii

$$EPD = \frac{4\gamma \cos\alpha}{\rho W g h} \approx \frac{2980}{h}$$

Where:
$\gamma = 72.8$ gm s^{-2} is pore water surface tension, $\rho W = 0.998$ gm cm^{-3} is water density, g = 980 cm s^{-2} is gravitational acceleration, and $\alpha \approx 0$ is the water-pore contact angle.

The equivalent pore diameter (EPD) of the smallest pore (mm) drained at matric potential of h (kPa). Pore size distribution was presented as percent pore volume of the total porosity occurring within a given range of matric potential.

Data analysis

All data collected in this study were subjected to statistical analysis of variance (ANOVA) as described by Snedecor and Cochran (1967). Using the SAS computer package (SAS, 2008) and differences among the treatment means were evaluated using Duncan Multiple Range Test (DMRT) (Duncan, 1955).

RESULTS

Characterization of Soil of the Study Area

The physical and chemical properties of soil of the study area are presented in Table 1. The soil is generally loam (L) in texture with moderately acidic soil reaction, moderate organic carbon, bulk density and infiltration rate; but poor in total nitrogen. It has very low available phosphorus, exchangeable calcium and cation exchange capacity. While exchangeable magnesium, potassium and Sodium are generally low.

Effect of tillage, cover crop and soil depth on soil moisture retention

Effect of tillage, cover crop and soil depth on soil moisture retention during the 2011 cropping season is presented in Figure 1. No-till consistently had significantly higher / better soil moisture retention at all suction point relative to RT and CT plots.

The different cover crops evaluated had no significant influence on the amount of moisture retained in soil at all the suction points evaluated. The surface soil (0-5cm) retained significantly more moisture than other soil depths all through the suction points from 0kPa (saturation) to -1500kPa (permanent wilting coefficient) except at -500kPa where depth 5-10cm had statistically similar soil moisture content as the top soil.

Table 1: Physical and chemical properties at soil depth of 0-15cm of the experimental site.

Soil property	**Mean values across 45 plots**	% CV
Sand (g kg^{-1})	431.11	5.93
Silt (g kg^{-1})	425.77	6.89
Clay (g kg^{-1})	143.11	14.09
Texture	Loam	-
pH (water)	6.3	1.56
pH ($CaCl_2$)	5.4	2.55
Organic carbon (g kg^{-1})	10.17	20.32
Total nitrogen (g kg^{-1})	0.72	19.41
Available P (mg kg^{-1})	2.56	24.33
Calcium (cmol kg^{-1})	1.96	32.05
Magnesium(cmol kg^{-1})	1.03	33.25
Potassium (cmol kg^{-1})	0.24	37.30
Sodium (c mol kg^{-1})	0.1	51.47
Cation exchange capacity (c mol kg^{-1})	4.3	22.34
Infiltration rate (mm hr^{-1})	54.9	
Bulk density (Mg m^{-3}) at 21.66% gravimetric moisture	1.47	7.68

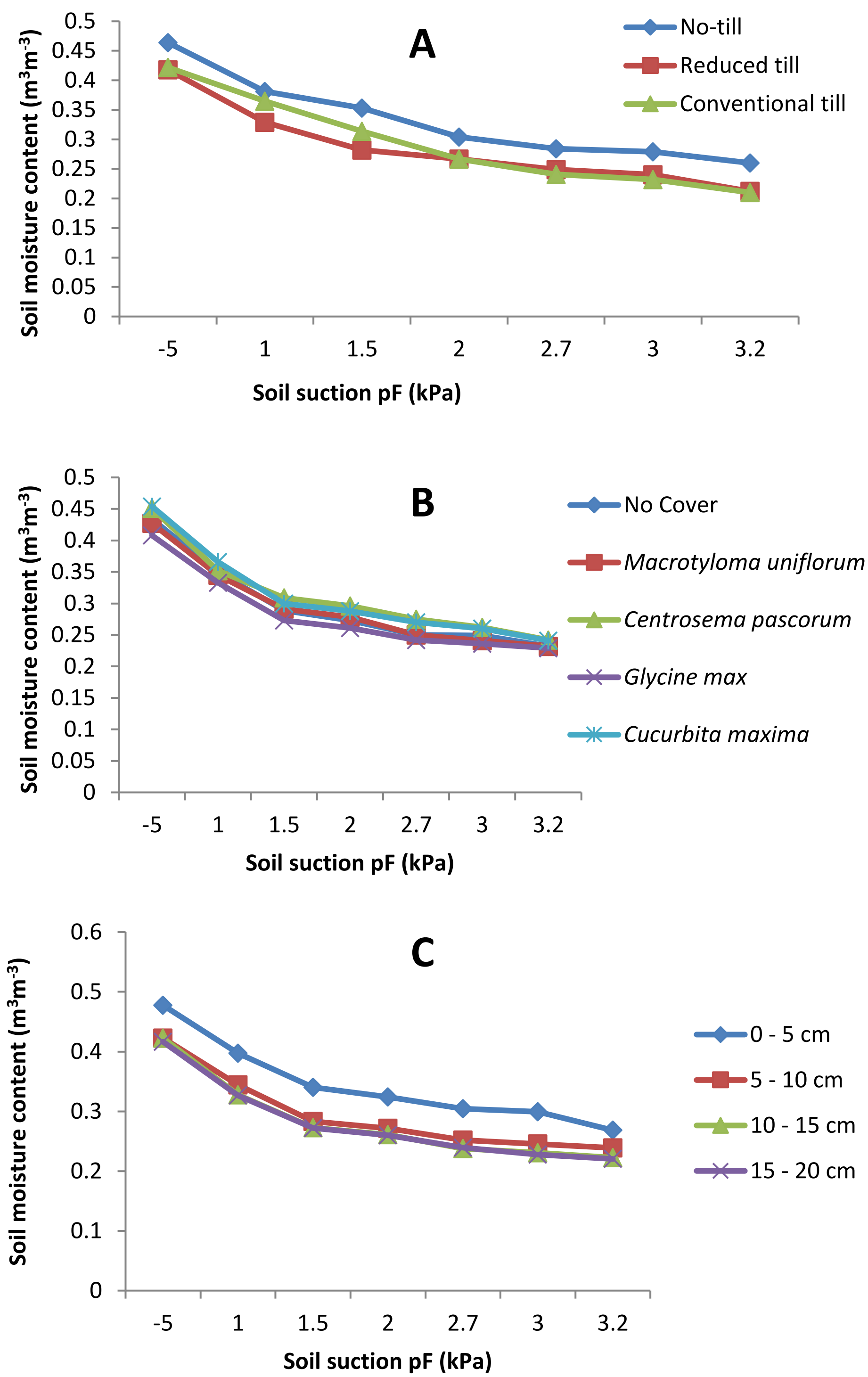


Figure. 1: Effect of Tillage (A), cover crop (B) and sampling depth (C) on soil moisture retention (m^3m^{-3}) during the 2011 cropping season at Samaru, Nigeria.

Tillage cover crop and sampling depth effect on soil moisture retention during the 2012 cropping season at Samaru is presented in Figure 2. No-till retained significantly more (5.91%) soil moisture at saturation (0kPa) relative to RT and conventionally tilled soil. However, moisture retained at -10kPa and other suction points between field capacity (-33kPa) and permanent wilting coefficient (-1500kPa) were not significantly influenced by tillage practices.

Soils with *Centrosema pascuorum* as cover crop significantly retained more (5 - 9 %) moisture at the different suction points evaluated relative to soils grown to other cover crops and the no cover crop plot, except at suctions -33 and -1000kPa under which the different cover crops grown did not significantly influence the amount of water retained in the soil. The surface soils (0-5cm) had significantly higher soil moisture retention at the different suction points relative to other soil depths. Soil moisture content however decreased (6 – 14 %) with increase in sampling depth except at suction of -1000 kPa where no significant difference was observed in moisture in moisture retained at different soil depths sampled.

Tillage and cover crop had no significant effect on soil moisture retained at the different suctions except at 0kPa and -10kPa under which no-till soils had higher soil moisture than the RT and CT soils during 2013 cropping season (Figure 3). Similarly, at suction of -500kPa soil under *Centrosema pascuorum* and *Cucurbita maxima* retained significantly higher (3 – 6 %) soil moisture relative to other cover crops (M*acrotyloma uniflorum* and *Glycine max*) treated soil and the bare soil (with no cover crop)

Moisture retained at the different suctions decreased (10 -17 %) significantly with increase in sampling depth. The surface soil (0-5cm) retained significantly more moisture than other sampled depths except at suction point -1000kPa, where soil sampling depths did not significantly influence amount of soil moisture stored.

Effect of tillage, cover crops and soil depth on fitted values of van Genuchten parameters

The effect of tillage, cover crops and soil depth on fitted values of van Genuchten parameters is presented in Table 2. Generally no significant difference was observed among the means of the predicted empirical parameters as a result of variation in tillage practices, growing of cover crops and soil depth, except in Mualem constraint (m values) and saturated hydraulic conductivity values where variation in the sampling depth showed that depth 0-5 and 5-10 cm conducted water better at soil saturation relative to depths 10-15 and 15-20 cm.

Effect of tillage, cover crop and soil sampling depth on soil physical characteristics

The effect of tillage cover crop and soil sampling depth on some soil physical indicators is presented in Table 3. Generally the tillage practices and cover crop treatment did not significantly influence all the soil physical quality indicators calculated but the structural stability index (SI), where the order of soil stability was NT>RT>CT.

Soils under *Centrosema pascuorum* as cover, offered significantly best structural stability; it was followed by soils under the other three cover crops (*Macrotyloma uniflorum, Glycine max and Cucurbita maxima*) that displayed similar influence on soil structural stability while, soils with no cover crop was the least stable.

Variation due to soil sampling depth also did not significantly influence soil physical indicators like S value, macro porosity (PMAC) and air capacity (AC) but significantly influenced structural stability index, relative field capacity (RFC) and plant available water capacity(PAWC). The top most soil (0-5 cm) offered significantly higher SI, RFC and PAWC, relative to the other soil depths sampled.

The effect of tillage, cover crops and soil sampling depth on percent soil pore volume distribution

The effect of tillage, cover crops and soil sampling depth on percent soil pore volume distribution is presented in Table 4. Generally variation in the tillage practices imposed, cover crops grown and depth of soil sampling did not significant influence the percentage volumes of various pore size classes viz -0.0075 to -6.3 (holding quickly permeating gravitational water),

-6.3 to -33 (slowly permeating gravitational water), -33 to -100 (accessible water to plants), -100 to -1500kPa (water accessible with difficulty) ranges of matric potential and above -1500kPa (holding water not available to plants), Except in the percentage of residual pore volume at above -1500kPa (holding water not available to plants), where the top soil (0 – 5 cm) possessed significantly higher percent pore volume relative to the other sampling depth, which were not statistically different in volume of pores.

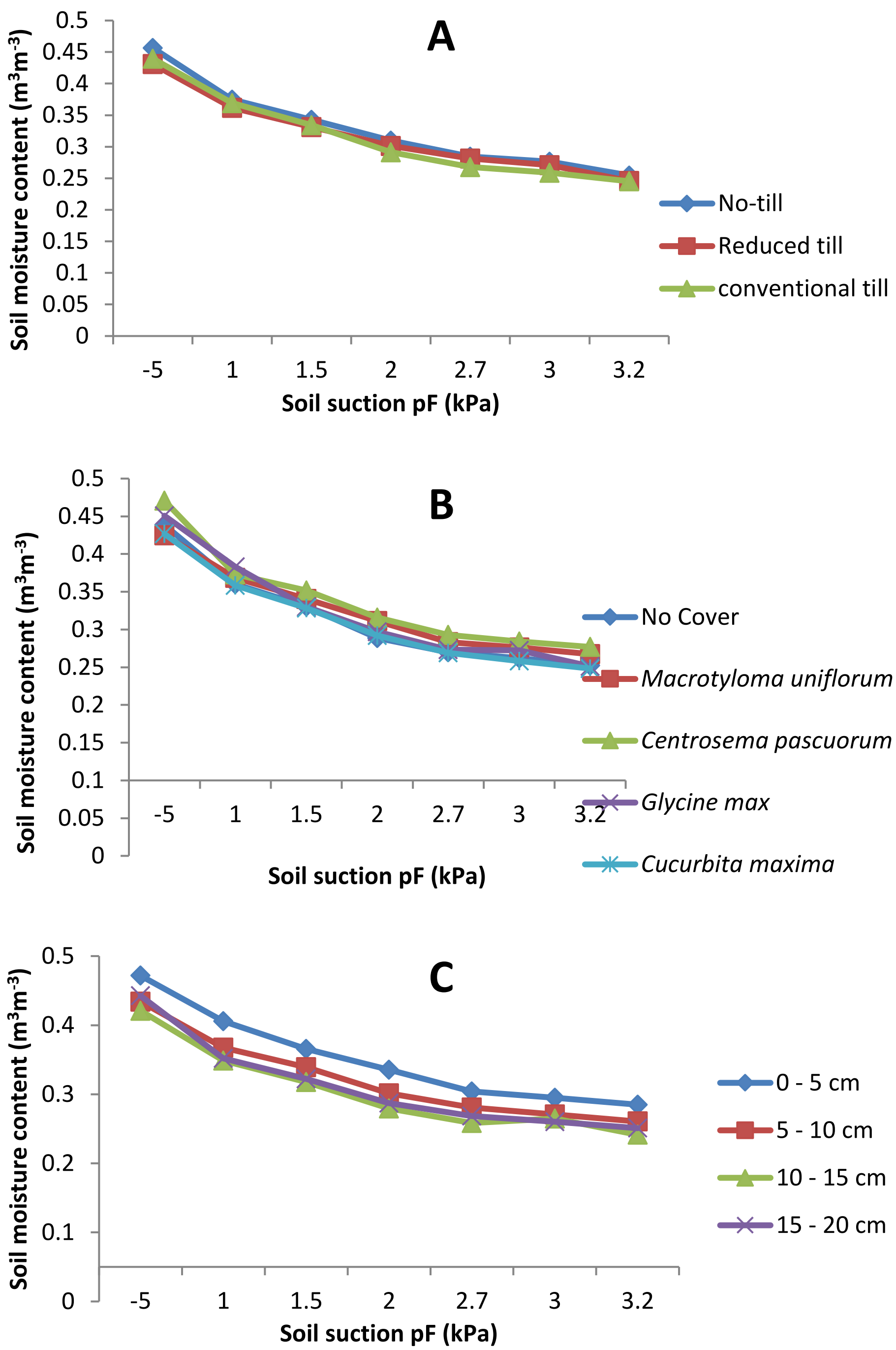
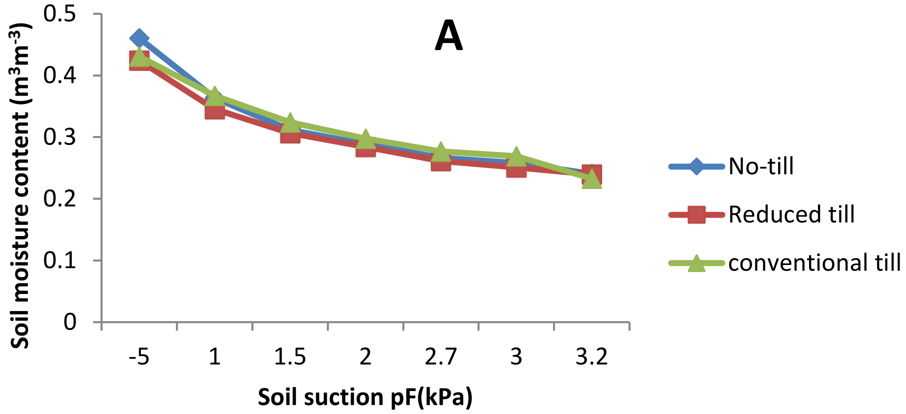
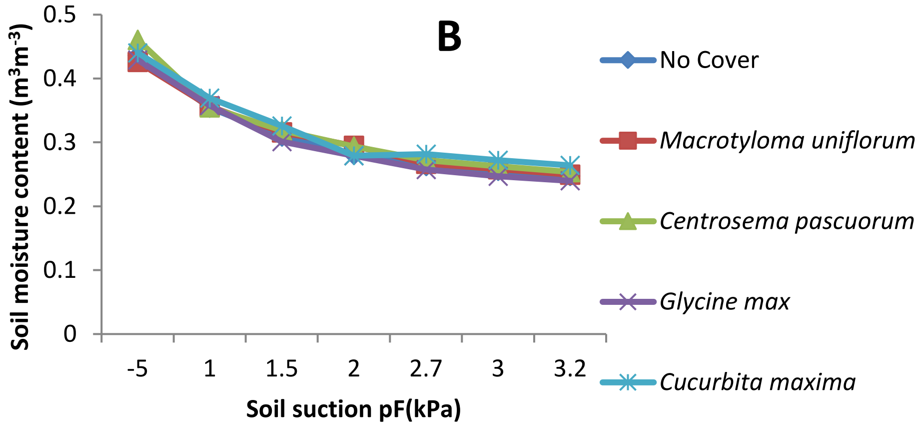


Figure. 2: Effect of Tillage (A), cover crop (B) and sampling depth (C) on soil moisture retention (m^3m^{-3}) during the 2012 cropping season at Samaru, Nigeria.





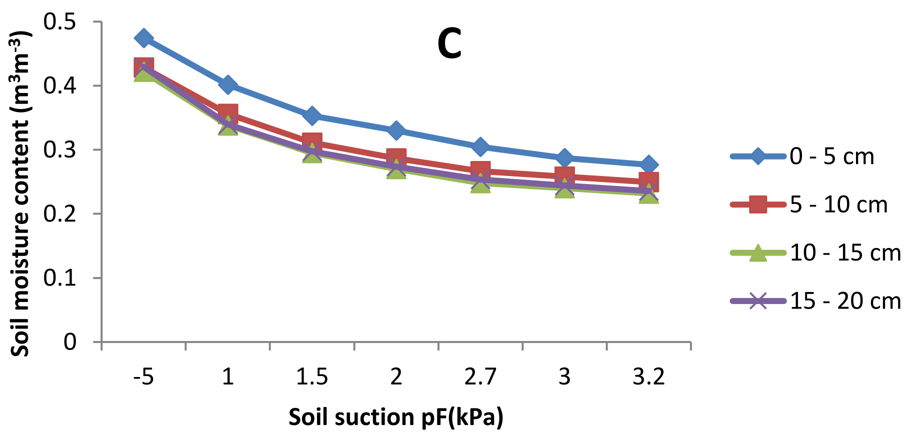


Figure. 3: Effect of Tillage (A), cover crop (B) and sampling depth (C) on soil moisture retention (m^3m^{-3}) during the 2013 cropping season at Samaru, Nigeria.

The effect of tillage, cover crops and soil sampling depth on percent equivalent pore diameter

Table 5 shows the effect of tillage, cover crops and soil sampling depth on percent equivalent pore diameter (EPD). Analysis of variance revealed no significant difference was observed among the means of equivalent pore diameter as regards variation in tillage, cover crops and soil sampling depth except for the residual pores holding water at >-1500 kPa which had significantly higher percentage (5 times more) of EPD at top soil depth (0-5 cm) relative to the other soil depth sampled.

DISCUSSION

In NT, the non disturbance of soil encourages stable soil aggregates and protects stable organic matter (OM) from microbial decomposition; consequently, this increase soil moisture holding capacity thus ensuring more water is retained within soil for cultivated crop use, especially in the relatively dry Northern Guinea Savanna of Nigeria where the trial was conducted. Higher soil moisture content observed in NT conforms to the findings of Hill *et al*. (1985), Chang and Lindwall (1989), Hammel (1989) Brandt (1992) and Abu and Abubakar (2013). Although, tillage did not significantly influence soil moisture retention in 2012 and 2013, nevertheless, NT still retained higher amount of soil moisture. Similarly, in 2011 NT was consistent in retaining higher soil moisture, at all suction points evaluated except at field capacity (-33kPa). Lower soil moisture retained in conventionally tilled soil can be attributed to higher disruption of soil pores and aggregate as a result of raindrop impacts on tilled soils. This condition becomes more severe under intense rains resulting in clay dispersion in aggregates that may end up clogging soil pores and creating a surface sealing which may increase run off and erosion and reduce infiltration and consequently reduce water stored in soil.

Table 2: Effect of tillage, cover crops and soil sampling depth on fitted values of van Genuchten parameters (mean across 2011, 2012 & 2013 cropping seasons) in a Typic haplusult at Samaru, Northern Nigeria

Treatments	θr ($m^3 m^{-3}$)	θs ($m^3\ m^{-3}$)	a	n	m	Ks (cm day^{-1})	θinflec (kg kg^{-1})	r^2
Tillage (T)								
No till (NT)	0.1091	0.4602	0.0407	1.269	0.21	39.32	0.4176	0.9768
Reduced (RT)	0.1167	0.461	0.0494	1.311	0.237	39.27	0.3819	0.9902
Conventional (CT)	0.1079	0.4539	0.0427	1.282	0.219	42.92	0.3991	0.9982
SE ±	0.01071	0.01803	0.00549	0.0275	0.0172	3.873	0.01424	0.01419
Significance	NS	NS	NS	NS	NS	NS	NS	NS
Cover Crops (C)								
No Cover	0.1181	0.4172	0.0482	1.315	0.239ab	34.4	0.3834	0.9969
Macrotyloma uniflorum	0.1172	0.4277	0.0496	1.296	0.228ab	44.3	0.3914	0.9975
Centrosema pascuorum	0.1172	0.4216	0.05093	1.278	0.217b	31.41	0.3848	0.9978
Glycine max	0.1257	0.4294	0.0498	1.362	0.264a	54.66	0.3987	0.9879
Cucurbita maxima	0.1311	0.4391	0.0499	1.331	0.2475ab	44.97	0.4055	0.9944
SE ±	0.00827	0.00925	0.00131	0.02382	0.01337	7.215	0.01038	0.00403
Significance	NS	NS	NS	NS	*	NS	NS	NS
Depth, D (cm)								
0-5	0.1193	0.4406a	0.0494	1.247b	0.1976b	25.35a	0.4000	0.987
5-10	0.1238	0.4212ab	0.0494	1.333a	0.2477a	39.04a	0.3888	0.9965
10-15	0.1058	0.3977b	0.0477	1.300ab	0.2305a	20.03b	0.3636	0.994
15-20	0.1193	0.3970b	0.0486	1.297ab	0.2288a	23.71b	0.3636	0.9968
SE ±	0.00522	0.01079	0.00096	0.0163	0.0085	3.734	0.00974	0.00613
Significance	NS	*	NS	*	**	**	NS	NS

Means with the same letters within the same column are not statistically different at 0.05 probability level, SE = standard error, NS = not significant,* = significant at $p \leq 0.05$, ** = significant at $p \leq 0.01$
θinflec = water content at inflection point, Ks = saturated hydraulic conductivity, θr & θs = residual and saturated moisture content respectively, m = mualem constraint (1-1/n) and r^2 = r^2 value between observed and fitted soil moisture content..

Table 3: Effect of tillage, cover crops and soil sampling depth on soil physical characteristics (mean across 2011, 2012 & 2013 cropping seasons) in a Typic haplusult at Samaru, Northern Nigeria

Treatments	S-value (-)	SI (%)	PMAC ($m^3 m^{-3}$)	RFC ($m^3 m^{-3}$)	AC ($m^3 m^{-3}$)	PAWC ($m^3 m^{-3}$)
Tillage (T)						
No till (NT)	0.0523	7.28 a	0.0966	0.6823	0.146	0.225
Reduced (RT)	0.0521	7.05 b	0.0707	0.6902	0.1295	0.1899
Conventional (CT)	0.0506	5.12 c	0.0715	0.6961	0.1344	0.2164
SE ±	0.00074	$1x10^{-8}$	0.01793	0.01758	0.0106	0.01913
Significance	NS	**	NS	NS	NS	NS
Cover Crops (C)						
No Cover	0.0505	6.65c	0.0627	0.6942ab	0.1277ab	0.1914ab
Macrotyloma uniflorum	0.0511	7.03b	0.0711	0.6936ab	0.1321ab	0.1985ab
Centrosema pascuorum	0.0476	7.78a	0.0616	0.7292a	0.1151b	0.2093a
Glycine max	0.0564	7.13b	0.0715	0.6559b	0.1481a	0.1767b
Cucurbita maxima	0.0538	7.09b	0.084	0.6788ab	0.1410ab	0.1870ab
SE ±	0.00256	0.047	0.0106	0.01624	0.00899	0.00796
Significance	NS	**	NS	*	*	*
Depth (cm) D						
0-5	0.0461	6.09a	0.039	0.793a	0.0916	0.2497a
5-10	0.0518	5.79b	0.065	0.691b	0.1301	0.1901b
10-15	0.0481	5.31c	0.059	0.694b	0.1218	0.1889b
15-20	0.0474	4.55c	0.058	0.698b	0.1202	0.1873b
SE ±	0.00158	0.116	0.0104	0.0226	0.01166	0.00871
Significance	NS	**	NS	*	NS	*
Optimal range	**>0.035**	>7	**>0.07**	**0.6-0.7**	**>0.14**	**>0.15**

Means with the same letters within the same column are not statistically different at 0.05 probability level
SE = standard error, NS = not significant, * = significant at $p \leq 0.05$, ** = significant at $p \leq 0.01$
RFC = relative field capacity; PAWC = plant-available water capacity; AC = air capacity; PMAC = macro porosity; SI = structural stability index; S-value = inflection point slope of gravimetric soil water release curve.

The higher moisture retained in soils under *Centrosema pascuorum* and *Cucurbita maxima* as cover crops could be attributable to the wider and overlapping nature of the leaves of *Cucurbita maxima* and the near 100% ground cover in *Centrosema pascuorum* that served as barrier to intercept impact of rain drop and allow more water to infiltrate and be stored since soil texture for the various plots was same. In bare plots with no cover crops, impact of raindrops probably trigger crusting and surface sealing with wet-dry events consequently, inhibiting water infiltration and facilitating erosion at the expense of soil moisture retention. Liu *et al.* (2013) reported decreased bulk density and increases soil porosity in mulched soils due to higher soil moisture retention. Other studies reported that keeping soil covered with straw promotes the activity of soil microorganisms and formation of a well structured soil aggregate, that resulted in increasing the soil water content (Liu *et al.*, 2011; Siczek and Lipiec, 2011; Siczek and Frac, 2012).

The higher organic matter content at the surface or top soil (0 – 5cm) must have influenced higher moisture storage at this depth. This is because top soil is richer in organic matter derived from plant residues. Organic matter behaves somewhat like a sponge, it could absorbs and hold up to 90% of its weight in water (USDA – WRCS, 2013) however; OM releases the entire water it holds for use by plants, in contrast to clay that holds great quantities of water but much of it is unavailable for plant use (USDA – WRCS, 2013).

Table 4: Tillage, cover crop and soil sampling depth effect on percentage pore volume distribution (during the 2011, 2012 and 2013 cropping season)in a Typic haplusult at Samaru, Northern Nigeria.

	Pore volumes (%)				
	Transmission		Storage		Residual
Treatments	0 to -6.3 kpa	-6.3 to -33 kpa	-33 to -100 kpa	-100 to -1500 kpa	>-1500 kpa
Tillage (T)					
No till (NT)	38.02	21.83	8.83	13.72	17.6
Reduced (RT)	38.42	22.54	9.55	13.22	16.55
Conventional (CT)	30.42	32.28	14.19	15.9	7.89
SE ±	3.811	4.208	1.308	1.279	7.128
Significance	NS	NS	NS	NS	NS
Cover Crops (C)					
No Cover	39.14	31.89	10.87	11.99	6.10bc
Macrotyloma uniflorum	34.21	24.74	11.65	13.6	15.80a
Centrosema pascorum	44.81	20.54	8.95	12.97	12.74ab
Glycine max	37.18	39.06	12.05	9.49	2.59c
Cucurbita maxima	40.09	26.93	10.71	12.09	10.15ab
SE ±	2.659	3.777	0.797	1.208	1.995
Significance	NS	NS	NS	NS	NS
Depth, D (cm)					
0-5	30.95	26.76	11.07	16.49	14.72a
5.-10	36.38	30.93	11.67	12.32	8.71b
10.-15	42.21	27.81	11.29	12.19	7.20b
15-20	43.14	25.96	9.94	12.38	8.61b
SE ±	1.194	2.668	0.581	3.213	1.386
Significance	NS	NS	NS	NS	*
Interactions					
T x C	NS	NS	NS	NS	NS
T x D	NS	NS	NS	NS	NS
D x C	NS	NS	NS	NS	NS
T x D x C	NS	NS	NS	NS	NS

Means with the same letters are not statistically different at 0.05 probability level SE = standard error NS = not significant * = significant at $p \leq 0.05$ ** = significant at $p \leq 0.01$

Significantly higher soil hydraulic conductivity at sampling depths of 0-5 and 5-10 cm is attributable to better soil aggregation and structurally stability at these depths.

The non-significant differences observed in residual and saturated soil moisture content (θr and θs respectively) and the moisture content at the inflection point of the plot of gravimetric water content, θg (kg kg^{-1}), versus natural logarithm of pore water tension head, can be attributed to identical distribution of pore sizes in soils of the study area, irrespective of tillage practice adopted, kind of cover crops grown or soil sampling depth. In addition, the non-significant difference in the values of n factor among these treatments indicates that not much difference in the capillary region for this soil. Also, similarities in the values of n factor, means that soil water release curves followed identical patterns irrespective of the treatments imposed. Value of α factor which is related to air entry region is generally small, indicating that the air entry region in this soil is broad; this is similar to the postulations of Ogunwole *et al*. (2015).

Table 5: Tillage, cover crop and soil sampling depth effect on percentage equivalent pore diameter distribution in a Typic haplusult at Samaru, Northern Nigeria.

	Equivalent pore diameter (%)				
	Transmission pores		**Storage pores**		**Residual pores**
Treatments	0 to -6.3 Kpa	-6.3 to -33 Kpa	-33 to -100 Kpa	-100 to -1500 Kpa	>-1500 Kpa
Tillage (T)					
No till (NT)	96.88	2.73	0.2827	0.0977	0.0031
Reduced (RT)	96.78	2.81	0.2977	0.0968	0.0035
Conventional (CT)	92.01	7.1	0.8767	0.244	0.0043
SE ±	1.476	1.383	0.17528	0.0507	0.00128
Significance	NS	NS	NS	NS	NS
Cover Crops (C)					
No Cover	94.55	4.87	0.4529	0.1224	0.0019
Macrotyloma uniflorum	95.41	3.97	0.481	0.0925	0.0556
Centrosema pascuorum	97.06	2.55	0.2884	0.0942	0.0028
Glycine max	94.19	5.35	0.4495	0.0866	0.0006
Cucurbita maxima	95.47	4.02	0.4203	0.1081	0.003
SE ±	0.885	0.811	0.07061	0.02206	0.02297
Significance	NS	NS	NS	NS	NS
Depth, D (cm)					
0-5	95.01	4.45	0.4424	0.048	0.0908a
5-10	95.92	3.59	0.3375	0.076	0.0024b
10-15	64.43	2.65	0.264	0.068	0.0018b
15-20	93.93	3.59	0.4716	0.048	0.0014b
SE ±	15.826	1.623	0.127	1.5667	0.0235
Significance	NS	NS	NS	NS	*
Interactions					
T x C	NS	NS	NS	NS	NS
T x D	NS	NS	NS	NS	NS
D x C	NS	NS	NS	NS	NS
T x D x C	NS	NS	NS	NS	NS

Means with the same letters are not statistically different at 0.05 probability level SE = standard error NS = not significant * = significant at $p \leq 0.05$ ** = significant at $p \leq 0.01$

The R Squared (r^2) values, for regression of observed vs fitted values of soil moisture content at the different pressure heads considered, indicated a very good fit as the r^2 values obtained were very close to unity. Further, suggesting that the soil hydraulic parameters (θs, θr, Ks, n) well described the water retention relationship irrespective of different treatments of tillage and cover cropping at the studied soil depth.

However, going by the optimal range of the indicators (Reynolds *et al*.,2009) presented in Table 3 the S-value obtained (ranging between 0.0564 to 0.0461) are all within the limits of very good to good soil physical and structural quality. Irrespective of the tillage practices implored or cover crops grown on this soil as well as the depth of soil sampling.

Soil structural stability index shows that soil under conservation tillage (no till or reduced till) and all those shielded by cover crops are at low risk of degradation, while soils under conventional tillage systems, those with no cover crops and soils at the different depth sampled are at a high risk of degradation.

The values of macro porosity (PMAC) obtained are optimal for plant growth ranging between 0.058 to 0.097 m^3m^{-3} thereby suggesting soil's ability to drain excess water ensure adequate soil aeration and facilitate crop root proliferation (Reynolds *et al*., 2009) and foraging for nutrient and water thus enhance proper anchorage for crops.

Values of RFC were also optimal, it ranged from 0.68 to 0.79 m^3m^{-3}, suggesting a desirable water and air contents (for maximum microbial production of crop-essential nitrate) more frequently and for longer time periods than soils that have larger or smaller ratios (Olness *et al*., 1998; Reynolds *et al*., 2002).

All values of AC obtained ranged from 0.12 to 0.15 m^3m^{-3}; indicating optimal range for plant growth. An AC $\geq$0.10 m^3m^{-3} has traditionally been recommended for minimum susceptibility to crop-damaging or yield reducing aeration deficits in the root zone (White, 2006).

All values of PAWC obtained in this study are within ideal to good for optimal root growth and function. A PAWC $\geq$0.20 m^3m^{-3} is often considered "ideal" for maximal root growth and function (Hall *et al*., 1977; Verdonck *et al*., 1983; Cockroft and Olsson, 1997), while 0.15$\leq$PAWC <0.20 m^3m^{-3} is "adequate", 0.10$\leq$PAWC<0.15 m^3m^{-3} is "limited", and PAWC <0.10 m^3m^{-3} is considered "poor" or "droughty" (Hall *et al*., 1977; Warrick, 2002, White, 2006).

The non-significant differences observed in percent pore volume distribution due to different tillage systems adopted or cover crops cultivated, is an indication that both the various tillage practice implored and the cover crops planted alongside maize did not significantly affect the amount of pore volume holding water at the different pressure or suction heads evaluated in these soils. Furthermore, owing to the fact that these soils are of the same texture (loam), may warrant the similar distribution of pores sizes at the selected pressure heads of water in all treatment plots. This further confirms that texture is an inherent static property of soil and thus not influenced by management practices, Franzlubbers and Haney (2006) reported such static physical property to be influenced by geological history and climate conditions. In addition it is possible that the period (3 years) of soil tillage is not long enough to have warranted significant changes in pore size distribution as soils of the study area had been on fallow for a period of 18 years before this trial was established. Abu and Abubakar (2013) observed no significant difference in percent pore volume of transmission in tilled and untilled soil. However, Singh *et al.* (1996) and Ranjan *et al*. (2006) reported less volume of transmission pores under direct drilling and no-till relative to conventionally tilled soil.

Higher amount of sand size particle and organic matter at the top soil must have facilitated better porosity at this depth. The non-significant effect of tillage and cover crops on EPD can be attributed to the non-significant differences observed in pore volume distribution under these treatment plots.

CONCLUSION

The study investigated the effect of tillage, cover crop and sampling depth on some soil physical quality indicators, pore volume distribution and hydraulic properties in the Northern Guinea Savanna of Nigeria. The use of RETC model predicted with high precision the hydraulic properties of soils of the study area under the different tillage practices, cover crops and sampling depths indicating its validity in the determination of hydraulic properties in this soil. Soil water retained at the different matric potential evaluated varied with different tillage practices, cover crop and soil depth. Generally the surface soils (0-5 cm) and soils under no-till where either *Centrosema pascuorum* or *Curcubita maxima* served as cover crops retained highest moisture at most of soil suction point studied. Physical quality indicators like RFC, AC, PMAC and PAWC were within the optimal range for normal plant growth irrespective of the kind of tillage practices or cover crops grown on the soil. Dexter S-index adjudged soils of the study area within the limits of very good to good soil physical quality. Soils under the conventional tillage practice and the bare soil with no cover crops showed threaten soil structural stability therefore predisposing the soil to a high risk of degradation. In regards to the result obtained, it is obvious that conservation tillage practice (NT and RT) and the growing of cover crops like *Centrosema pascuorum* or *Curcubita maxima* improved soil hydro physical properties and place soil of the study area at a lower risk of degradation.

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