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CHANGES IN THE STRUCTURE OF A NIGERIAN SOIL UNDER DIFFERENT LAND MANAGEMENT PRACTICES

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ABSTRACT

Quantification of soil physical quality (SPQ) and pore size distribution (PSD) can assist understanding of how changes in land management practices influence dynamics of soil structure, and this understanding could greatly improve the predictability of soil physical behavior and crop yield. The objectives of this study were to measure the SPQ index under two different land management practices (the continuous arable cropping system and natural bush fallow system), and contrast the effects of these practices on the structure of PSD using soil water retention data. Soil water retention curves obtained from a pressure chamber were fitted to van Genuchten's equation, setting $m (= 1-1/n)$. Although values for soil bulk density were high, soils under the continuous arable cropping system had good SPQ, and maintained the capacity to support root development. However, soils under the natural bush fallow system had a worse structure than the continuous arable system, with restrictions in available water capacity. These two management systems had different PSDs. Results showed the inferiority of the natural bush fallow system with no traffic restriction (which is the common practice) in relation to the continuous arable cropping system in regard to physical quality and structure.

Keywords: arable cropping, bush fallow, soil water retention, soil physical quality index.

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RESUMO: MUDANÇAS NA ESTRUTURA DE UM SOLO DA NIGÉRIA EM DIFERENTES PRÁTICAS DE MANEJO

Compreender como mudanças nas práticas de manejo do solo influenciam a dinâmica da estrutura dele, a partir da quantificação da sua qualidade física e da distribuição do tamanho de poros, pode em muito melhorar a previsão do comportamento físico do solo e do rendimento das culturas agrícolas. Os objetivos deste estudo foram determinar índices para quantificar a qualidade física do solo, em dois sistemas de manejo distintos (pousio e aração); e analisar o impacto desses dois sistemas na distribuição do tamanho de poros, obtido a partir de dados de retenção de água no solo. As curvas de retenção foram medidas utilizando câmaras de Richards, e os dados experimentais foram ajustados pelo modelo de van Genuchten ($m = 1-1/n$). Embora os valores de densidade do solo encontrados sejam altos, o solo em sistema de aração apresentou bons índices de qualidade física, com manutenção da capacidade para permitir bom desenvolvimento radicular. No entanto, o solo em sistema de pousio apresentou uma estrutura pior com restrições de água disponível em relação ao sistema de aração. Esses dois sistemas de manejo apresentaram distintas distribuições de tamanhos de poros. Os resultados evidenciaram que o solo em sistema pousio sem restrição de tráfego, comum nesse tipo de prática, apresentou resultados piores em relação aos obtidos pelo sistema de aração em termos de estrutura e qualidade física.

Palavras-chave: sistema de aração, sistema de pousio, curva de retenção, índices de qualidade física do solo.

INTRODUCTION

Soil structure is probably the most widely known and studied attribute of soil quality after soil organic matter, largely due to its direct effects on water retention and transmission, soil C sequestration, root growth and development, and crop production. Changes in soil structure can be due to modification in soil aggregates or pores or both (Sasal et al., 2006). The soil pore system is critical to agriculture and the environment since it is the principal pathway for water and air transport in soils, and can be modified by land management practices (Schwen et al., 2011; Guedes et al., 2012). Therefore, understanding land management-induced changes that soil pore systems undergo becomes important for sound land use planning and management.

In many densely populated dry-land areas, the bush fallow or “slash and burn” system can no longer provide the basic needs for farming communities, and intensification of crop production on agricultural land has become inevitable. The possibility of the bush fallow system as a means of sustaining agricultural production has received considerable attention, and it is widely accepted as a sustainable and efficient land management system in the tropics (Goudie, 2002; De Rouw and Rajot, 2004; Valentin et al., 2004).

A search in the literature has shown, however, that this inference is particularly linked with results emanating from organic matter and chemical fertility based studies (Young and Wright, 1979; Juo et al., 1995; Harris, 1999). The few soil physical studies carried out used changes in infiltration rate (Wilkinson, 1975; Wilkinson and Aina, 1976) and the aggregate stability test (Valentin et al., 2004) to infer Soil Physical Quality (SPQ). For adequate

understanding of transport processes under land management practices, knowledge of the resulting soil structure is necessary.

In order to describe the effect of land use or land-related management on soil and its functions, soil parameters such as bulk density and air capacity (Reynolds et al., 2007), aggregate size analysis (Ogunwale, 2008; Lawal et al., 2009), and soil penetration resistance (Ogunwale, 2005; Figueiredo et al., 2011) have been used in many studies. In contrast, Pires et al. (2008a) and Dexter and Richard (2009) used the Pore Size Distribution (PSD) approach to study soil structure, and this approach is relevant to fluid transport in soils. Several studies have discussed other methods for evaluating soil porous systems, such as micro-morphological analysis, mercury intrusion porosimetry, N adsorption, and computed tomography (Hajnos et al., 2006; Kutílek et al., 2006; Lipiec et al., 2007; Pires et al., 2007, 2008b), to mention a few.

Adoption of the soil water retention curve (SWRC) approach to estimate PSD is advancing, mainly due to its usefulness in unsaturated soil mechanics, its requirement for modeling (Gould et al., 2011) and, ease of determination in the laboratory. The SWRC is the relationship between soil water content (θ) and pressure head (h) for a given soil at a given temperature. Empirical SWRC [$S(h)$ or $\theta(h)$] and its derivative curve produce the PSD (Kosugi, 2004; Yuki et al., 2006; Kutílek, 2007; Cássaro et al., 2008).

Based on size, three categories of pores were designated: non-capillary or macropores, capillary or micropores, and submicroscopic pores (Kutílek, 2004). Using the Luxmoore pore classification, mesopores were introduced, and pore radii (r) >0.5 mm were designated as macropores and $5 \mu\text{m} < r < 0.5$ mm as mesopores (Schwen et al.,

2011). In the paper of Sasal et al. (2006), pore radii $>30\text{ }\mu\text{m}$ were designated as macropores, $7.5\text{--}30\text{ }\mu\text{m}$ as mesopores, and $<7.5\text{ }\mu\text{m}$ as micropores. An equivalent pore radius of $1.0\text{--}1.5\text{ mm}$ has been defined as the boundary between macro- and micropores in soils (Kutílek, 2004). Kutílek et al. (2006), however, cautioned in regard to the inappropriateness of pore classification on the basis of “subjectively defined fixed boundary values” for all soils.

One important feature of the SWRC is the inflection point. In most structured soils, SWRCs have more than one inflection point, typically two. On the derivative curve of the SWRC, using the log-normal distribution function of the pore radius (Kosugi, 1994), the two inflection points will coincide with two distinct peaks of capillary pores, which are separated by the minimum with the lowest value at h_A into textural or matrix pore domain ($h < h_A$) and structural pore ($0 > h > h_A$) domain (Kutílek, 2007; Pires et al., 2008a).

Textural pores are induced by the solid particle size distribution (i.e., texture) and arrangement of particles. These pores are relatively more stable intra-aggregate pores than the inter-aggregate structural pores induced by fractures and micro-cracks. Structural pores are more influenced by climate, cropping systems, and land management practices (Lal and Shukla, 2004). Furthermore, at the inflection point of the SWRC, a new physical quality indicator for soils, referred to as Dexter's S-index, S-value, or S-theory, has been defined (Dexter, 2004) as the slope of the SWRC ($\log h$, θ) at that point. Reports abound that the S-index is a robust indicator of soil physical quality in structured soils and for studies involving root ramification in soils and compaction (Reynolds et al., 2009).

Our main hypothesis was that different land management practices will modify the soil structure differently, and that PSD can help identify these changes. We expect a decrease in soil physical quality under the bush fallow system, due to unrestricted animal traffic, and contrasting PSD between the two practices. Hence, the objective of this study was to assess the impact of the two land management practices on the near-surface soil structure (i.e. SPQ and PSD). Soil water retention was measured for the $0\text{--}20\text{ cm}$ soil depth under the two land management practices. Subsequently, the SWRCs plotted were used to estimate SPQ and analyze changes in the structure of PSD.

MATERIAL AND METHODS

Experimental site

Soil samples were obtained from fields under the continuous arable cropping system (hereafter

referred to as “arable system”) and the natural bush fallow system (referred to as “fallow system”) located adjacent to one another and close to the Experimental Farm of the Institute for Agricultural Research, Samaru, Nigeria ($11^\circ 11' \text{ N}$, $07^\circ 37' \text{ E}$; 686 m a.s.l.). In the arable system, maize and cowpea were cropped for several years in rotation (i.e., cowpea was cropped after two seasons of maize cropping). The maize crop received $120\text{ kg ha}^{-1} \text{ N}$, $60\text{ kg ha}^{-1} \text{ P}_2\text{O}_5$, and $60\text{ kg ha}^{-1} \text{ K}_2\text{O}$ through NPK and urea fertilizers, whereas no fertilizer was applied when cowpea was grown. At harvest, crop residues were left standing in the field until the next cropping season, at which time they were plowed into the soil before harrowing and ridging. In contrast, the fallow system was under natural vegetation dominated by grass and shrub/tree species like *Cyperus rotundus* L., *Andropogon gayanus* L., *Loudetia annua*, *Piliostigma reticulatum*, *Daniellia oliveri*, and *Guera senegalensis*. However, free and unrestricted grazing by ruminants (cattle, sheep, and goats) takes place under this system.

The soil is a Typic Haplustalf overlying basement complex rocks (Ogunwole et al., 2001). The site has a sub-humid climate with mean annual pluvial precipitation of $1,011 \pm 161\text{ mm}$ concentrated entirely in five months (May/June to September/October). Mean daily temperature is 26.5°C and mean daily relative humidity is 46.3% .

Sampling and laboratory analysis

The soil sampling technique adopted in the study was a stratified random sampling technique (Petersen and Calvin, 1986) that divided the large field into five pseudo-replicates. Composite loose samples, and undisturbed core ($5 \times 5\text{ cm}$) samples were obtained at four depths (D) [$0\text{--}5$ (D1), $5\text{--}10$ (D2), $10\text{--}15$ (D3), and $15\text{--}20\text{ cm}$ (D4)]. There were a total of 40 core samples [two (management systems) \times four (depths) \times five (replications/depth)]. Composite, disturbed (loose) samples were air dried, crushed, and sieved through a 2.0 mm sieve for determination of particle size distribution using the hydrometer method, with sodium hexametaphosphate as a dispersant (Gee and Bauder, 1986).

Batches of the undisturbed soil core samples were wetted through capillarity to saturation for about 48 h. These soil core samples were later drained on a pressure plate apparatus at pressure heads (h) of 0, 2, 5, 10, 33, 100, 500 and $1,500\text{ kPa}$ (Klute, 1986). Each soil sample was measured per h and, corresponding θ was determined gravimetrically by drying samples in a laboratory oven at 105°C for 24 h. The saturated θ of the soil was determined by equilibrating the soil samples on a tension table at 0 kPa . Soil bulk density (ρ_b) was determined as the mass of oven-dried soil divided by the volume of the soil core (Klute, 1986). The five replicates of each soil depth per treatment were used to generate the mean SWRC.

Data analysis procedure

The experimental data of the SWRC (h , θ) were adjusted utilizing the van Genuchten (1980) equation with the Mualem (1986) restriction by using the RETC (2008) computer program. The previously analyzed average ρ_b and particle size distribution were fed into the neural network code of the RETC program to obtain the various empirical parameters (α , θ_r , θ_s , m , and n) that govern the shape of the SWRC. Effective soil water saturation (S_e) for each treatment depth was obtained by transforming θ data into S_e using the van Genuchten (1980) equation by:

$$S_e(h) = \frac{\theta - \theta_r}{\theta_s - \theta_r} = \frac{1}{[1 + (\alpha h)^n]^m} \quad \text{Eq. 1}$$

here θ_r and θ_s denote residual and saturated soil water contents, respectively; and α , n , and m ($= 1-1/n$) are empirical parameters that govern the shape of the SWRC.

After the SWRC adjustment, the hydraulic capacity function (C_w) was obtained, which represents the slope of the SWRC or the derivative of θ in relation to h ($d\theta/dh$), determined by:

$$C_w(h) = \frac{-\alpha^n (\theta_s - \theta_r) m n (h)^{n-1}}{[1 + (\alpha h)^n]^{m+1}} \quad \text{Eq. 2}$$

Specifically in this study, C_w is being used to access the pore size distribution. In this way, graphs of the frequency of pore size distribution were constructed. Since the pressure head is related to the pore radii (r , μm), conversion of h to r (Kutílek and Nielsen, 1994) was performed by:

$$r = \frac{1490}{|h|} \quad \text{Eq. 3}$$

where h is expressed in cm in this case.

The PSD was also analyzed through a smooth curve obtained after fitting the experimental data of S_e versus $\ln h$ into a cubic spline function. The summation curves of $dS_e(\ln h)/\ln h$ versus $\ln h$ gives the pore-size distribution (Kutílek et al., 2006).

We also performed analysis of the S factor (Dexter, 2004). According to this theory, the slope at the inflection point (h_{inf}) of the SWRC is given by:

$$S_{inf} = \frac{-n (\theta_{gs} - \theta_{gr})}{[1 + (1/m)]^{m+1}} \quad \text{Eq. 4}$$

where the index g represents the gravimetric soil water content.

RESULTS AND DISCUSSION

Soil physical characteristics

Soil bulk density was higher throughout the different soil depths in fallow system soils compared

to soils of the arable system; only at D1 (0-5 cm) was ρ_b slightly higher in soil under the arable system (1.50 kg dm^{-3}) than in the fallow system (Figure 1a).

The highest ρ_b was at lower depths (10-20 cm) of the fallow system (1.63 kg dm^{-3}). On average, ρ_b under the fallow system was 6.2 % higher than in the soil of the arable system, and these high ρ_b values may be due to the unrestricted cattle grazing that characterizes natural bush fallow of the West African systems. The values of the ρ_b for both soils exceed the upper ρ_b limit ($1.25\text{-}1.30 \text{ kg dm}^{-3}$) for adequate aeration in fine texture soil (Drewry et al., 2001; McQueen and Shepherd, 2002) and may fall into the ideal range for root growth and development. Volumetric soil moisture contents at 33 kPa (θ_{FC}) and 1,500 kPa (θ_{PWP}) (Figures 1b and 1c) were larger under the fallow system compared to soils under the arable system; however, the difference between these moisture contents, which is the plant available water θ_{PAW} (Figure 1d), was larger in the latter system than the former by 4.6 % (Figure 1). The low θ_{PAW} of the fallow system stems from its high θ_{PWP} (Figure 1c), whereas the soil of the arable system fall within the lower limit of optimum θ_{PAW} (except for D2) (Hall et al., 1977); the θ_{PAW} for fallow system soils indicate water limitation (Reynolds et al., 2009). The SPQ indicators used here to assess the soils under the two management systems (arable system and fallow system) were consistent with the results of the S-index presented in table 1.

Soil water retention curves

Results of the measured SWRC for the arable system (Figure 2a) show that there are no great differences among depths for the water retained for the distinct potentials. This result is corroborated by the similarity of the n factor among depths (Table 1) and it is an indication that there are no great differences in the capillary region for this management system. The α factor related to the air-entry region only demonstrates erratic behavior among depths.

In the fallow system (Figure 2b), there is no difference among D1, D3, and D4 for $h > 10 \text{ kPa}$. In contrast, when the $h < 10 \text{ kPa}$ was analyzed, important differences were observed among these depths, and this indicates the existence of distinct distributions of large pores among them. The SWRCs for D3 and D1 are identical, and this result is corroborated by the similarity between the n values for these depths (Table 1). However, the smaller value of α for D1 indicates that the air-entry region is broad for this depth. The greater n factor value for D2 represents that this depth has a steeper curve, followed by D4, and this result reflects differences mainly in the capillary region of the SWRCs.

Comparison between the arable and fallow systems (Figure 3) indicates a higher θ at near

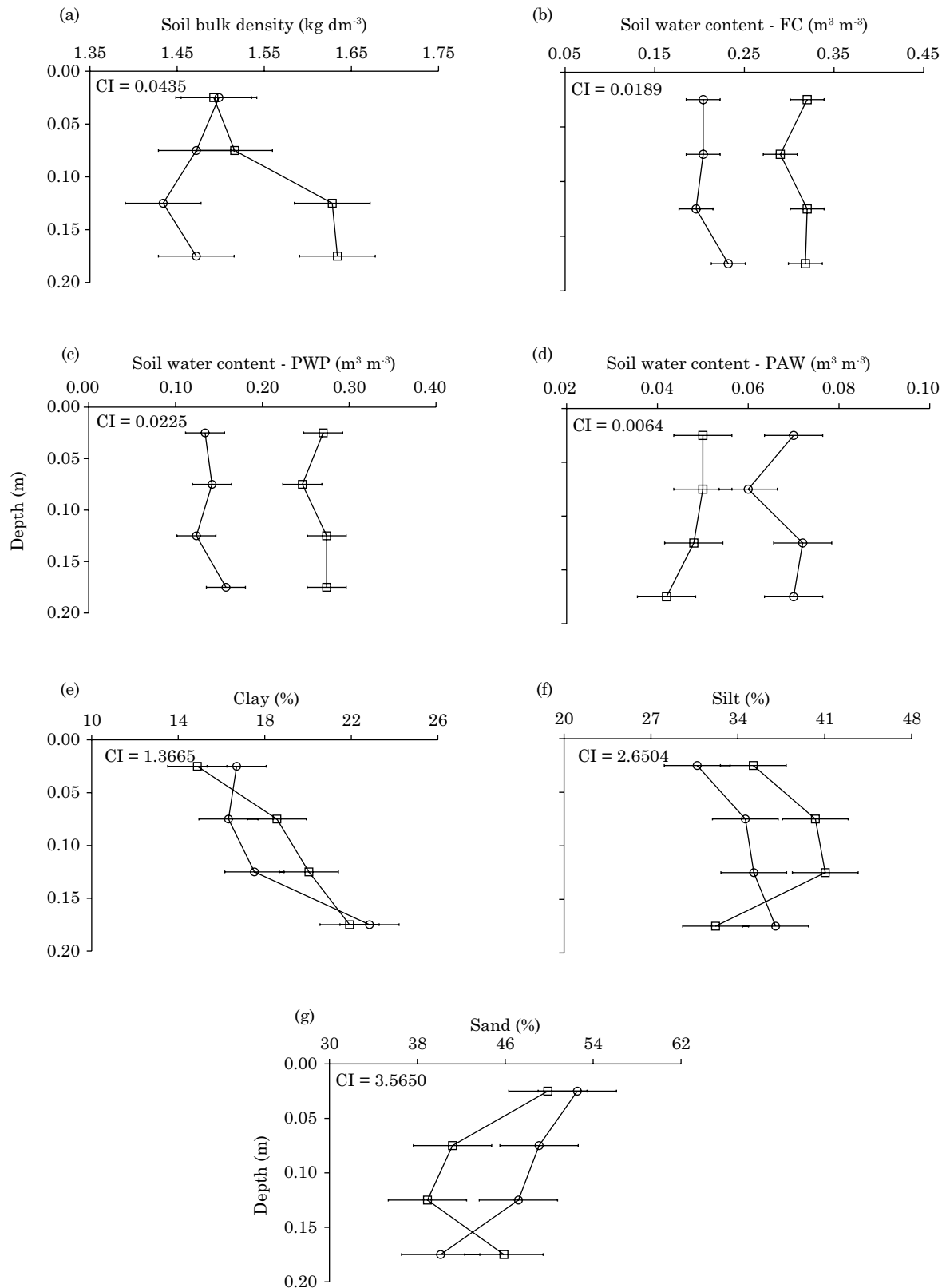
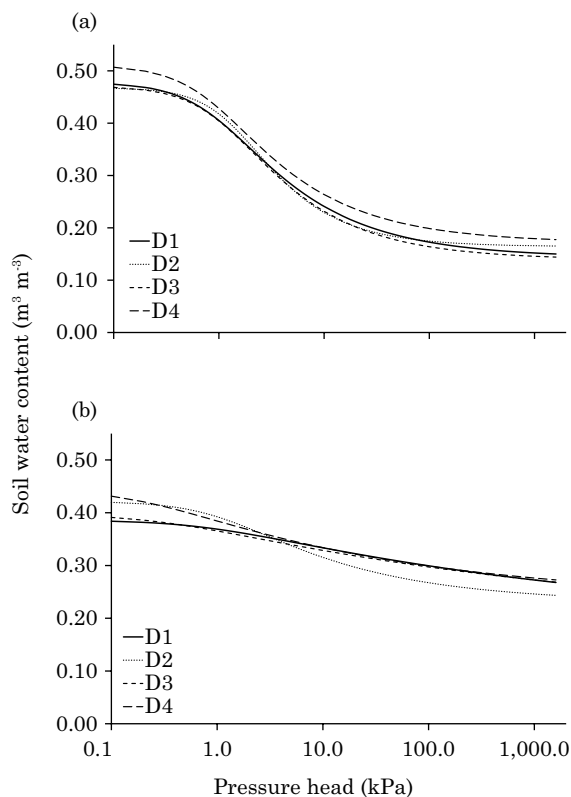


Figure 1. Soil bulk density - ρ_b (a), volumetric water content (θ) at field capacity θ_{FC} ($h = 33 \text{ kPa}$) (b), permanent wilting point θ_{PWP} ($h = 1,500 \text{ kPa}$) (c), plant available water θ_{PAW} ($\theta_{FC} - \theta_{PWP}$) (d), and particle size distribution (clay, silt, and sand contents) (e-g) at the four depths (D1: 0-5 cm, D2: 5-10 cm, D3: 10-15 cm, and D4: 15-20 cm) under the arable cropping (○) and natural bush fallow (□) systems. Bars represent the confidence interval (CI) ($p < 0.05$).

Table 1. van Genuchten parameters obtained from fitting soil water retention data of natural bush fallow and arable cropping systems into the RETC computer program

van Genuchten parameter	Arable cropping				Bush fallow			
	D1	D2	D3	D4	D1	D2	D3	D4
θ_s ($\text{m}^3 \text{m}^{-3}$)	0.478	0.468	0.471	0.511	0.386	0.422	0.397	0.444
θ_r ($\text{m}^3 \text{m}^{-3}$)	0.143	0.164	0.139	0.171	0.180	0.230	0.185	0.234
α (kPa^{-1})	1.026	0.682	0.902	1.155	1.325	0.897	3.634	5.419
n	1.524	1.795	1.576	1.529	1.112	1.361	1.107	1.185
m	0.344	0.443	0.366	0.346	0.101	0.265	0.097	0.156
S-index	0.072	0.083	0.079	0.071	0.048	0.043	0.041	0.036

**Figure 2. Soil water retention curves (SWRCs) for soil under continuous arable cropping system (a) and natural bush fallow system (b) for depths D1 (0-5 cm), D2 (5-10 cm), D3 (10-15 cm), and D4 (15-20 cm).**

saturation in soils under the arable system over those of the fallow system. That is indicative of higher soil porosity in the arable system (Pires et al., 2008a), which may have been facilitated by the annual pulverization of soil under the arable system. At the higher h of 100-1,500 kPa, soils under the fallow system held larger amounts of water than arable soils, and this result is related to the differences in soil microporosity between systems (0.241 - D1, 0.238 - D2, 0.235 - D3, and 0.266 $\text{m}^3 \text{m}^{-3}$ - D4 for the arable system; and 0.337 - D1, 0.322 -

D2, 0.333 - D3, and 0.340 $\text{m}^3 \text{m}^{-3}$ - D4 for the fallow system). These results are an indication of changes in soil water retention due to land management practices (Reichardt and Timm, 2004).

As can be seen in the SWRCs (Figure 3), the potential near 4 kPa represents a point of inversion in water retention between systems for all depths analyzed. This inversion is related to changes in pore size distribution in this region. The higher values of the n factor for the arable system in comparison to the fallow system indicate steeper SWRCs (Table 1). Another interesting result is that, regardless of depth, the pattern of the SWRCs is practically the same between systems. Adjustment of the van Genuchten/Mualem model of the measured SWRC had sums of squares (SSQ) of 0.0025 (highest for arable soils) and 0.0003 (highest for fallow soils); and coefficients of determination (R^2) of 0.974 (lowest for arable soils) and 0.985 (lowest for fallow soils). This indicates that adjustments of estimated parameters to the measured soil water retention data were well fitted.

The S index for the four depths within the soils under the arable and fallow systems had a range in the SPQ from well to very well structure. A critical S-index value of 0.035 has been provided by Dexter and Bird (2001) and Dexter (2004) for most soil, indicating soil capacity for maintaining and supporting root activities. At $S < 0.035$, soil physical quality is considered as poor, whereas the value of $S \geq 0.050$ is indicative of "very well-structured soil"; and $0.035 \leq S < 0.050$ is "well-structured soil". Soil is considered "degraded" if $S < 0.020$, and of poor quality if $0.020 \leq S < 0.035$ (Dexter and Czyż, 2007; Tormena et al., 2008; Reynold et al., 2009). Considering the reference S values proposed by Dexter (2004), soils under the arable system were better structured compared to soils of the fallow system (Table 1). The S-index for all soils under the arable system was > 0.070 at all depths, which is greater than the lower limit for very good physical quality. In the case of the fallow system, soils had S values from 0.036 to 0.048. It was only the soil samples collected in the D4 layer that had marginally good physical quality. One reason for

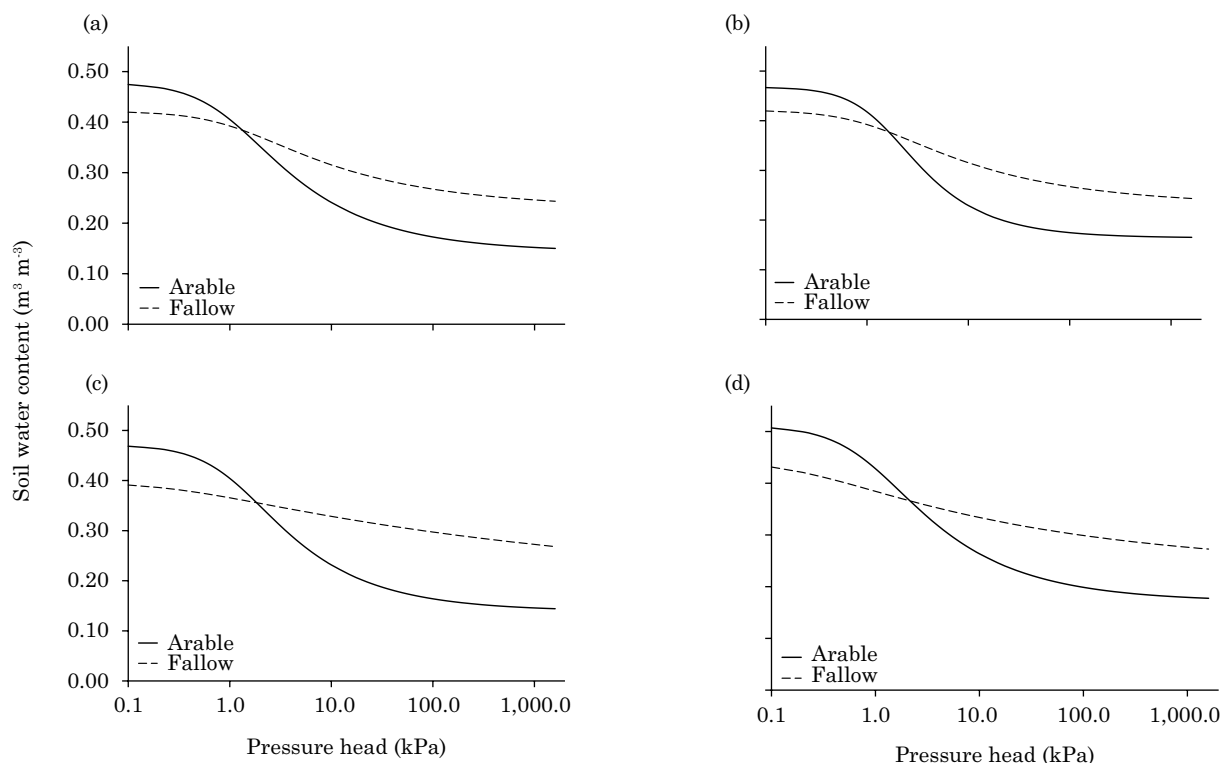


Figure 3. Soil water retention curves (SWRCs) for soil under the continuous arable cropping system and natural bush fallow system for depths D1 (0-5 cm) (a), D2 (5-10 cm) (b), D3 (10-15 cm) (c), and D4 (15-20 cm) (d).

poorer quality of the soil under the fallow system may be due to the unrestricted free grazing by animals in the fallow system.

Pore size distribution via hydraulic capacity function

The frequency distribution functions for pore size obtained after the derivative of θ with respect to h for both management systems are shown in figure 4.

As expected, there are practically no differences among depths for the arable system (Figure 4a), and this is mainly related to the similarity among SWRCs. In the case of depth D2, there is a small shift of the distribution to smaller pore sizes in comparison to the other sizes, which is a consequence of the air-entry region parameter. In contrast, the fallow system exhibits important differences among depths (Figure 4b). In relation to size distribution, there is no great difference between D3 and D4, which is a result of the similarity between the n and α parameters for these depths. Similar to the arable system, D2 exhibits a shift of the distribution to smaller pore sizes, followed by D1. This result is mainly related to the air-entry region parameter.

In comparison of depths between systems, we can observe that for all depths the peak related to the most frequent pore sizes occurred for larger sizes in the fallow system in comparison to the arable

system. The frequency of pores not shown in the normalized distributions (Figure 4) was greater for the arable than the fallow system, which is an indication of the presence of a great number of pores for the former system. This result can be confirmed by analysis of the θ_s parameter obtained in the mathematical adjustment of the SWRC (Table 1). It may also be observed that the arable system had a greater volume of meso- and micropores in comparison to the fallow system, considering pore diameters from 30 to 0.2 μm , which are important for water redistribution and storage for plants. This corroborates the results of water availability obtained (Figure 1d).

Pore size distribution via spline function

The spline function curves of S_e versus $\ln h$ and the derivative curves $dS_e(\ln h)/d\ln h$ are shown in figure 5.

Results for the arable system (Figures 5a and 5b) show that there are only slight differences among depths. Depths D1, D3, and D4 show practically the same results in the structural region of PSD, with the greatest frequency of pores for D3 in comparison to the other depths. In the matrix region there are no differences among D1, D3, and D4. The peak associated with the structural domain for these three depths corresponds approximately to pores of 64 μm . In the case of the 5-10 cm depth (D2), it corresponds

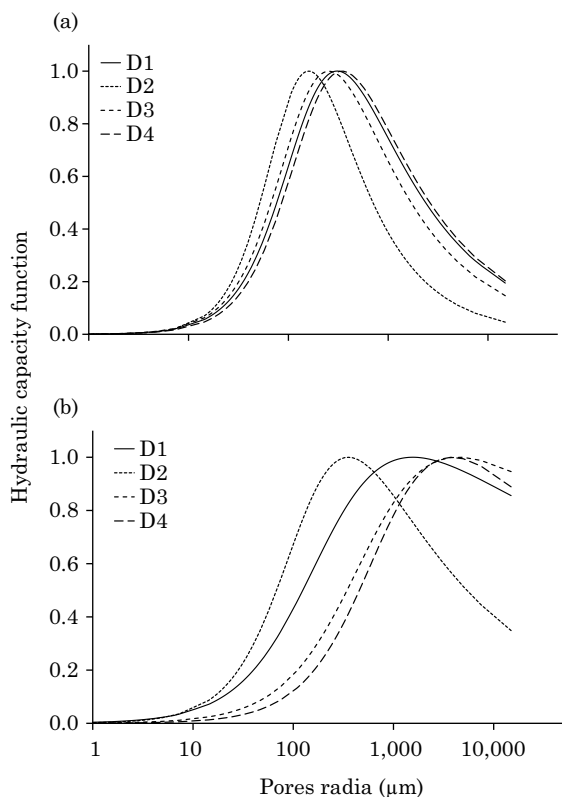


Figure 4. Normalized contrasting pore size distributions (PSDs) obtained by using the hydraulic capacity function (C_w) under the continuous arable cropping system (a) and natural bush fallow system (b) for depths D1 (0-5 cm), D2 (5-10 cm), D3 (10-15 cm), and D4 (15-20 cm).

to approximately 44 μm . The pore radius (r_a) that separates the structural from the matrix domain occurred at approximately 2.3 μm for D1, D3, and D4 and 1.9 μm for D2. According to Tuller and Or (2002), the matrix domain contains pore sizes that range from 0.1 to 10 μm . Kutílek et al. (2006) and Pires et al. (2008a) also observed similar results for the matrix domain.

In the fallow system (Figure 5c and 5d) the results are more complex than in the case of the arable system. The main differences among depths occurred principally in the structural domain of PSD. The peak associated with the structural domain varied widely among depths, and was approximately 53 μm (D1), 44 μm (D2), 116 μm (D3), and 96 μm (D4). The greatest frequency of pores in the structural domain was obtained for D2, followed by D4. The pore radius that separates the structural from the matrix domain occurred at approximately 9.0 μm for D1, 6.1 μm for D2, 13.4 μm for D3, and 9.0 μm for D4. The results for both systems demonstrate that the structural domain was more affected by the management system. This result is expected since large pores are usually more affected by natural or human processes.

The variation of r_a , especially for the fallow system, also corroborates the results obtained by Kutílek et al. (2006). According to these authors, the boundary between soil categories cannot be taken as a fixed value. This pore radius will depend on soil type and also land use.

Comparing the different systems in relation to depths for soils under the arable system, the first peak occurred in pore regions that range from 0.05 to 2.2 μm , and the second peak in pore regions from 2.2 to 300 μm . However, in soils under the fallow system, the first peak ranges from 1 to 12 μm , and the second peak from 12 to 300 μm (Figure 6). The peak ranges here suggest an overlap in the size distributions of textural and structural pores in these soils (Dexter and Richard, 2009). The PSDs of soils under the arable system have greater similarity throughout depths, with sharp and defined peaks, compared to the peaks of the fallow system, which are flatter and more broadly extended and with a trend toward smaller pore radii.

The structure of the PSDs is another indication of better structure in soils under the arable system than those of the fallow system as PSD structures displayed by soils under the fallow system depict a certain similarity to compressed soils under compaction (Kutílek et al., 2006). The higher bulk density displayed by this soil (Figure 1a) may be explained by (i) indiscriminate cattle grazing on fallow lands (which was not quantified in this study), which could have exacerbated soil susceptibility to structural deterioration, thus making it unsustainable (Proffitt et al., 1995; Tarawali et al., 1999; Hoshino et al., 2009), and (ii) heavy grazing, which makes surface soil become bare and open to direct impact of raindrops, which further deteriorate soil structure by promoting crusting and hard-setting when dry (Lal and Shukla, 2004).

Comparison of soil depths in the two treatments showed that difference occurs in the PSDs of D2 (5-10 cm). Calculated total porosity (Cássaro et al., 2011), $\phi = 1 - (\rho_b/2.65)$, is an average of 8.5 % greater for soils of arable systems (44.6 %) compared to soils under fallow systems (40.9 %).

Land-management induced changes in PSDs demonstrate the ability of soil pores to hold water (Schwen et al., 2011). The change in porosity can be better appreciated when we look at pore size in a functional manner. Analyses of h and r data showed that the average proportion of soil pores under the arable system can be grouped as 35, 28, and 37 % for transmission, storage, and residual pores, respectively; whereas for soils under the fallow system, these averages are 9, 18, and 73 % respectively. These results further reflect the comparative values of plant available water θ_{PAW} , (i.e., storage pores) of both land management systems (Figure 1d); and such changes in pore configuration place further restrictions on hydraulically effective

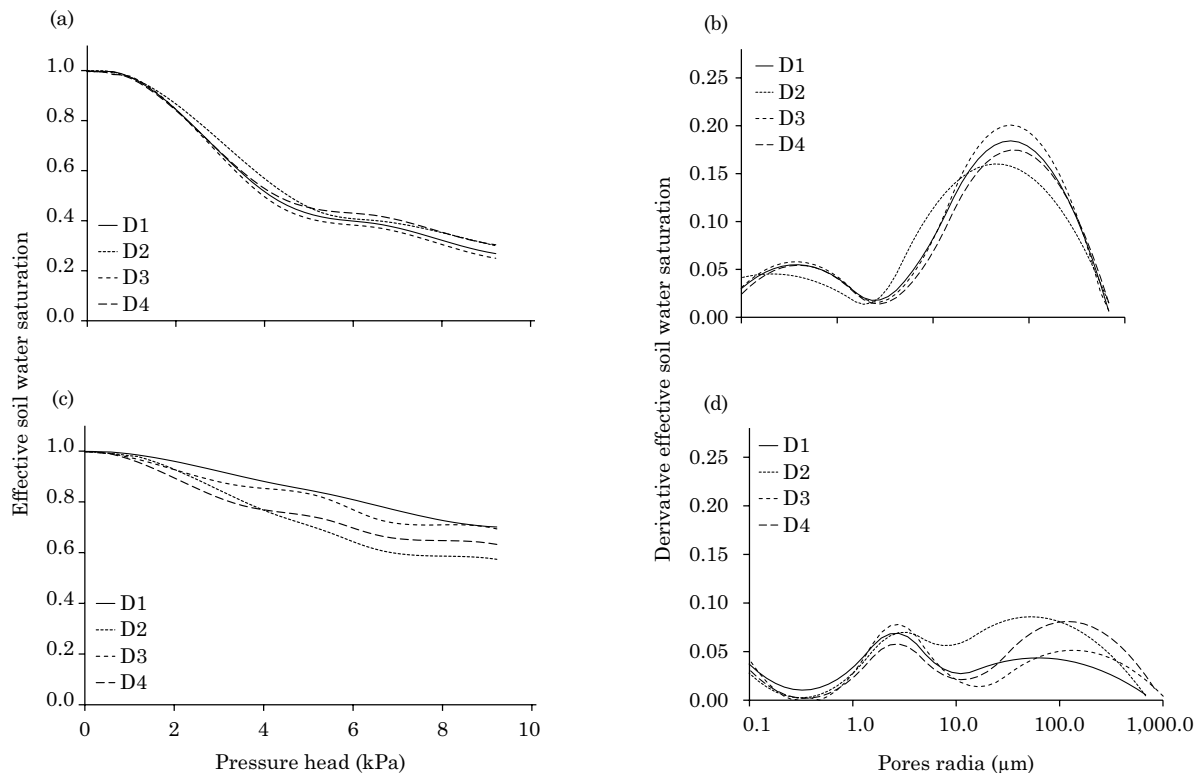


Figure 5. Effective soil water saturation (S_e) curves versus water pressure head (h) and contrasting pore size distributions (PSDs) under the continuous arable cropping system (a,b) and natural bush fallow system (c,d) for depths D1 (0-5 cm), D2 (5-10 cm), D3 (10-15 cm), and D4 (15-20 cm).

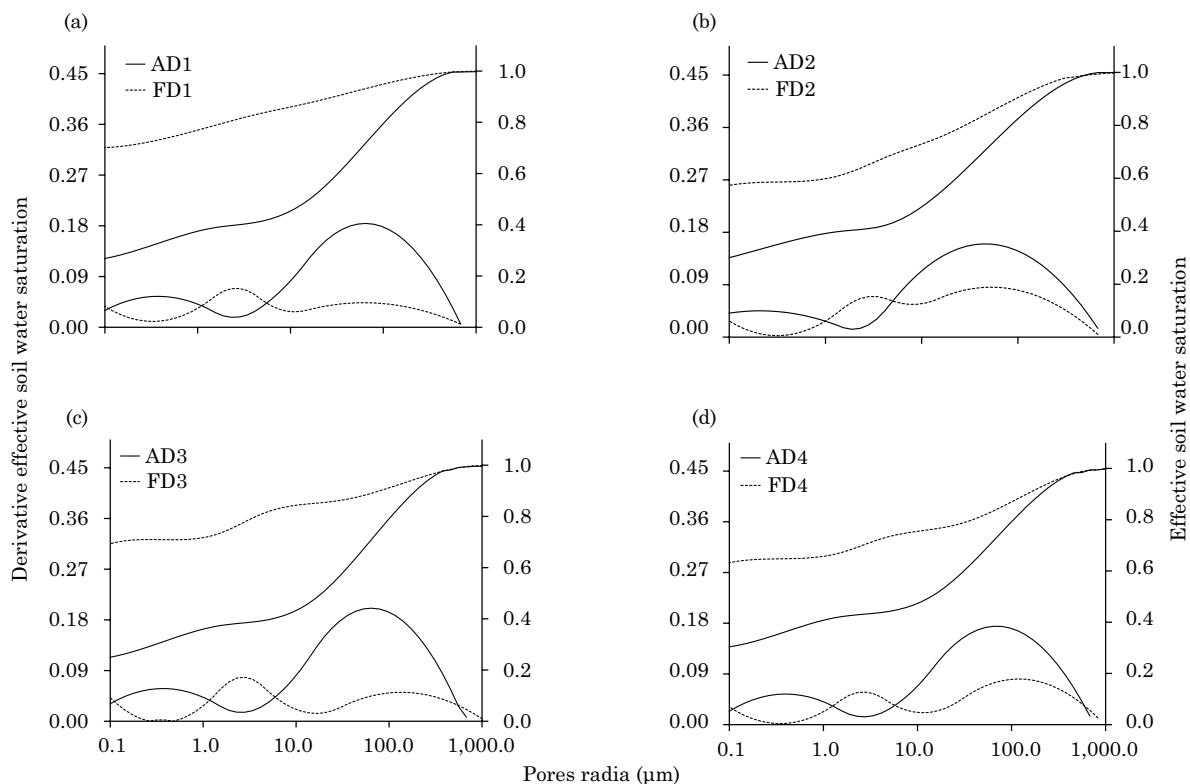


Figure 6. Effective soil water saturation (S_e) curves versus water pressure head (h) and contrasting pore size distributions (PSDs) under the continuous arable (A) cropping system and the natural bush fallow (F) system for depths D1 (0-5 cm) (a), D2 (5-10 cm) (b), D3 (10-15 cm) (c) and D4 (15-20 cm) (d).

(fluid conductivity) pores in fallow system soils (Kutílek, 2004; Schwen et al., 2011).

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REFERENCES

- Cássaro FAM, Pires LF, Santos RA, Giménez D, Reichardt, K. Funil de Haines modificado: curvas de retenção de solos próximos à saturação. *R Bras Ci Solo*. 2008;32:2555-62.
- Cássaro FAM, Borkowski AK, Pires LF, Rosa JA, Saab SC. Characterization of a Brazilian clayey soil submitted to conventional and no-tillage practices using pore size distribution analysis. *Soil Till Res*. 2011;111:175-9.
- De Rouw A, Rajot JL. Nutrient availability and Pearl Millet production in Sahelian farming systems based on manuring and fallowing. *Agric Ecosyst Environ*. 2004;104:249-62.
- Dexter AR, Soil physical quality. Part 1. Theory, effects of soil texture, density and organic matter, and effects on root growth. *Geoderma*. 2004;120:201-14.
- Dexter AR, Richard G. Tillage of soils in relation to their bi-modal pore size distributions. *Soil Till Res*. 2009;103:113-8.
- Dexter AR, Czyż EA. Applications of S-theory in the study of soil physical degradation and its consequences. *Land Degrad Develop*. 2007;18:369-81.
- Dexter AR, Czyż EA, Gałe OP. Soil structure and the saturated hydraulic conductivity of subsoils. *Soil Till Res*. 2004;79:185-9.
- Dexter AR, Bird NRA. Methods for predicting the optimum and the range of soil water contents for tillage based on the water retention curve. *Soil Till Res*. 2001;57:203-12.
- Drewry JJ, Cameron KC, Buchan GD. Effect of simulated dairy cow treading on soil properties and ryegrass pasture yield. *NZ J Agric Res*. 2001;44:181-90.
- Figueiredo GC, Silva AP, Tormena CA, Giarola NFB, Moraes SO, Almeida BG. Improvement of a testing apparatus for dynamometry: Procedures for penetrometry and influence of strain rate to quantify the tensile strength of soil aggregates. *R Bras Ci Solo*, 2011;35:373-87.
- Gee GW, Bauder JW. Particle size analysis. In: Klute A, editor. *Methods of soil analysis: Physical and mineralogical methods*. Madison: ASA; 1986. Pt 1. p.383-411.
- Gould SJF, Kodikara J, Rajeev P, Zhao X-L, Burn S. A void ratio-water content-net stress model for environmentally stabilized expansive soils. *Can Geotechnol J*. 2011;48:867-77.
- Goudie A. *The human impact on the natural environment*. 5th ed. Malden: Blackwell Publishing; 2002.
- Guedes EMS, Fernandes AR, Lima HV, Serra AP, Costa JR, Guedes RS. Impacts of different management systems on the physical quality of an Amazonian Oxisol. *R Bras Ci Solo*. 2012;36:1269-77.
- Hajnos M, Lipiec J, Świeboda R, Sokolowska Z, Witkowska-Walczak B. Complete characterization of pore size distribution of tilled and orchard soil using water retention curve, mercury porosimetry, nitrogen adsorption and water desorption methods. *Geoderma*. 2006;135:307-14.
- Hall DGM, Reeve MJ, Thomasson AJ, Wright VF. *Water retention, porosity and density of field soils*. Rothamsted: [UK]; 1977. (Soil Survey Tech. Monogr., 9).
- Harris FA. Nutrient management strategies of smallholder farmers in a short fallow farming system in northeast Nigeria. *Geogr J*. 1999;165:275-85.
- Hoshino A, Tamura K, Fujimaki H, Asano M, Ose K, Higashi T. Effects of crop abandonment and grazing exclusion on available soil water and other properties in a semi arid Mongolian grassland. *Soil Till Res*. 2009;105:228-35.
- Juo ASR, Franzluebbers K, Dabiri A, Ikhile B. Changes in soil properties during long term fallow and continuous cultivation after forest clearing in Nigeria. *Agric Ecosyst Environ*. 1995;56:9-18.
- Klute A. Water retention: Laboratory methods. In: Klute A, editor. *Methods of soil analysis: Physical and mineralogical methods*. Madison: ASA; 1986. Pt 1. p.635-62.
- Kutílek M. Soil hydraulic properties as related to soil structure. *Soil Till Res*. 2004;79:175-84.
- Kutílek M. The influence of tillage and compression upon soil physical properties. Trieste, [Italy]: Abdus Salam International Centre for Theoretical Physics; 2007. (Lecture notes).
- Kutílek M, Nielsen DR. *Soil hydrology*. Cremlingen Destedt: Catena Verlag; 1994.
- Kutílek M, Jendele L, Panayiotopoulos KP. The influence of uniaxial compression upon pore size distribution on in bi-modal soils. *Soil Till Res*. 2006;86:27-37.
- Kosugi K. Three-parameter lognormal distribution model for soil water retention. *Water Resour Res*. 1994;30:891-901.
- Lal R, Shukla MJ. *Principles of soil physics*. New York: Marcel Dekker; 2004. p.149-63.
- Lawal HM, Ogunwole JO, Uyovbisere EO. Changes in soil aggregate stability and carbon sequestration mediated by land use practices in a degraded dry savanna Alfisol. *Trop Subtrop Agro-Ecosyst*. 2009;10:423-9.
- Lipiec J, Walczak R, Witkowska-Walczak B, Nosalewicz A, Słowińska-Jurkiewicz A, Sławiński C. The effect of aggregate size on water retention and pore structure of two silt loam soils of different genesis. *Soil Till Res*. 2007;97:239-46.
- McQueen DJ, Shepherd TG. Physical changes and compaction sensitivity of a fine-textured, poorly drained soil (Typic Endoaquept) under varying durations of cropping, Manawatu Region. *Soil Till Res*. 2002;63:93-107.
- Mualem Y. Hydraulic conductivity of unsaturated soils: Prediction and formulas. In: Klute A, editor. *Methods of soil analysis: Physical and mineralogical methods*. Madison: ASA; 1986. Pt 1. p.799-823.
- Ogunwole JO. Aggregate characteristics and organic carbon concentrations after 45 annual applications of manure and inorganic fertilizer. *Biol Agric Hort*. 2008;25:223-33.

- Ogunwole JO. Changes in an Alfisol under long-term application of manure and inorganic fertilizer. *Soil Use Manage.* 2005;21:260-1.
- Ogunwole JO, Babalola OA, Oyinola EY, Raji BA. A pedological characterization of soils in the Samaru area of Nigeria. *Samaru J Agric Res.* 2001;17:71-7.
- Pires LF, Bacchi OOS, Reichardt K. Assessment of soil structure repair due to wetting and drying cycles through 2D tomographic image analysis. *Soil Till Res.* 2007;94:537-45.
- Pires LF, Cássaro FAM, Reichardt K, Bacchi OOS. Soil porous system changes quantified by analyzing soil water retention curve modifications. *Soil Till Res.* 2008a;100:72-7.
- Pires LF, Cooper M, Cássaro FAM, Bacchi OOS, Reichardt K. Micromorphological analysis to characterize modifications in the internal structure of soil samples submitted to wetting and drying cycles. *Catena.* 2008b;72:297-304.
- Petersen RG, Calvin LD. Sampling. In: Klute A, editor. *Methods of soil analysis: Physical and mineralogical methods.* Madison: American Society of Agronomy; 1986. Pt 1. p.33-51.
- Proffitt APB, Bendotti S, Mc Garry D. A comparison between continuous and controlled grazing on a red duplex soil. 1. Effects on soil physical characteristics. *Soil Till Res.* 1995;35:199-210.
- Reichardt K, Timm LC. Solo, planta e atmosfera: Conceitos, processos e aplicações. Barueri: Manole; 2004. p.87-145.
- Reynolds F, Drury CF, Yang XM, Fox CA, Tan CS, Zhang TX. Land management effects on the near-surface physical quality of a clay loam soil. *Soil Till Res.* 2007;96:316-30.
- Reynolds F, Drury CF, Tan CS, Fox CA, Yang XM. Use of indicators and pore volume- function characteristics to quantify soil physical quality. *Geoderma.* 2009;152:252-63.
- Sasal MC, Andriulo AE, Taboada MA. Soil porosity characteristics and water movement under zero tillage in silty soils in Argentinian Pampas. *Soil Till Res.* 2006;87:9-18.
- Schwen A, Hernandez-Ramirez G, Lawrence-Smith EJ, Sinton SM, Carrick S, Clothier BE, Buchan GD, Loiskandl W. Hydraulic properties and the water conducting porosity as affected by subsurface compaction under tension infiltrometers. *Soil Sci Soc Am J.* 2011;75:822-31.
- Tarawali G, Manyong VM, Carsky RJ, Vissoh PV, Osei-Bonsu P, Galiba M. Adoption of improved fallows in West Africa: Lessons from mucuna and stylo case studies. *Agrofor Syst.* 1999;47:93-122.
- Tormena CA, Silva AP, Imhoff SDC, Dexter AR. Quantification of the soil physical quality of a tropical Oxisol using the S index. *Sci Agric.* 2008;65:56-60.
- Tuller M, Or D. Unsaturated hydraulic conductivity of structured porous media. A review. *Vadose Zone J.* 2002;1:14-37.
- Valentin C, Rajot JL, Mitja D. Response of soil crusting, runoff and erosion to fallowing in the subhumid and semiarid regions of West Africa. *Agric Ecosyst Environ.* 2004;104:287-302.
- van Genuchten MT. A closed-form equation for predicting the hydraulic conductivity of unsaturated soils. *Soil Sci Soc Am J.* 1980;44:892-8.
- Wilkinson GE. Effect of grass fallow rotations on the infiltration of water into a savannah zone soil of northern Nigeria. *Trop Agric.* 1975;52:97-103.
- Wilkinson GE, Aina PO. Infiltration of water into two Nigerian soils under secondary forest and subsequent arable cropping. *Geoderma.* 1976;15:81-9.
- Young A, Wright ACS. Rest period requirements of tropical and subtropical soils under annual crops. *FAO/UNFPA Project INT/75/P13, land resources for populations for the future.* Rome: FAO; 1979. (Working paper, 6).
- Yuki H, Kosugi K, Takahisa M. Changes in pore size distribution and hydraulic properties of forest soil resulting from structural development. *J Hydrol.* 2006;331:85-102.