Comissão 3.3 - Manejo e conservação do solo e da água

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 (Ogunwole, 2008; Lawal et al., 2009), and soil penetration resistance (Ogunwole, 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 θ(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 µm < r < 0.5 mm as mesopores (Schwen et al., 2011). In the paper of Sasal et al. (2006), pore radii >30 µm were designated as macropores, 7.5-30 µm as mesopores, and <7.5 µm as micropores. An equivalent pore radius of 1.0-1.5 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 (logh, 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 0-20 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° 11' N, 07° 37' 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 kg ha^{-1} N, 60 kg ha^{-1} P_2O_5, and 60 kg ha^{-1} K_2O 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 ± 161 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 × 5 cm) samples were obtained at four depths (D) [0-5 (D1), 5-10 (D2), 10-15 (D3), and 15-20 cm (D4)]. There were a total of 40 core samples [two (management systems) × four (depths) × 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 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:

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

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 (dθ/dh), determined by:

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

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:

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

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:

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

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 (1.25-1.30 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 kPa. In contrast, when the h<10 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

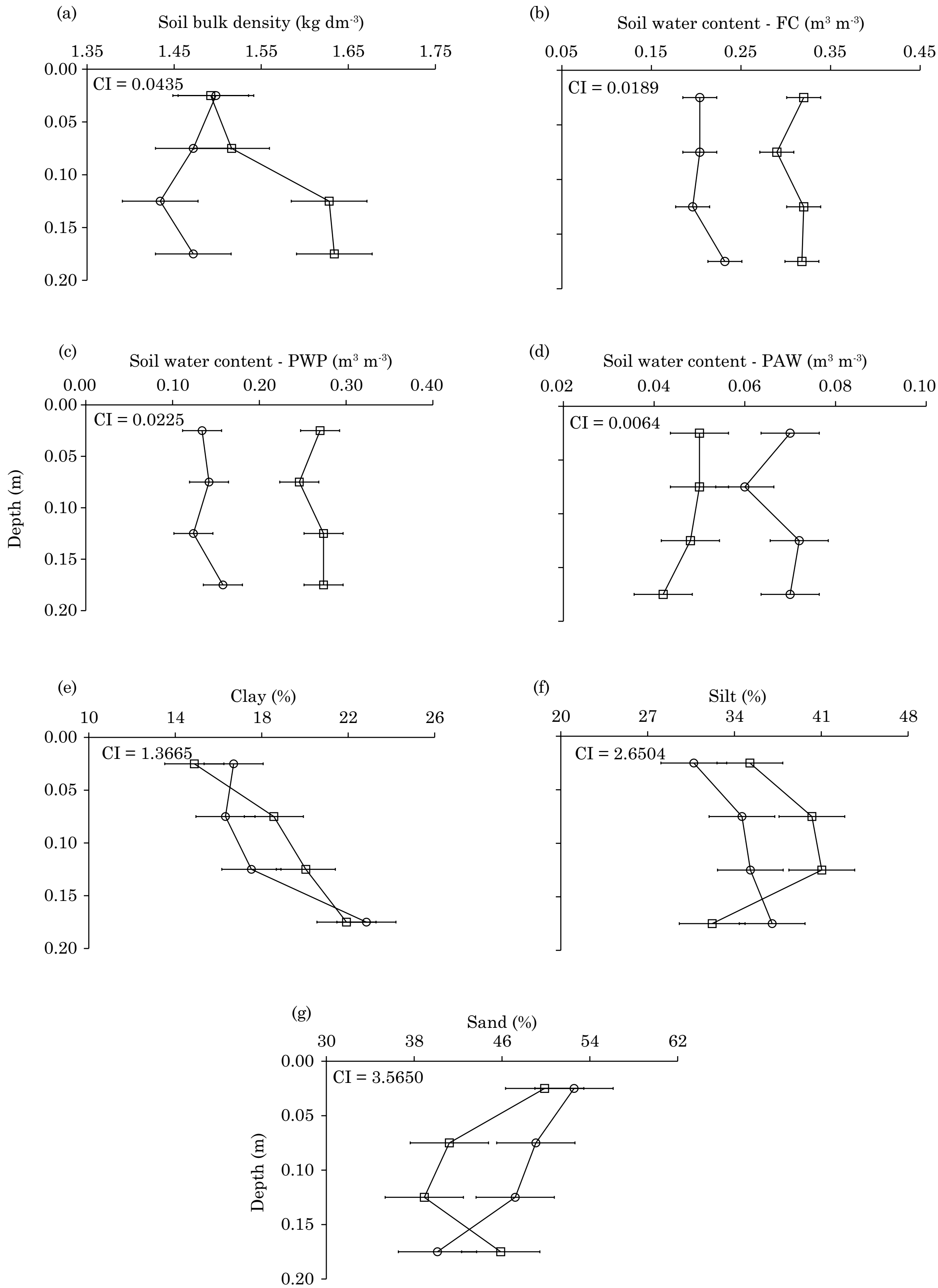

Figure 1. Soil bulk density - ρ_b (a), volumetric water content (θ) at field capacity θ_{FC} (h = 33 kPa) (b), permanent wilting point θ_{PWP} (h = 1,500 kPa) (c), plant available water θ_{PAW} (θ_{FC}-θ_{PWP}) (d), and particle size distribution (clay, silt, and sand contents) (e-g) at the four depths (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 (m^3 m^{-3})	0.478	0.468	0.471	0.511	0.386	0.422	0.397	0.444
θ_r (m^3 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

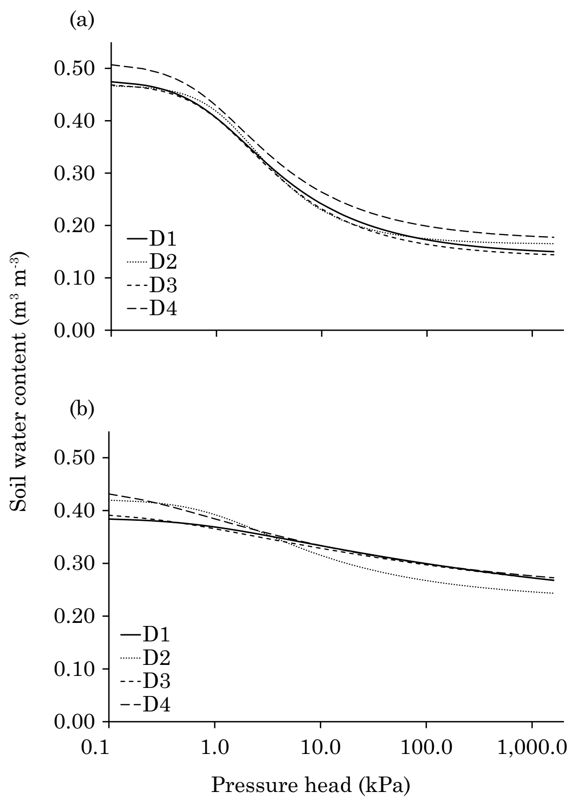

Figure 2. Soil water retention curves (SWRCs) for soil under continuous arable cropping system (a) and natural bush fallow system (b) for depths D1 (0-5 cm), D2 (5-10 cm), D3 (10-15 cm), and D4 (15-20 cm).

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 m^3 m^{-3} - D4 for the arable system; and 0.337 - D1, 0.322 - D2, 0.333 - D3, and 0.340 m^3 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 $S\geq0.050$ 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

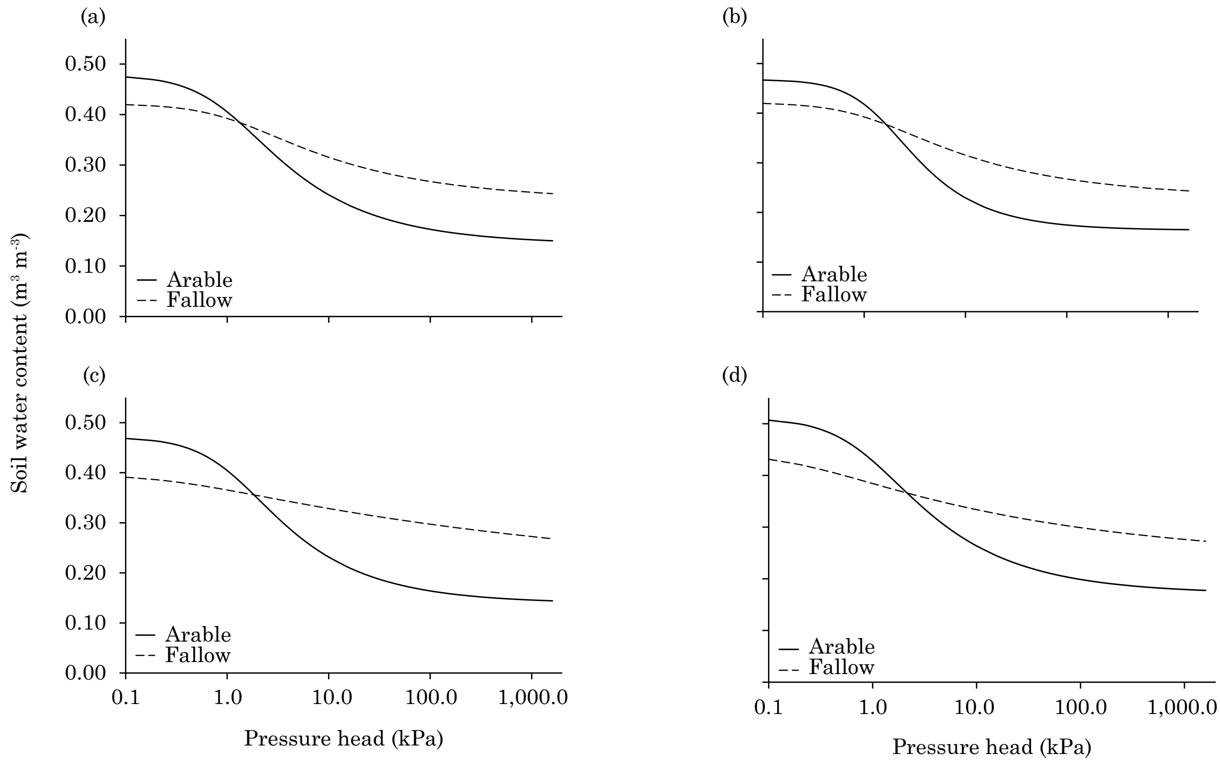

Figure 3. Soil water retention curves (SWRCs) for soil under the continuous arable cropping system and natural bush fallow system for depths D1 (0-5 cm) (a), D2 (5-10 cm) (b), D3 (10-15 cm) (c), and D4 (15-20 cm) (d).

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

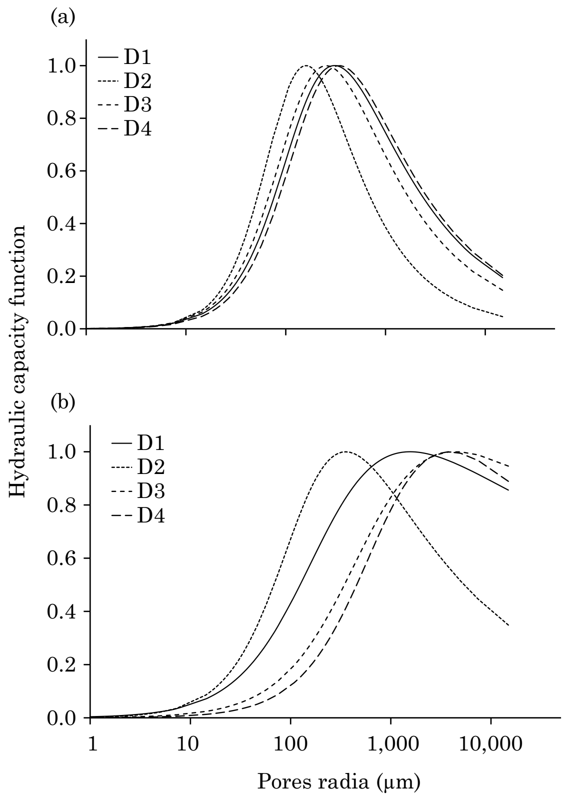

Figure 4. Normalized contrasting pore size distributions (PSDs) obtained by using the hydraulic capacity function (C_w) under the continuous arable cropping system (a) and natural bush fallow system (b) for depths D1 (0-5 cm), D2 (5-10 cm), D3 (10-15 cm), and D4 (15-20 cm).

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 at 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), φ [= 1- (ρ_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

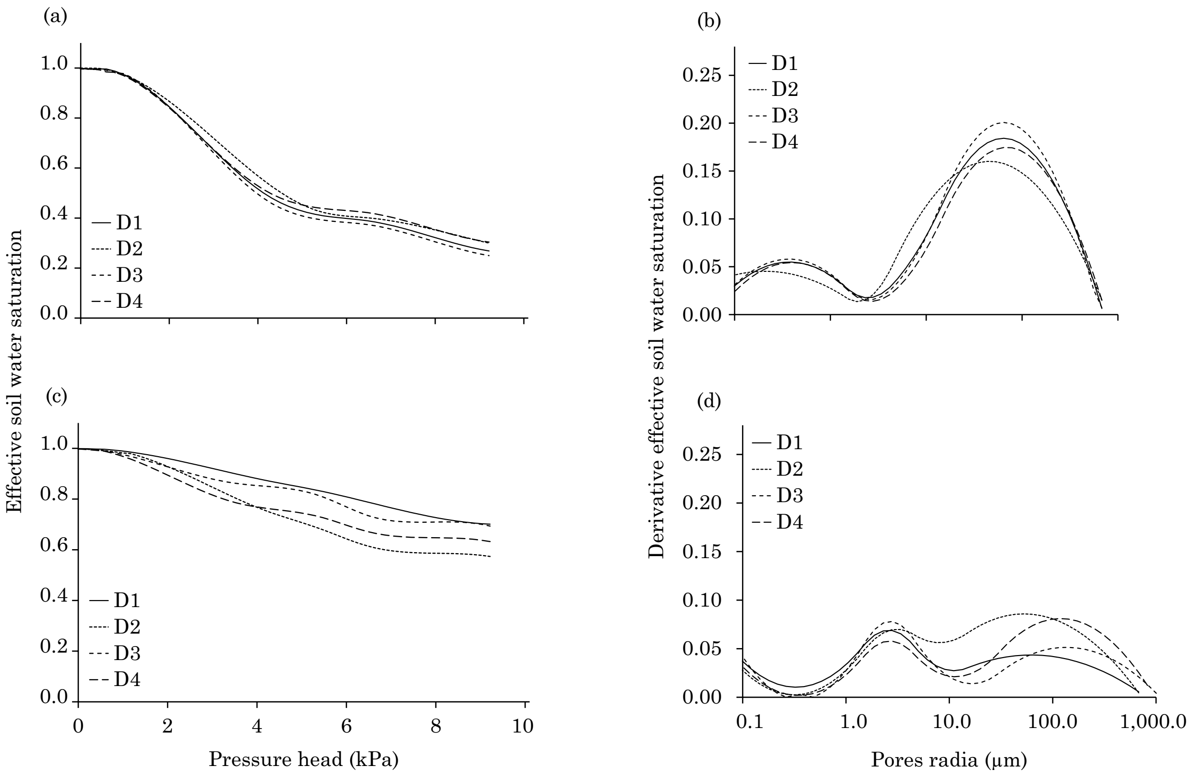

Figure 5. Effective soil water saturation (S_e) curves versus water pressure head (h) and contrasting pore size distributions (PSDs) under the continuous arable cropping sytem (a,b) and natural bush fallow system (c,d) for depths D1 (0-5 cm), D2 (5-10 cm), D3 (10-15 cm), and D4 (15-20 cm).

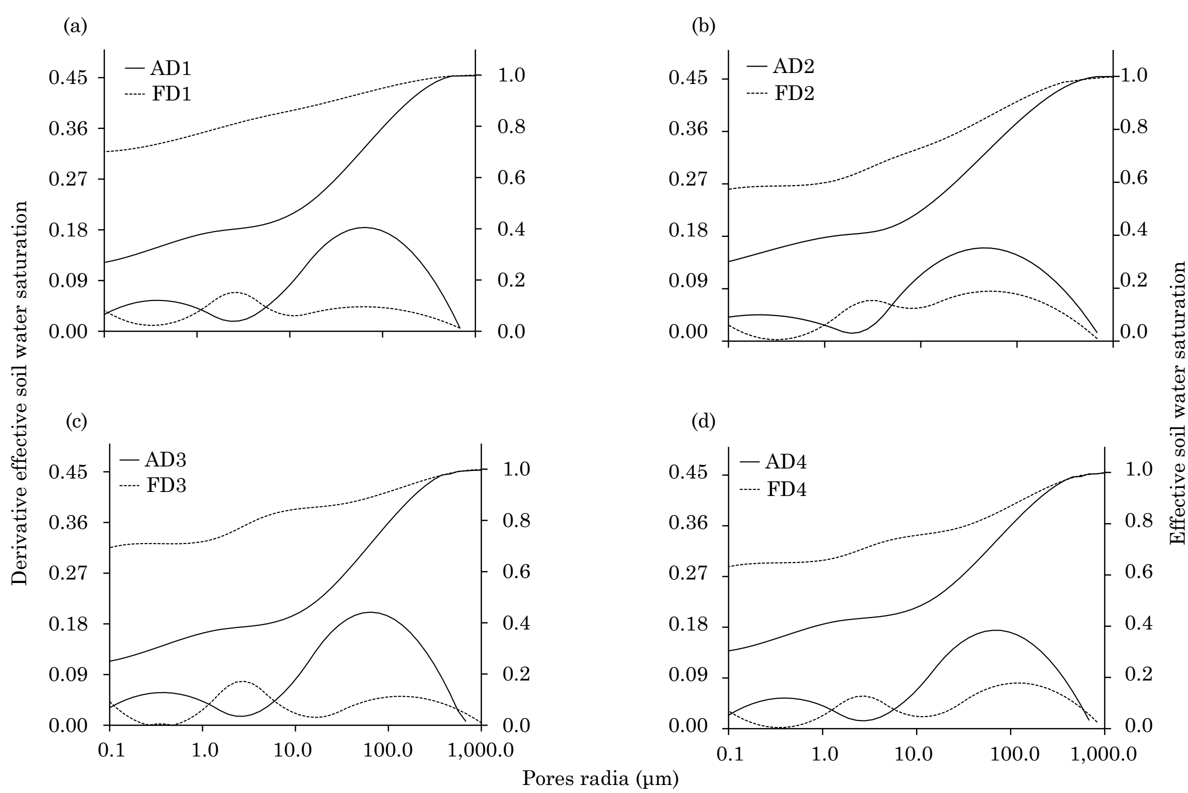

Figure 6. Effective soil water saturation (S_e) curves versus water pressure head (h) and contrasting pore size distributions (PSDs) under the continuous arable (A) cropping system and the natural bush fallow (F) system for depths D1 (0-5 cm) (a), D2 (5-10 cm) (b), D3 (10-15 cm) (c) and D4 (15-20 cm)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

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

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