Comissão 2.2 - Física do solo

INFLUENCE OF CRUST FORMATION UNDER NATURAL RAIN ON PHYSICAL ATTRIBUTES OF SOILS WITH DIFFERENT TEXTURES(1)

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SUMMARY

One of the main negative anthropic effects on soil is the formation of crusts, resulting in soil degradation. This process of physical origin reduces soil water infiltration, causing increased runoff and consequently soil losses, water erosion and/or soil degradation. The study and monitoring of soil crusts is important for soil management and conservation, mainly in tropical regions where research is insufficient to explain how soil crusts are formed and how they evolve. The purpose of this study was to monitor these processes on soils with different particle size distributions. Soil crusts on a sandy/sandy loam Argissolo Vermelho-Amarelo (Typic Hapludult), sandy loam Latossolo Vermelho-Amarelo (Typic Hapludox) and a clayey Nitossolo Vermelho eutroférrico (Rhodic Kandiudalf) were monitored. The soil was sampled and data collected after 0, 3, 5 and 10 rain storms with intensities above 25 mm h^{-1}, from December 2008 to May 2009. Soil chemical and particle size distribution analysis were performed. The changes caused by rainfall were monitored by determining the soil roughness, hydraulic conductivity and soil water retention curves and by micromorphological analysis. Reduced soil roughness and crust formation were observed for all soils during the monitored rainfall events. However, contrary to what was expected according to the literature, crust formation was not always accompanied by reductions in total porosity, hydraulic conductivity and soil water retention.

Index terms: surface crusting, soil roughness, micromorphology.

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(1) Study funded by FAPESP (2006/57233-3). Received for publication in February 19, 2010 and approved in September 15, 2011.

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(4) *In memoriam.*

RESUMO: *INFLUÊNCIA DA FORMAÇÃO DE CROSTAS SOB CHUVA NATURAL SOBRE ALGUNS ATRIBUTOS FÍSICOS DE SOLOS COM TEXTURAS CONTRASTANTES*

O encrostamento superficial do solo é um dos principais efeitos negativos provocados pela atividade humana e favorece a degradação do solo. Este processo, de origem física, diminui a infiltração de água no solo aumentando o escorrimento superficial ("runoff") e consequentemente a erosão hídrica e degradação do solo. O estudo e monitoramento das crostas superficiais são importantes para o manejo e conservação do solo e da água, principalmente em regiões de clima tropical, nas quais os trabalhos realizados são insuficientes para entender como os processos de formação e evolução das crostas ocorrem. O objetivo principal deste estudo foi monitorar a formação e evolução das crostas em solos de texturas contrastantes. Foram monitoradas crostas formadas em Argissolo Vermelho-Amarelo de textura arenosa/média, Latossolo Vermelho-Amarelo de textura média e Nitossolo Vermelho eutroférrico argiloso. As coletas e medições foram realizadas após 0, 3, 5 e 10 eventos chuvosos com intensidade acima de 25 mm h^{-1} *durante o período de dezembro de 2008 a maio de 2009. A caracterização dos solos foi realizada por meio de análises químicas e granulométricas. Para o monitoramento das modificações do solo causadas pela chuva foram realizadas medições de rugosidade superficial do solo, condutividade hidráulica, além da coleta de amostras indeformadas para construção das curvas de retenção de água e análise micromorfológica. A redução da rugosidade superficial e a formação de crostas superficiais foi observada para todos os solos ao longo de todos os eventos acompanhados. Entretanto, ao contrário do que era esperado segundo a literatura, a formação de crostas nem sempre foi acompanhada por uma redução da porosidade total, da condutividade hidráulica e da retenção de água no solo.*

Termos de indexação: encrostamento superficial, rugosidade do solo, micromorfologia.

INTRODUCTION

The erosion process consists in the detachment, transport and deposition of soil particles (Pimentel et al., 1995). As in other tropical countries, the main agent responsible for soil erosion in Brazil is water (Pagliai et al., 2003). Changes and the intensification of land use in agricultural areas can affect the soil structure, porosity, aeration, infiltration and productivity, as well as expose the soil to the direct impact of raindrops, promoting the appearance of soil surface crusts, one of the main factors of soil degradation (Valentin & Bresson, 1997; Jones, 2002). Some soil types are more susceptible to the crusting process, e..g, soils with higher silt and fine sand content and lower aggregate stability (Le Bissonnais & Bruand, 1993).

The influence of soil crusting on water infiltration was first studied by Duley (1939) and McIntyre (1958) and more recently some authors have looked into the phenomenon in tropical climate (Faria et al., 1997; Schaefer et al., 2002; Brandão et al., 2006). Brandão et al. (2006) determined multiple regression equations to estimate the hydraulic resistance of crusts originated by the direct impact of raindrops as well as the rate of infiltration into crusted soils.

Studies on loamy soils in Northeastern France showed that the formation of structural crusts can reduce the soil hydraulic conductivity from 45–60 mm h^{-1} to nearly 6 mm h^{-1}, and depositional crusts can reduce the hydraulic conductivity to nearly 1 mm h^{-1} (Martin et al., 1997). Reduction in soil infiltration of 50 to 100 % can occur in a single rainfall event and infiltration rates are higher in sloped areas where high erosion rates minimize crusting (Morgan, 2005).

Soil surface sealing that occurs during the formation of surface crusts and the loss of roughness seem to be the subprocesses responsible for high runoff rates and soil erosion (Le Bissonais & Bruand, 1993; Bajracharya & Lal, 1999; Darboux et al., 2001). The purpose of this study was to monitor the evolution of surface crusts in three soil types in relation to the accumulative effect of natural rainfall events, and to evaluate the effect of surface crusts on soil porosity, roughness and water infiltration and retention in the surface soil layer.

MATERIAL AND METHODS

The experiment was conducted in the region of Piracicaba-SP, Brazil, in 5 x 5 m plots, on three soils: Typic Hapludult (sandy/sandy loam Argissolo Vermelho-Amarelo), mean slope 4 %, Typic Hapludox (sandy loam Latossolo Vermelho-Amarelo), mean slope 3 %, and a Rhodic Kandiudalf (clayey Nitossolo Vermelho eutroférrico), mean slope 10 %. The particle size distribution of the Typic Hapludult and the Typic Hapludox were very similar (200, 70 and 700 g kg^{-1} clay, silt and sand, respectively) (Table 1). The clay content in the Rhodic Kandiudox was higher (500 g kg^{-1}) and sand content lower (400 g kg^{-1}).

Table 1. Particle size distribution of the studied soils

	Depth	Clay	Silt	Sand
	m		g kg^{-1}	
Typic Hapludox	Surface (0–0.05)	210	70	720
Typic Hapludox	Subsurface (0.10–0.15)	240	70	690
Typic Hapludult	Surface (0–0.05)	220	70	710
Typic Hapludult	Subsurface (0.10–0.15)	190	70	740
Rhodic Kandiudox	Surface (0–0.05)	500	110	390
Rhodic Kandiudox	Subsurface (0.10–0.15)	450	130	420

To ensure homogeneity of the surface conditions of all soils when setting up the experiment, the plots were tilled with a heavy disk and leveling harrow, simulating cropping conditions. A 16 disk harrow was used (depth 0.3 m) and tractioned by a Ford 6610 tractor. The initial soil cover was eliminated by a broad spectrum herbicide (glyphosate) to maintain the soil bare during the entire experimental period. A herbicide dose of 3 L ha^{-1} was applied by a manual backpack sprayer.

Surface crusting and soil roughness evolution were observed in the rainy season (November 2008 to May 2009). To monitor the evolution, the soil surface was maintained bare throughout this period. Field measurements and soil sampling were carried out four times, according to the sequence of rainfall events considered erosive. In this study, rainfall events were considered erosive at an intensity of < 25 mm h^{-1} (Hudson, 1965). The four measurements and samplings were determined: the first after soil tillage (T0), the second after the occurrence of three erosive rainfalls (T3), the third after the occurrence of five erosive rainfall events (T5) and the last after the occurrence of 10 erosive rainfall events (T10). Measurements and sampling were always performed in three replicates and 24 h after the end of each rainfall, to permit the drainage of any excess water from the study area.

The rainfall data were supplied by the automatic agrometeorological station of the Biosystems Engineering Department of ESALQ-USP, (available at <http://www.esalq.usp.br/departamentos/leb/postoaut.html>).

To characterize the surface horizons, soil particle size distribution and chemistry were analyzed in disturbed samples collected from the layers 0–0.05m and 0.1–0.15m. Five samples per plot were collected and homogenized to blend a sample for analysis. The particle size distribution was analyzed by the methodology proposed by Camargo (1986). Chemical analyses determined pH ($CaCl_2$ and H_2O), H + Al (Quaggio & Raij, 2001), Al^{3+} (Cantarella et al., 2001), Ca^{2+}, Mg^{2+}, K^+ and P contents (Raij & Quaggio, 2001), and Cu, Zn, Mn and Fe free ions (Abreu et al., 2001). Sulphur in the sulphate form (S-SO_4^{2-}) (Cantarella & Prochnow, 2001), and organic matter (Cantarella et al., 2001) were also analyzed. Total CEC (T), effective CEC (t), Al saturation (m), sum of bases or exchangeable cations (S), and base saturation (V) were calculated following the recommendations of Embrapa (1997).

Micromorphometrical, soil roughness and hydrophysical studies were used to monitor the formation and evolution of the surface crusts on the studied soils. The undisturbed soil samples used in the micromorphometrical studies were collected in three replicates in cardboard boxes (0.12 x 0.07 x 0.05 m). The samples were air-dried for 15 days and in a ventilated oven at 40 ºC for 48 h. The samples were impregnated with polyester resin and UVITEX OB (Cyba-Geigy®) fluorescent pigment (Murphy et al., 1977). After hardening, polished blocks were prepared and digital images captured for pore analysis and quantification. The distribution and pore morphology characteristics proposed by Murphy et al. (1977) and Ringrose-Voase (1991) were assessed using Noesis® Visilog 5.4 and macros developed in Microsoft Excel®. The pore quantity, size and type, as well as total porosity of the samples were calculated based on digital image analysis (Cooper et al., 2005; Juhász et al., 2007), and the porosity graphs constructed using SigmaPlot® software.

For the determination of the characteristic soil water retention curve and soil bulk density, undisturbed samples were collected in 50 10^{-6} m^3 stainless steel cylinders from the layers 0–0.05 m from each plot, in three replicates. The soil water retention curves were drawn for the matric potentials -1, -3, -5, -6, -8 and -10 kPa using the Haines funnel, and the potentials -33, -50, -70 and -100 kPa determined by Richards´ porous plate apparatus.

Soil water infiltration and hydraulic conductivity were calculated using the TRIMS multidisc infiltrometer and the protocol developed by Ankeny et al. (1991), based on Wooding's (1968) equation. This protocol estimates hydraulic conductivity $K(\psi)$ using only one disk in the measurements performed with the infiltrometer. Hydraulic conductivity was determined for the matric potentials -1, -3, -5 and -10 kPa.

Soil surface roughness was measured with a laser distancemeter mounted on a portable roughness scanner adapted from Arvidsson & Bölenius (2006) with a capacity of measuring an area of 1 m^2, with a vertical resolution of 0.05 mm and a horizontal grid of 2.00 mm, totaling 500,000 sampling points per plot.

Variograms were created using the GS+® software package to analyze the roughness evolution and the variances between the measured points.

Means were compared in tests to detect the differences between the data. The experiment was evaluated in a randomized block design considering the soil type as blocks and rainfalls as treatments. Tukey's test at 5 % probability and the statistical analyses were performed using the SAS® package.

RESULTS AND DISCUSSION

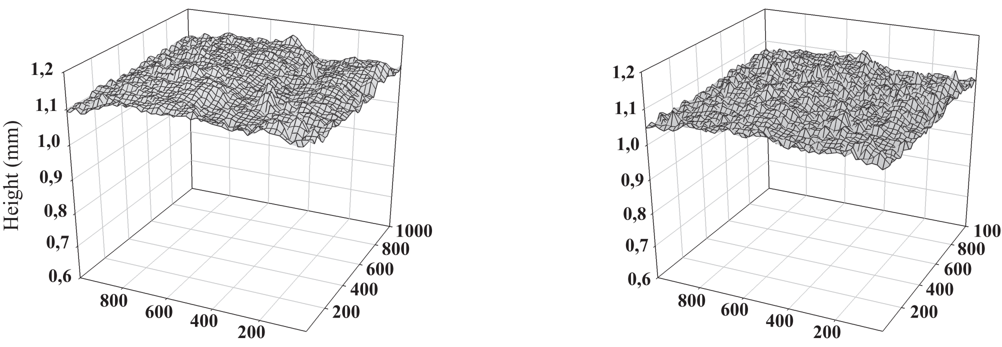
The evolution of the soil surface roughness along the sequence of the 10 rainfall events can be observed in figures 1 to 6, which show the roughness evolution at time zero (T0), after 3 (T3), after 5 (T5) and after 10 rainfalls (T10). The initial roughness of the Typic Hapludox was high, with a rugged microtopography in spite of the high pulverization of the aggregates caused by tillage (Figures 1 and 2). After the third rainfall (T3), changes were observed in surface conditions, with a less rough soil and a less undulating microrelief than at T0. Between the 3rd and 5th rainfall, the roughness measurements were similar, showing that in spite of some changes in the microtopography, the soil surface changed little between those rainfalls. After the 10th rainfall (T10) there was a significant reduction in roughness, forming a surface with a high smoothness degree (Figures 1 and 2).

The reduction in roughness of the Typic Hapludult (Figure 3) followed the same patterns observed in the Typic Hapludox, with a marked reduction from T0 to T10 and less accentuated between T0, T3 and T5. On the other hand, the concentration of soil aggregates at the soil surface after tillage (T0) was higher in the Typic Hapludult (Figure 4) than the Typic Hapludox.

The greatest changes were observed in the Rhodic Kandiudalf. At T0, the soil surface of the Rhodic Kandiudalf was rough with clods of various sizes (Figure 6) that were reduced with the sequence of rainfalls (Figures 5, 6a,b). The surface was smoothened after the rainfall sequence, but some of the clods remained and the appearance of fissures due to contraction and expansion processes of the clayey material by wetting and drying cycles was observed.

In the three soils studied, the roughness reduction was accompanied by a lowering of the soil surface evidenced by the modifications in the height measurements (Figures 1, 3 and 5). This process may have occurred due to the removal and redeposition of soil material by the natural accommodation of the soil particles, reducing the soil pore volume.

(a) Typic Hapludox T0 (b) Typic Hapludox T3



(c) Typic Hapludox T5 (d) Typic Hapludox T10

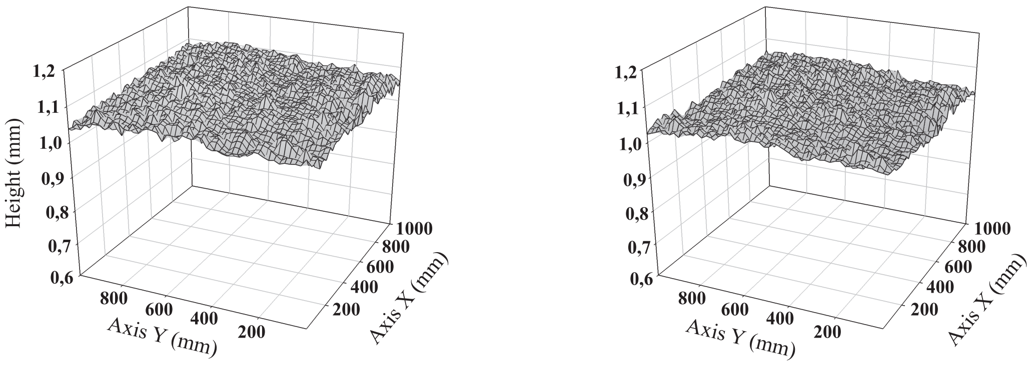


Figure 1. Roughness evolution of the Typic Hapludox during the rainfall events T0, T3, T5 and T10.

Soil surface roughness plays an important role in the control of runoff and is known as determinant of the capacity of a soil surface to retain, transport and deposit material (Darboux et al., 2001). A loss in surface roughness results in a loss of depressions of the microrelief that can alter the hydraulic resistance, runoff and increase water retention (Croft et al., 2009). The loss of soil surface roughness can be considered an important factor contributing to the time reduction of runoff formation. The smoothening of the soil surface diminishes the capacity of the soil surface to retain water and runoff can initiate as soon as the rainfall intensity surpasses the soil water infiltration rate (Darboux, 2001; Assouline, 2004; Croft et al., 2009).

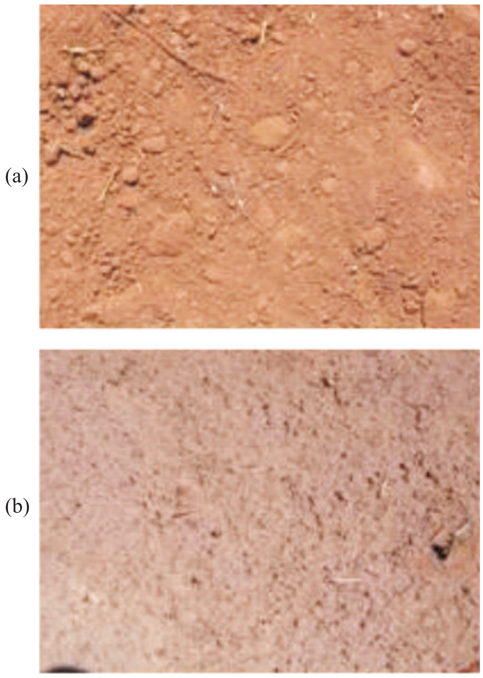
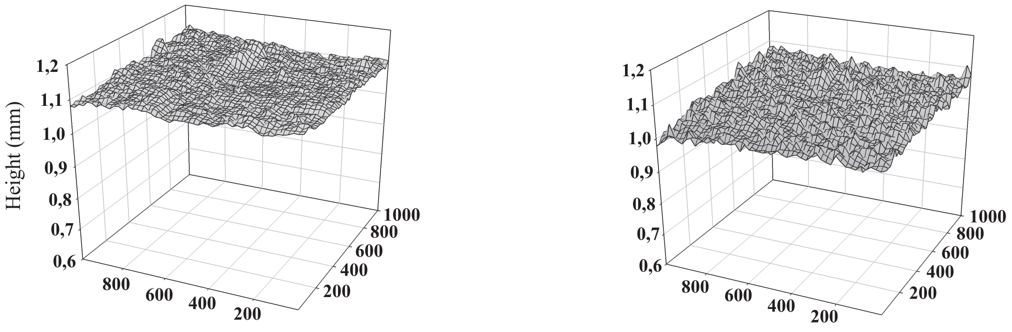


Figure 2. Surface roughness of the Typic Hapludox after tillage (T0) (a), and after 10 rainfall events (T10) (b).

The impact of raindrops on the soil surface, apart from modifying the surface roughness, can affect the soil structure and some of the soil physical properties. Among these modifications, changes in porosity caused by compression and remobilization of soil material can be cited. To evaluate how the raindrop impact affects soil porosity, micromorphometrical studies were performed to quantify and qualify the types of pores present in each sampling period of the experiment.

The images of the studied soils showed the formation of a crust made up of a apparently finer material than the material immediately below the crust. The Typic Hapludox presented high total porosity and number of pores in T0. In all monitored rainfalls, a low number of complex pores occupying a great area was observed. This indicates the high connectivity between pores in this soil. After three rainfall events (T3), few changes in total porosity, number of pores, and in the pore morphology and


(a) Typic Hapludult T0 (b) Typic Hapludult T3

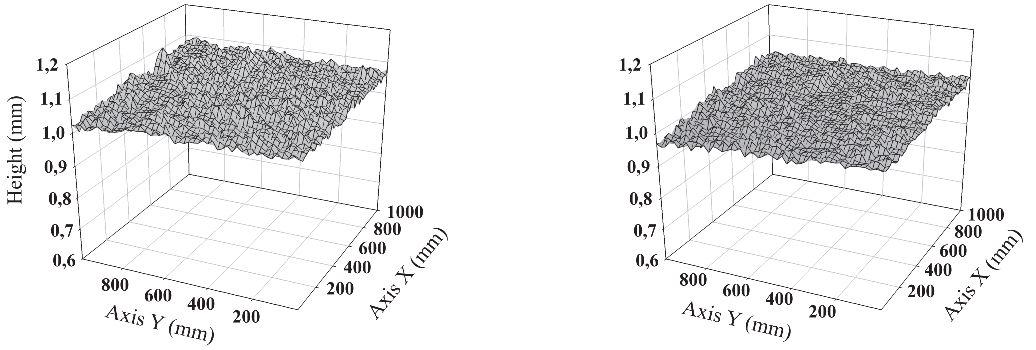

(c) Typic Hapludult T5 (d) Typic Hapludult T10

Figure 3. Roughness evolution of the Typic Hapludult during the rainfall events T0, T3, T5 and T10.

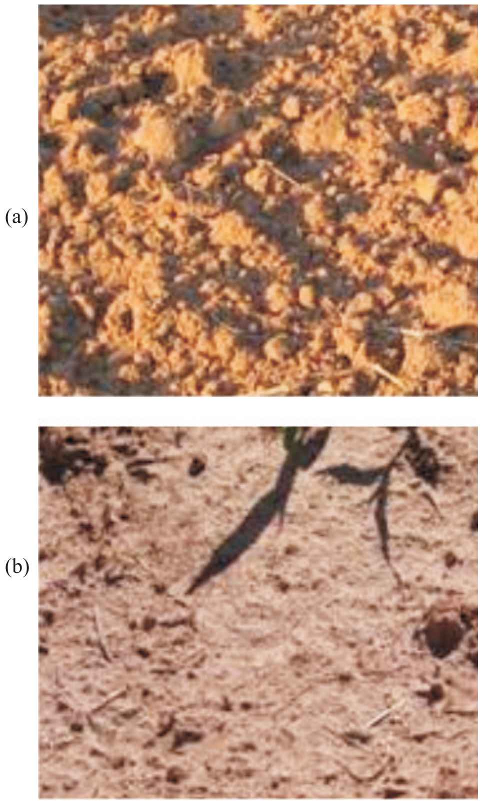


Figure 4. Surface roughness of the Typic Hapludult after tillage (T0) (a), and after 10 rainfall events (T10) (b).

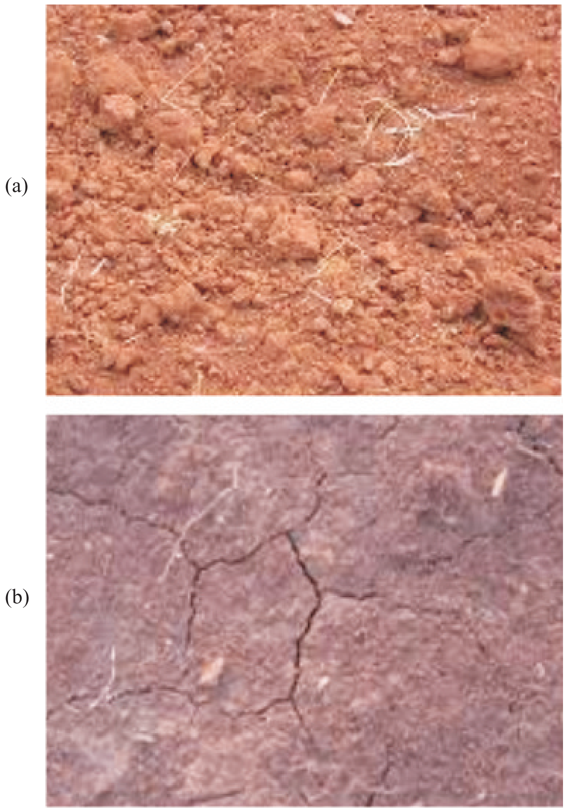


Figure 6. Surface roughness of the Rhodic Kandiudalf after tillage (T0) (a), and. after 10 rainfall events (T10) (b).

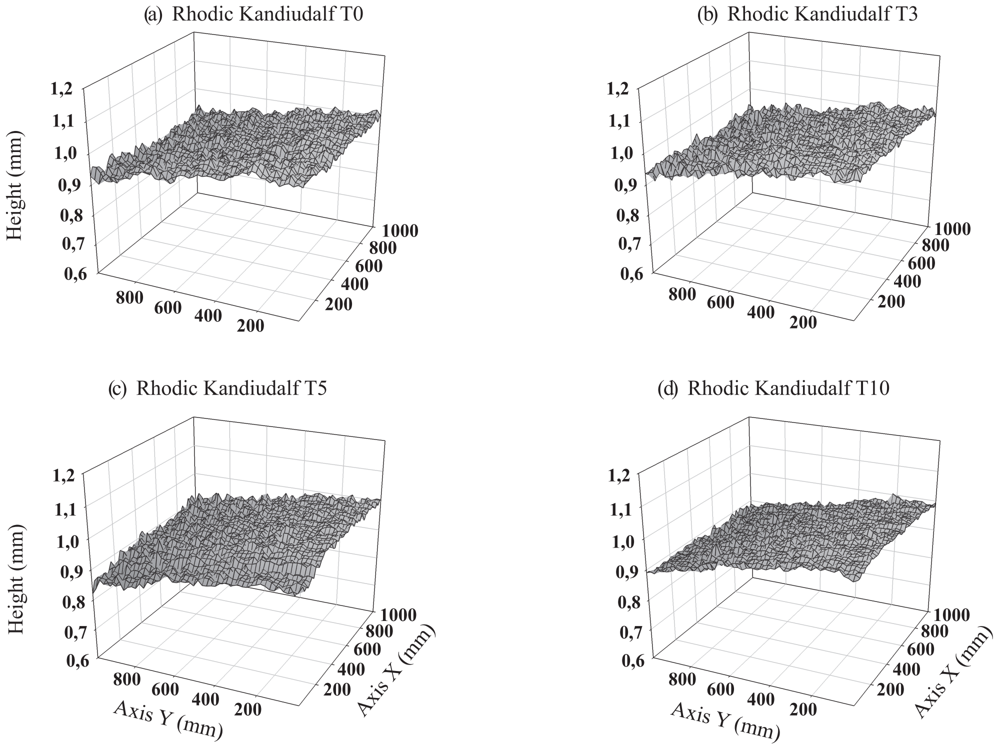


Figure 5. Roughness evolution for the Rhodic Kandiudalf during the rainfall events T0, T3, T5 and T10.

distribution were observed, whereas a loss in small elongated pores (20–50 μm) was recorded. At T5 and T10, the tendency was the same as at T3; the pore morphology and distribution were little altered, although some irregular and elongated pores were lost. This evolution did not affect total porosity.

No significant differences were detected in the changes in porosity (Table 2) that occur due to the redistribution of soil particles caused by the raindrop impact. The modifications in the soil structure induced by soil tillage that favor soil pulverization, together with the low clay contents, promote the detachment and mobilization of soil particles during rainfall (Morgan, 2005). The sequence of rainfall events caused

Table 2. Total porosity analysis of the studied soils

Treatment	Soil		
	Typic Hapludox	Typic Hapludult	Rhodic Kandiudalf
Rainfall	%		
0	60.44	45.06	41.14
3	42.75	51.87	40.68
5	43.52	55.26	28.31
10	50.16	58.6A	35.7

Means in each column do not differ statistically by Tukey's test ($p < 0.05$).

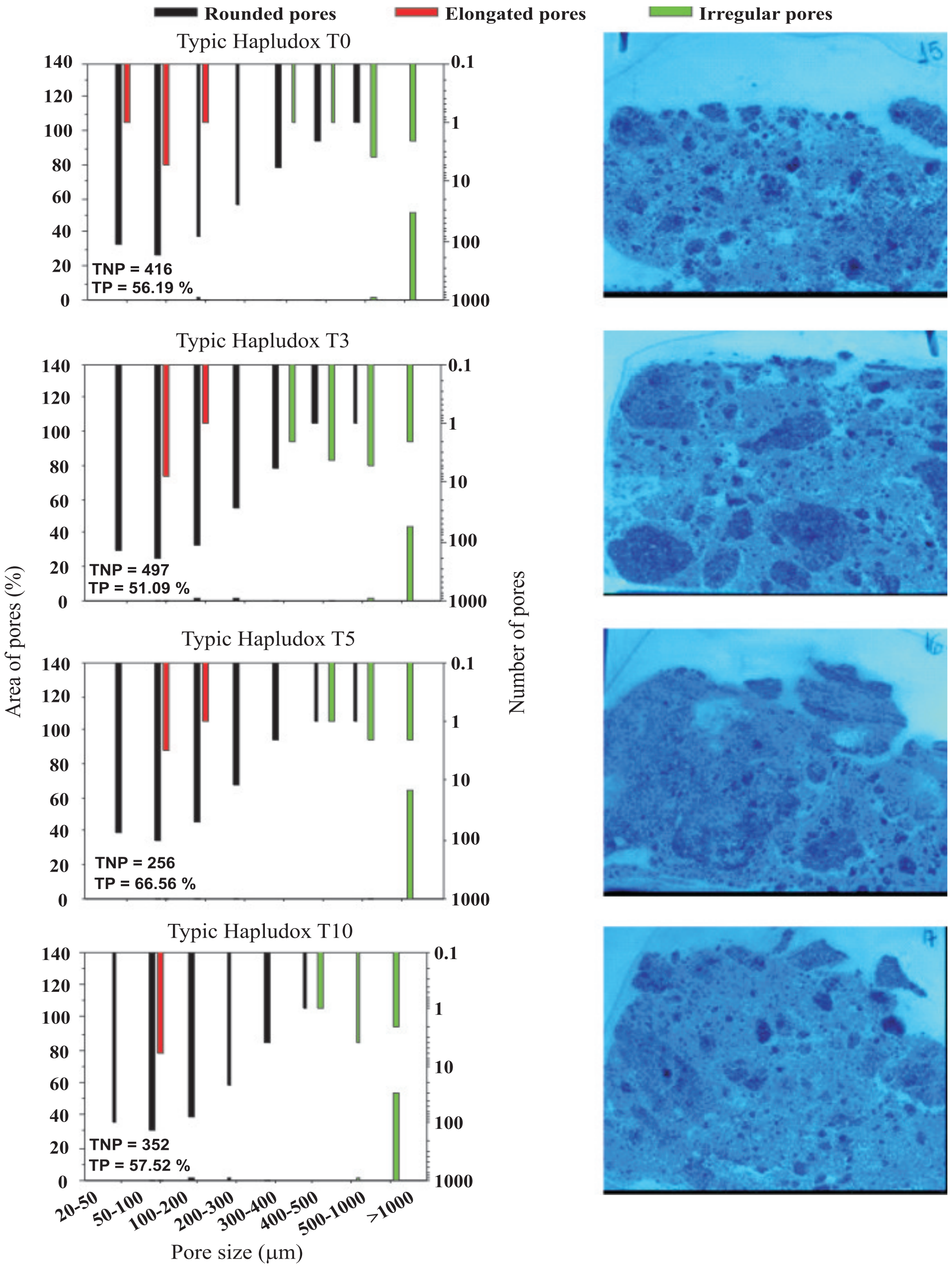


Figure 7. Number of pores and total porosity distribution in pore diameter classes for the Typic Hapludox after T0, T3, T5 and T10 rainfall events. TNP: total number of pores and TP: total porosity.

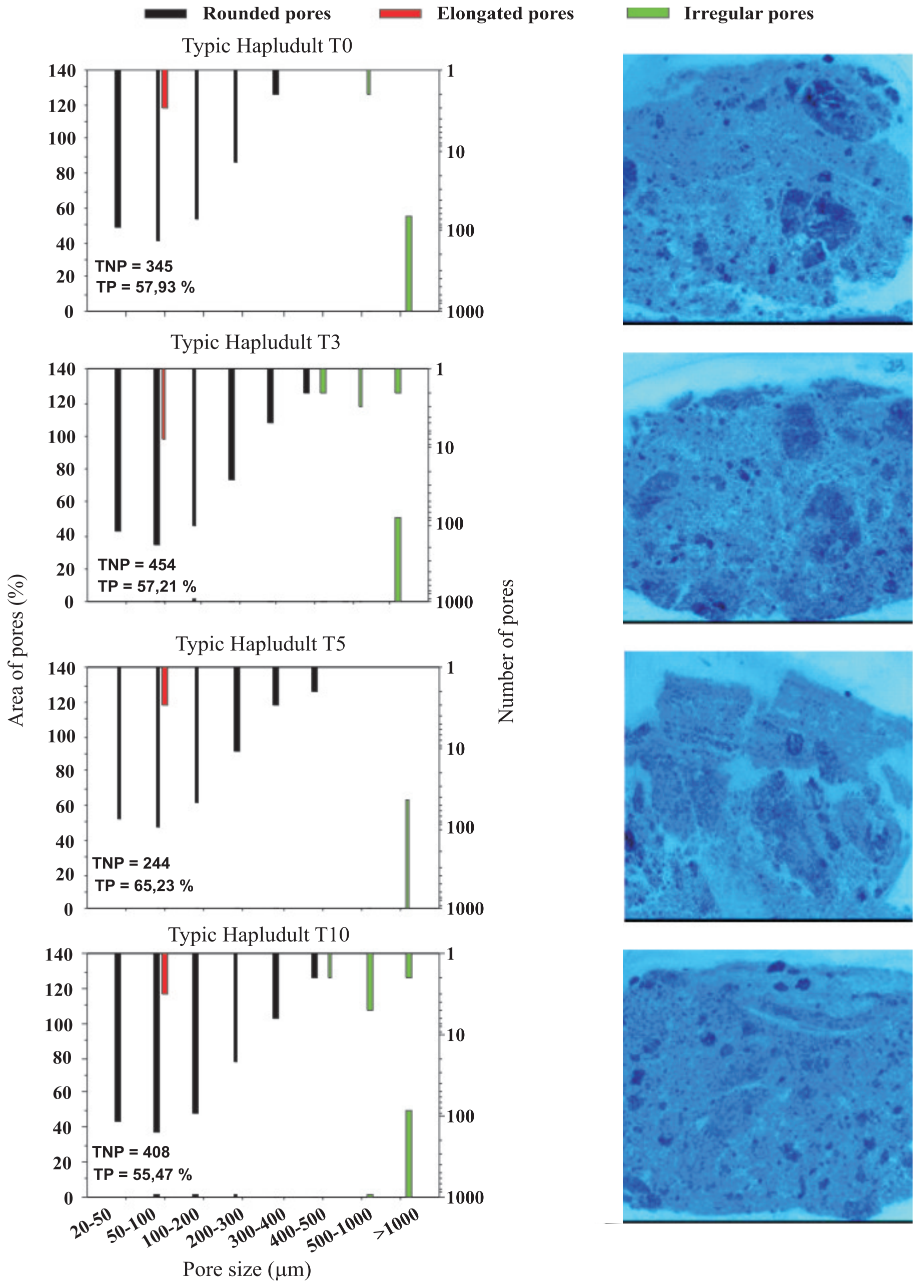


Figure 8. Number of pores and total porosity distribution in pore diameter classes for the Typic Hapludult after T0, T3, T5 and T10 rainfall events. TNP: total number of pores and TP: total porosity.

remobilization of soil material, but this remobilization caused no alterations in pore shape and organization, or in total porosity.

The total porosity of the Typic Hapludult was high at T0 (Figure 8) with well interconnected pores. As in the Typic Hapludox, the sequence of erosive rainfalls caused few changes in pore morphology, distribution and occupied area. The changes in porosity of the Typic Hapludult were not significant (Table 2). The mobilization and reassembly of the sandy material due to the rainfall sequence caused few changes in the surface porosity of this soil.

The greatest changes in porosity were observed in the Rhodic Kandiudalf, with a decrease in the area occupied by pores and modification of the pore morphology and distribution at each rainfall event, except at T10 (Figure 9). This reduction can be explained by the redistribution of the detached soil particles and soil compression due to raindrop impact on the soil surface (Huang et al., 1983), reducing the quantity of irregular and elongated pores. At T10, an increase in irregular pores was noted that can be explained by the appearance of elongated pores (fissures) which, as they coalesce due to intense

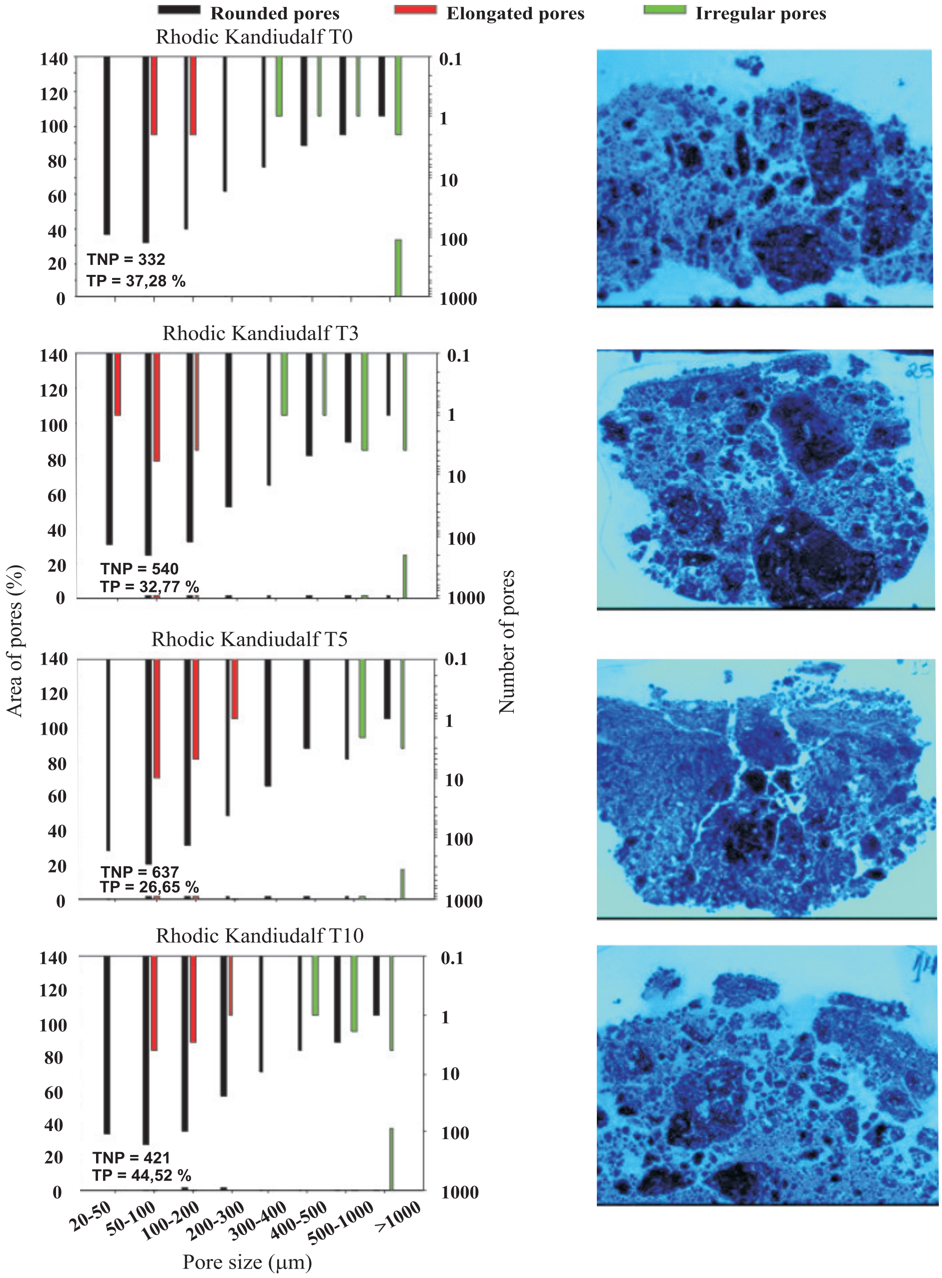


Figure 9. Number of pores and total porosity distribution in pore diameter classes for the Rhodic Kandiudalf after T0, T3, T5 and T10 rainfall events. TNP: total number of pores and TP: total porosity.

fissuration of this material caused by wetting and drying cycles that occur along the rainfall sequence, act as irregular pores. Despite the changes in porosity, no significant differences were observed for this property in the Rhodic Kandiudox (Table 2).

The low significant changes observed in soil porosity are confirmed by the few alterations observed in hydraulic conductivity. Different from results in the bibliography (McIntyre, 1958; Valentin & Bresson, 1992; Schaefer et al., 2002; Fox et al., 2004), the hydraulic conductivity measured between the analyzed periods (T0, T3, T5 and T10) did not decrease, showing that the crusting effect on the hydraulic conductivity for these soils is low.

The soil classification in relation to water conducting capacity was defined by Olson et al. (1996) who classified soil permeability in very low, low, moderate and high, based on the following respective permeability values: $< 8\ 10^{-5}$; $8\ 10^{-5}$ to $2\ 10^{-4}$; $2\ 10^{-4}$ to $3\ 10^{-4}$ and $> 3\ 10^{-4}$ m s^{-1}.

The hydraulic conductivity of the Typic Hapludox and Typic Hapludult is considered high and continued high during the whole experimental period (Figure 10a,c), without significant differences between rainfalls (Table 3). The slight rearrangement of porosity at T3, T5 and T10 (Figures 7 and 8) caused a minor decrease inhydraulic conductivity in these soils compared to T0, due to a small loss in the hydraulically active pores (Souza et al., 2007).

The greatest modifications in hydraulic conductivity were observed in the Rhodic Kandiudalf (Figure 10e), although no significant differences were observed among rainfalls, regardless of despite the high variability between measurements (Table 3).

The measured values for hydraulic conductivity at T0 were slightly higher (although without significant differences) than the measured values for the rainfall sequence and in relation to the other soils, although the Rhodic Kandiudalf is classified as a clayey soil (nearly 50 % clay). Great quantities of dispersible clay can have negative effects on hydraulic conductivity, once these particles are fine, hydrophilic and form micropores that favor water retention. However, when these fine particles form aggregates, the porosity and permeability of these soils increases, due to the formation of structural pores between the aggregates that promote soil drainage and hydraulic conductivity. Aggregates with high clay quantities are stable and take longer for changes aggregates formed in loamy texture soils (Le Bissonnais, 1996).

For the Rhodic Kandiudalf, the sequence of rainfalls caused changes in the total area occupied by pores, in the total number of pores (Figure 9) and the pore size and type, causing changes in soil hydraulic conductivity. Due to the modifications caused at the soil surface by the rainfall events, the hydraulic conductivity of this soil passed from a soil with high permeability to a soil with intermediate permeability (Olson et al., 1996). Although the differences in hydraulic conductivity of the Rhodic Kandiudalf were not significant, they were greatly reduced as the rainfall events proceeded, leading to lower values of hydraulic conductivity at T3, T5 and T10 than at T0.

In most cases, surface crusts are formed by the orientation and redistribution of soil material, with higher density and smaller pores than uncrusted soil (Souza et al., 2007). This increase in microporosity increases the soil water retention capacity and restricts water flux in these areas (Silva & Ribeiro, 1997).

The few changes in porosity observed in the Typic Hapludox and the Typic Hapludult also caused little changes in soil water retention (Figure 10b,d), once the pore distribution was not significantly modified. On the other hand, for the Rhodic Kandiudalf the changes in porosity affected soil water retention.

The soil water retention curves for the Typic Hapludox (Figure 10b) showed no significant differences in pore distribution and water retention patterns. This soil water retention behavior along the rainfall events was due to the pore morphology and distribution described in the image section. The dominance of irregular pores in this soil explains the course of the water retention curve along the rainfall events. The crust formation on the Typic Hapludox caused no changes in the water retention patterns.

The water retention measurements of the Typic Hapludult showed no differences (Figure 10d). The water retention curves show a well-drained soil with well-developed macroporosity with retention characteristics that were unaffected during the

Table 3. Hydraulic conductivity in the studied soils

Treatment	Soil		
	Typic Hapludox	Typic Hapludult	Rhodic Kandiudox
Rainfall		K (m s^{-1})	
		Ψ_m =-1 kPa	
0	1.63E-04	1.55E-04	8.92E-04
3	3.11E-04	9.69E-05	1.55E-04
5	8.68E-04	7.84E-04	5.78E-04
10	9.34E-05	1.28E-04	1.97E-04
		Ψ_m =-3.5 kPa	
0	2.75E-04	6.98E-05	3.77E-04
3	1.36E-04	3.48E-04	2.74E-05
5	7.40E-05	3.48E-04	3.53E-04
10	4.84E-05	7.88E-05	9.78E-05
		Ψ_m =-10.0 kPa	
0	3.91E-05	2.65E-05	1.33E-04
3	3.05E-04	2.81E-04	1.52E-05
5	1.31E-04	2.81E-04	1.16E-03
10	2.72E-05	3.54E-05	3.30E-05

Means in each column do not differ statistically by Tukey's test ($p < 0.05$).

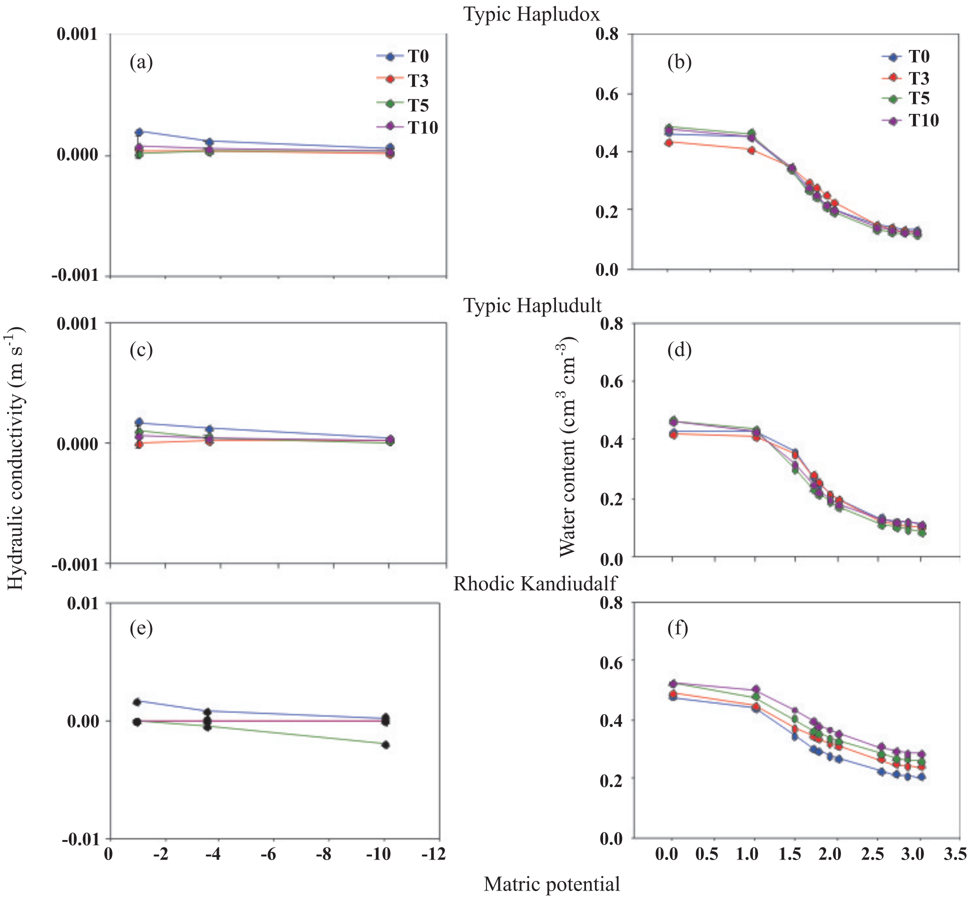


Figure 10. Hydraulic conductivity for the three soils after T0, T3, T5 and T10 rainfall events (a,c,e) and soil water retention curves for the soils after T0, T3, T5 and T10 rainfall events (b,d,f).

rainfall events. Similar to the Typic Hapludox, no changes were observed in the water retention patterns of the Hapludult due to crust formation. The evidences observed in pore morphology studies explain the shape of the water retention curves as the rainfall events occurred.

The variability of the water retention curves for the Rhodic Kandiudalf was higher than for the other studied soils (Figure 10f). Similar to the behavior of pore morphology after 10 rainfall events, the soil water retention curves also indicated changes during the rainfall sequence. The curves showed increased water retention at all matric potentials measured between T0 and T10. The pore morphology evolution from T0 to T10 showed a decrease in irregular pores from T0 to T5 and an increase at T10. At the same time, a higher quantity of elongated and rounded pores was formed. The increase in water retention, mainly at the matric potentials between -30 kPa and -1000 kPa, is a result of the modified pore morphology. The transformation of conducting (irregular and large elongated) pores to retention (rounded and small to medium elongated) pores would explain the higher retention at these matric potentials. On the other hand, the increase in the quantity of elongated pores and their probable coalescence, forming irregular pores after T10, caused increased retention at lower matric potentials (saturation up to -10 kPa), though below the increase observed in matric potentials above -30 kPa (Silva & Ribeiro, 1997).

CONCLUSIONS

1. The formation of surface crusts was observed for all soils analyzed, and soil texture was an important factor in the differentiation of the formation of these crusts.

2. The hydraulic conductivity in the Rhodic Kandiudalf was reduced and pore morphology and water retention patterns varied due to the crust formation as the rainfall events succeeded.

3. The crust formation on the Typic Hapludox and the Typic Hapludult did not significantly affect pore morphology, soil hydraulic conductivity rates and water retention patterns.

4. Soil surface roughness was reduced with the occurrence of rainfalls, independently of the clay content of the soil.

5. Our results suggests that the eventual runoff formation from tropical soils with loamy and clayey texture seems to be more related to a reduction in the soil surface roughness, that would reduce the surface water storage, than to changes in porosity and reduction of the soil hydraulic conductivity.

ACKNOWLEDGEMENTS

The authors wish to thank FAPESP (Fundação de Amparo à Pesquisa do Estado de São Paulo) for funding the project (no. 2006/57233-3) and the CNPq (Conselho Nacional de Desenvolvimento Científico e Tecnológico) for the scholarships. They are also indebted to Carlos Eduardo Pinto Juhász, Pedro Lian D.B. Castanho, Lucas P.R. Conte, Raul S. Toma, Jaqueline D. Rosa, João Medeiros, Tatiana Rittl, Ariane Teato, Renata C. Bovi, Gabriela Rabello, Renata S. Momoli, for their help at various stages of this research.

LITERATURE CITED

ABREU, C.A.; ABREU, M.A. & ANDRADE, J.C. Determinação de cobre, ferro, manganês, zinco, cádmio, cromo, níquel e chumbo em solos usando a solução de DTPA em pH 7,3. In: RAIJ, B.van; ANDRADE, J.C.; CANTARELLA, H. & QUAGGIO, J.A., ed. Análise química para avaliação da fertilidade de solos tropicais. Campinas, Instituto Agronomico de Campinas, 2001. p.240-250.

ANKENY, M.D.; AHMED, M.; KASPAR, T.C. & HORTON, R. Simple field method for determining unsaturated hydraulic conductivity. Soil Sci. Soc. Am. J., 55:467-470, 1991.

ARVIDSSON, J. & BÖLENIUS, E. Effects of soil water content during primary tillage – laser measurements of soil surface changes. Soil Till. Res., 90:222-229, 2006.

ASSOULINE, S. Rainfall-induced soil surface sealing: A critical review of observations, conceptual models and solutions. Vadose Zone J., 3:570-591, 2004.

BAJRACHARYA, R.M. & LAL, R. Land use effects on soil crusting and hydraulic response of surface crusts on a tropical Alfisol. Hydrol. Proc., 13:59-72, 1999.

BRANDÃO, V.S.; SILVA, D.D.; RUIZ, H.A.; PRUSKI, F.F.; SCHAEFER, C.E.G.R.; MARTINEZ, M.A. & MENEZES, S.J.M.C. Resistência hidráulica da crosta formada em solos submetidos a chuvas simuladas. R. Bras. Ci. Solo, 30:13-21, 2006.

CAMARGO, O.A.; MONIZ, A.C.; JORGE, J.A. & VALADARES, J.M.A.S. Métodos de análise química, mineralógica e física de solos do Instituto Agronômico de Campinas. Campinas, Instituto Agronômico de Campinas, 1986. 94p. (Boletim Técnico, 106)

CANTARELLA, H. & PROCHNOW, L.I. Determinação de sulfato em solos. In: RAIJ, B.van; ANDRADE, J.C.; CANTARELLA, H. & QUAGGIO, J.A., ed. Análise química para avaliação da fertilidade de solos tropicais. Campinas, Instituto Agronômico de Campinas, 2001. p.225-230.

CANTARELLA, H.; QUAGGIO, J.A. & RAIJ, B.van. Determinação da matéria orgânica. In: RAIJ, B.van; ANDRADE, J.C.; CANTARELLA, H. & QUAGGIO, J.A., ed. Análise química para avaliação da fertilidade de solos tropicais. Campinas, Instituto Agronômico de Campinas, 2001. p.173-180.

CANTARELLA, H.; RAIJ, B.van; COSCIONE, A.R. & ANDRADE, J.C. Determinação de alumínio, cálcio e magnésio trocáveis em extrato de cloreto de potássio. In: RAIJ, B.van; ANDRADE, J.C.; CANTARELLA, H. & QUAGGIO, J.A., ed. Análise química para avaliação da fertilidade de solos tropicais. Campinas, Instituto Agronômico de Campinas, 2001. p.213-224.

COOPER, M.; VIDAL TORRADO, P. & CHAPLOT, V. Origin of microaggregates in soils with ferralic horizons. Sci. Agric., 62:256-263, 2005.

CROFT, H.; ANDERSON, K. & KUHN, N.J. Characterizing soil surface roughness using a combined structural and spectral approach. Eur. J. Soil Sci., 60:431-442, 2009.

DARBOUX, F.; DAVY, P.; GASCUEL-ODOUX, C. & HUANG, C. Evolution of soil surface roughness and flowpath connectivity in overland flow experiments. Catena, 46:125-139, 2001.

DULEY, F.L. Surface factors affecting the rate of intake of water by soils. Soil Sci. Soc. Am. Proc., 4:60-64, 1939.

EMBRAPA BRASILEIRA DE PESQUISA AGROPECUÁRIA - EMBRAPA. Manual de métodos de análise de solos. 2.ed. Rio de Janeiro, Centro Nacional de Pesquisa de Solos, 1997. 212p.

FARIA, J.C.; SCHAEFER, C.E.; RUIZ, H.A. & COSTA, L.M. Soil physical degradation and sealing development: the effects of weed control methods. In: SIMPÓSIO BRASILEIRO DE RECUPERAÇÃO DE ÁREAS DEGRADADAS, 3., Ouro Preto, 1997. Anais... Ouro Preto, 1997. p.187-193.

FOX, D.M.; BRYAN, R.B. & FOX, C.A. Changes in pore characteristics with depth for structural crusts. Geoderma, 120:109-120, 2004.

HUANG, C.; BRADFORD, J.M. & CUSHMAN, J.H. A numerical study of raindrop impact phenomena: the elastic deformation case. Soil Sci. Soc. Am. J., 47:855-861, 1983.

HUDSON, N.W. The influence of rainfall on the mechanics of soil erosion with particular reference to Southern Rhodesia. Cape Town, University of Cape Town, 1965. (Tese de Mestrado)

JONES, R.J.A. Assessing the vulnerability of soils to degradation. In: PAGLIAI, M. & JONES, R.J.A., ed. Sustainable land management – environmental protection: A soil physical approach. Catena, 35:33-44, 2002.

JUHÁSZ, C.E.P.; COOPER, M.; CURSI, P.R.; KETZER, A.O. & TOMA, R.S. Savanna woodland soil micromorphology related to water retention. Sci. Agric., 64:344-354, 2007.

LE BISSONNAIS, Y. Aggregate stability and assessment of soil crustability and erodibility: I. Theory and methodology. Europ. J. Soil Sci., 47:425-437, 1996.

LE BISSONNAIS, Y. & BRUAND, A. Crust micromorphology and runoff generation on silty soil materials during different seasons. In: POESEN, J.W.A. & NEARING, M.A., ed. Soil surface sealing and crusting. Catena, 24:1-16, 1993 (Supplement, 24)

MARTIN, P.; Le BISSONNAIS, Y.; BENKHADRA, H.; LIGNEAU, L. & OUVRY, J.F. Mesures du ruissellement et de l'érosion diffuse engendrés par les pratiques culturales en Pays de Caux (Normandie). Géomorphol. Relief Proc. Environ., 2:143-154, 1997.

McINTYRE, D.C. Permeability measurements of soil crusts formed by raindrop impact. Soil Sci., 85:185-189, 1958.

MORGAN, R.P.C. Soil erosion and conservation. 3.ed. New York, Blackwell Publishing, 2005. 320p.

MURPHY, C.P.; BULLOCK, P. & TURNER, R.H. The measurement and characterization of voids in soil thin sections by image analysis. Part I. Principles and techniques. J. Soil Sci., 28:498-508, 1977.

OLSON, G.L.; McQUAID, B.F.; EASTERLING, K.N. & SCHEYER, J.M. Quantifying soil condition and productivity in Nebraska. In: DORAN, J.W. & JONES, A.J., ed. Methods for assessing soil quality. Soil Sci. Soc. Am., 49:357-369, 1996. (SSSA Special Publication, 49)

PAGLIAI, M.; MARSILI, A.; SERVADIO, P.; VIGNOZZI, N. & PELLEGRINI, S. Changes in some physical properties of a clay soil in Central Italy following the passage of rubber tracked and wheeled tractors of medium power. Soil Till. Res., 73:119-129, 2003.

PIMENTEL, D.; HARVEY, C.; RESOSUDARMO, P.; SINCLAIR, K.; KURZ, D.; McNAIR, M.; CRIST, S.; SHPRITZ, L.; FITTON, L.; SAFFOURI, R. & BLAIR, R. Environmental and economic costs of soil erosion and conservation benefits. Science, 267:1117-1122, 1995.

QUAGGIO, J.A. & RAIJ, B.van. Determinação do pH em cloreto de cálcio e da acidez total. In: RAIJ, B.van; ANDRADE, J.C.; CANTARELLA, H. & QUAGGIO, J.A., ed. Análise química para avaliação da fertilidade de solos tropicais. Campinas, Instituto Agronômico de Campinas, 2001. p.173-180.

RAIJ, B.van & QUAGGIO, J.A. Determinação de fósforo, cálcio, magnésio e potássio extraídos com resina trocadora de íons. In: RAIJ, B.van; ANDRADE, J.C.; CANTARELLA, H. & QUAGGIO, J.A., ed. Análise química para avaliação da fertilidade de solos tropicais. Campinas, Instituto Agronômico de Campinas, 2001. p.189-199.

RINGROSE-VOASE, A.J. Micromorphology of soil structure: Description, quantification, application. Austr. J. Soil Res., 29:777-813, 1991.

SCHAEFER, C.E.R.; SILVA, D.D.; PAIVA, K.W.N.; PRUSKI, F.F.; ALBUQUERQUE FILHO, M.R. & ALBUQUERQUE, M.A. Perdas de solo, nutrientes, matéria orgânica e efeitos microestruturais em Argissolo Vermelho-Amarelo sob chuva simulada. Pesq. Agropec. Bras., 37:669-678, 2002.

SILVA, A.J.N. & RIBEIRO, M.R. Caracterização de Latossolo Amarelo sob cultivo contínuo de cana-de-açúcar no Estado de Alagoas: Atributos morfológicos e físicos. R. Bras. Ci. Solo, 21:677-684, 1997.

SOUZA, E.S.; ANTONINO, A.C.D.; LIMA, J.R.S.; GOUVEIA NETO, G.C.; SILVA, J.M. & SILVA, I.F. Efeito do encrostamento superficial nas propriedades hidráulicas de um solo cultivado. R. Bras. Ci. Agric., 2:69-74, 2007.

VALENTIN, C. & BRESSON, L.M. Morphology, genesis and classification of surface crusts in loamy and sandy soils. Geoderma, 55:225-245, 1992.

VALENTIN, C. & BRESSON, L.M. Soil crusting. In: LAL, R.; BLUM, W.H.; VALENTIN, C. & STEWART, B.A., ed. Methods for assessment of soil degradation. Boca Raton, 1997. p.89-107.

WOODING, R.A. Steady infiltration from a shallow circular pond. Water Res. Res., 4:1259-1273, 1968.