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ORIGINAL ARTICLE

Porosity and structure in Brazilian hardsetting soils: an evaluation by 2D-image analysis

Porosidade e estrutura de solos coesos brasileiros: uma avaliação por análise de imagens em 2D

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Estrutura do solo

ABSTRACT: Limited knowledge about the hardsetting attribute in soils of the southeast and northeast regions of Brazil have restricted the exploitation of expressive agricultural areas, especially with eucalyptus, citrus and sugarcane. Aiming to evaluate how hardsetting behavior is manifested in terms of structural organization and distribution of pore shape and size classes, three hardsetting horizons were sampled in Dystrophic Yellow Argisols (Ultisols) in the Coastal Tablelands and submitted to micromorphological analysis. To this end, intact, vertically oriented soil blocks were collected from each hardsetting horizon. The blocks were impregnated with resin and fluorescent pigment and then cut into thin sections. A detailed study of pore classes was conducted by 2-D image analysis in eight captured images of thin sections, which represented approximately 80% of the total surface of the sections. By image analysis, it was possible to evaluate the distribution of pore area and number, as well as shape, size and preferential orientation (direction) in relation to the block surface. Our findings confirm the hypothesis that hardsetting horizons in the coastal tablelands of Brazil are similar regarding structural organization and pore network, and that pore size can be modified by soil management practices. The number and distribution of pore size classes revealed that the pore network in hardsetting soils exhibits random distribution and that the elongated pores are reduced in length owing to their low interconnectivity.

RESUMO: *O conhecimento limitado sobre o caráter coeso de solos das regiões Sudeste e Nordeste do Brasil vem restringindo a exploração agrícola de áreas expressivas, especialmente com as culturas de eucalipto, citrus e cana-de-açúcar. Com o objetivo de avaliar como o caráter coeso se manifesta em termos de organização estrutural e distribuição do tamanho e da forma de poros, foram amostrados três horizontes coesos provenientes de Argissolos Amarelos Distróficos da faixa dos Tabuleiros Costeiros, sendo esses horizontes submetidos a um estudo micromorfológico. Para tanto, foram coletados blocos de solo indeformados e verticalmente orientados de cada horizonte coeso. Os blocos foram impregnados com resina e pigmento fluorescente, e posteriormente cortados em lâminas finas. O estudo detalhado do espaço poroso foi realizado por análise de imagens em 2D em oito imagens capturadas das lâminas finas, que representavam cerca de 80% da superfície das lâminas. A análise de imagens permitiu verificar a distribuição da área e do número de poros, bem como a forma, o tamanho e a orientação – ou direção – preferencial dos mesmos em relação à superfície do bloco. Os resultados confirmaram a hipótese de que os horizontes hardsetting avaliados apresentaram características similares em termos de organização estrutural e de sistema poroso, e que o tamanho dos poros pode ser modificado pelas práticas de manejo. O número e a distribuição de poros por classes de tamanho revelaram que a rede de poros nos horizontes hardsetting exibe uma distribuição aleatória e os poros alongados ocorrem em número reduzido em razão da sua pequena conectividade.*

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1 Introduction

Brazilian hardsetting soils have been studied for approximately forty years, but the hardsetting effect still has not been explained. The natural densification of soil constitutes a significant contribution to the hardening process (GIAROLA et al., 2003; GIAROLA; SILVA, 2002), because the densification process increases the contact area between solid particles, which in turn, increases the effective stress, and tends to hold soil particles together more strongly on drying (GIAROLA et al., 2003).

The densification of hardsetting horizons confers effects very similar to the process of mechanical compaction on soils in terms of structural alterations and, as a consequence, of pore space (GIAROLA et al., 2003). Modifications in the pore space lead to a reduction in water infiltration in the soil and an increase in soil resistance to root penetration. The geometry of pore space, particularly the size, shape and continuity of pores, affects the development of roots because this feature limits the paths of elongation. Indirectly, owing to its effect on aeration and infiltration, pore space geometry affects water redistribution and drainage (LAWRENCE, 1977; RINGROSE-VOASE; BULLOCK, 1984).

Few studies have used pore space characteristics, established through image analysis, to better understand the behavior of hardsetting horizons (CHARTRES; NORTON, 1994; GIAROLA et al., 2003; BRESSON; MORAN, 2004; LIMA et al., 2006). In Brazil, a pioneering study by Lima et al. (2006) demonstrated that hardsetting horizons, compared with non-hardsetting horizons, present more medium and large-sized rounded pores, and that the few occurring elongated pores showed a preferential orientation towards horizontal direction, thus explaining many of the physical aspects which are typical of these systems. Although exclusive to Brazilian hardsetting soils, Lima's study was performed using Gray Argisol (Ultisol), a soil which is inexpressive both economically and geographically in this country. Other hardsetting soils such as Yellow Argisols (Ultisols) and Yellow Latosols (Oxisols) are more widely distributed and support important crops such as eucalyptus, sugarcane, papaya, and citrus, which contribute approximately with 30% of the Gross National Product (GNP) (CINTRA; LIBARDI; SAAD, 2000).

This study examines the hypothesis that Brazilian hardsetting horizons present similar characteristics regarding structural organization and pore network, specifically the shape, size and orientation of pores.

In this study, we aimed to evaluate how hardsetting behavior is manifested in terms of structure and porosity in horizons of Yellow Argisols in the Coastal Tablelands of Brazil using image analysis techniques.

2 Materials and Methods

This study was carried out in three modal hardsetting soil profiles located on the Brazilian coast, represented geologically by sediments of the Barreiras Group. The typical landscapes of these sediments are extensive plateaus, generally dissected by deep, steep walled valleys, with average altitude ranging from 60 to 200 m on the coastal tablelands. Soil 1 (H1) was collected near the municipality of Campos dos Goytacazes (21°45'S; 41°19'W) in Rio de Janeiro state, in an abandoned pasture, with the hardsetting horizon identified at the depth of 0.60 m. Soil 2 (H2) was collected near the municipality of Porto Seguro (16°26'S; 39°05'W) in Bahia state, under tropical forest, presenting the hardsetting horizon at the depth of 0.38 m. Soil 3 (H3) was collected near the municipality of Aracruz (19°50'S; 40°03'W), in Espírito Santo state (Figure 1), under an experimental area of eucalyptus, where the hardsetting horizon was encountered at the depth of 0.60 m. All sampled soils were classified as Dystrophic Yellow Argisol (EMBRAPA, 2006).

The soils were highly weathered and kaolinitic (Ki < 2.2, where Ki = $\frac{\%SiO_2 \times 1.7}{\%Al_2O_3}$) (RAIJ; VALADARES, 1979), with low organic matter content (established by oxidation with potassium dichromate) and low cation exchange capacity (CEC) (extracted using an ion exchange resin) (EMBRAPA, 1997) (Table 1). Only the hardsetting horizons (Bt1) were studied in these soils, as characterized in Table 1.

Based on the preliminary morphological descriptions, undisturbed, vertically oriented soil samples (0.15 × 0.10 × 0.10 m) were collected from the most homogeneous and representative portions of the profiles studied, and were impregnated with polyester resin containing fluorescent dye (JONGERIUS; HEINTZBERGER, 1975). Thin sections were observed under a stereomicroscope using UV light. The characteristics of the soils were described according to the procedures suggested by Brewer (1976) and Bullock et al. (1984).

Eight sections (12 × 15 mm) were cut and removed from each soil sample for image analysis. Digital images were captured from impregnated blocks using a color CCD camera with a resolution of 1024 × 768 pixels, at 25x magnification, equivalent to 25 μm^2 pixel (0.000025 mm^2). Images were processed using the Noesis Visilog® image analysis software.

The analysis was performed on 2D image. The representation of soil porosity did not consider the three-dimensional aspects of continuity between pores, in which space is computed according to the area and not the volume (MORAN et al., 1988). Total soil porosity and soil pore distribution were measured using the shape and size of pores. Two indices were applied (LIMA et al., 2006) in order to define shape: the first index, $\mathbf{I}_1$, was used to differentiate rounded pores ($\mathbf{I}_1$=1) from non-rounded pores ($\mathbf{I}_1 \neq 1$); the second index, $\mathbf{I}_2$, was used to differentiate elongated pores ($\mathbf{I}_2 \leq 2.2$) from complex pores ($\mathbf{I}_2 > 2.2$). Pore distribution into size classes included micropores (< 0.03 mm diameter (∅)), mesopores (0.03 and 0.08 mm diameter), and macropores (>0.08 mm diameter) (BREWER, 1976; LUXMOORE, 1981). The orientation or direction of pores was calculated only for the elongated pore class, using the horizontal (*Fh*) and vertical (*Fv*) Feret diameters, where: *Fh* = *Fv* corresponds to no orientation, *Fh* > *Fv* to negative orientation, and *Fh* < *Fv* to positive orientation (MURPHY; BULLOCK; BISWELL, 1977).

Statistical analysis was carried out by employing the Least Significant Difference (LSD) test at the 5% probability level, using the GLM procedure of the SAS software package. All means (±SD) were derived from eight replicate samples.

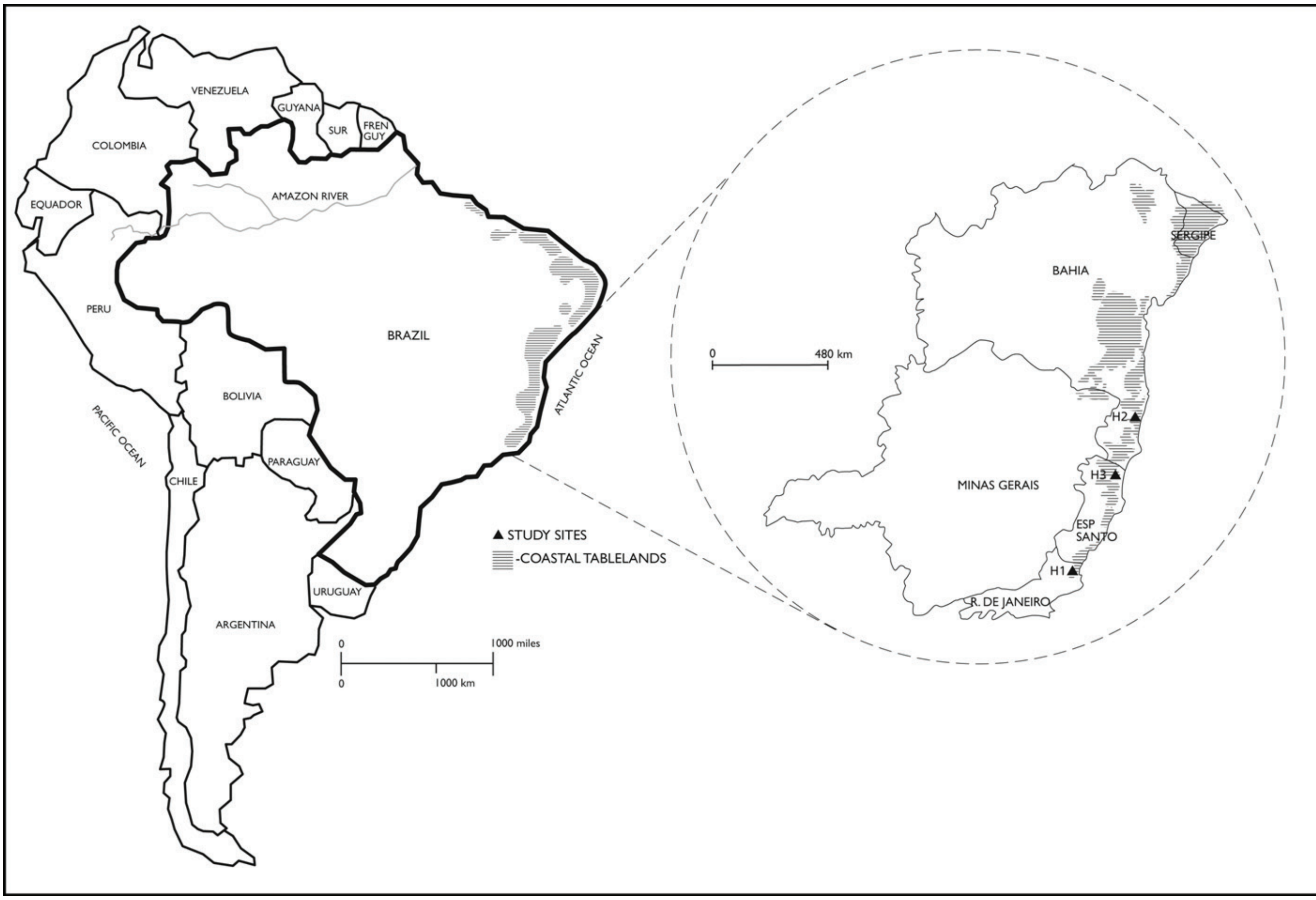

Figure 1. Study areas in the Coastal Tablelands of Brazil: H1 - municipality of Campos dos Goytacazes (Rio de Janeiro state); H2 - municipality of Porto Seguro (Bahia state;) and H3 - municipality of Aracruz (Espírito Santo state).

Table 1. Chemical and physical properties of three Brazilian hardsetting soil horizons.

Profile and Hardsetting horizon	Organic Matter g kg^{-1}	CEC mmol$_c$ kg^{-1}	Ki	Particle Density Mg m^{-3}	Bulk density Mg m^{-3}	Clay	Silt	Sand[1] VC	C	M	F	VF	Total	Textural class
						g kg^{-1}								
H1 -Bt1	5	30.3	1.68	2.68	1.43	460	40	30	90	140	200	40	500	Sand clay
H2 -Bt1	5	36.1	1.56	2.63	1.47	440	40	40	120	120	190	50	520	Sand clay
H3 -Bt1	13	37.3	1.54	2.65	1.55	440	40	40	130	150	170	30	520	Sand clay

[1]VC = very coarse (2-1 mm), C = coarse (1-0.5 mm), M = medium (0.5-0.25 mm), F = fine (0.25-0.1 mm) and VF = very fine (0.1-0.05 mm).

3 Results and Discussion

The soil porosity (ρ) established by image analysis for the hardsetting horizons in Porto Seguro and Aracruz showed no significant differences ($p > 0.05$), although both differed from the Campos hardsetting horizon (ρ = 18.0 ± 7.95%) (Figure 2) owing to the lower bulk density (Bd) of the latter (Table 1). The lack of significant differences in soil porosity between the horizons in Porto Seguro (ρ =10 ± 3.37%) and Aracruz (ρ = 6 ± 3.24%) probably derives from the ample data variability, as indicated by the high standard deviations (Figure 2).

The low soil porosity found in this study results from the prevalence of denser areas, which represent 85% of the total area of the soil block from the hardsetting horizon. Lima et al. (2006) also noted both more and less dense areas in a hardsetting horizon located in Ceará state (Brazil) that exhibited soil porosities of 36 and 6%, respectively. However, the denser areas represented 80% of the hardsetting horizon. The less dense areas contribute to increase in soil porosity, as seen in the Campos hardsetting horizon (Figure 2); however, these less dense areas are insufficiently expressed to reduce cohesion and high bulk density. In the non-hardsetting horizons examined by Lima et al. (2006), which lie within the same geographical area, the denser areas constituted only 20% of the total area.

The denser areas are characterized by a thick plasma (fine fraction < 0.002 mm), which coats and fills the empty spaces between the coarse fractions (quartz grains). The largest amount of denser areas with low soil porosity (Figure 2) suggests that the cohesion observed in hardsetting horizons results from physical processes that promote greater contact between soil particles. The increase of the contact area among particles favors the development of matric forces in the soil, conferring greater effective stress during the drying process and, consequently, an increase in soil resistance (MULLINS, 1999). In hardsetting horizons in Australia, Chartres and Norton (1994) noted connectivity in the skeleton (sand grains) by common bridges consisting predominantly of fine silt and clay.

The distribution of the area occupied by each class of pore size in the block surface, together with the corresponding number of pores in each class interval in the three hardsetting horizons studied are shown in Figure 3. In all horizons, macropores occupied an average of 80% of the image area (786.432 pixels). Concerning mesopores and micropores, occupation was just 14 and 5%, respectively. Thus, image analysis reveals that the classes of micropores (≤ 0.0007 mm^2) and mesopores (> 0.0007 and ≤ 0.004 mm^2) occurred in greater numbers, and can contribute to the physical processes in hardsetting horizons. The innumerable micropores, or pores of smaller diameter, which were not quantified owing to the minimum pixel size of the image (125 μm^2), should be considered.

The pore size distribution classes found on the block surface (Figure 3) show that the Campos and Porto Seguro horizons present a larger number of macropores with area greater than 0.1 mm^2, tending towards a distribution skewed to the right (large pores). The Aracruz horizon shows a symmetrical distribution of pore areas and an absence of pores with area greater than 0.4 mm^2 (Figure 3). This difference in pore area distribution reveals greater structural degradation in the Aracruz horizon, which is confirmed by the smaller total number of pores (TNP = 393). This difference is probably due to soil movement caused by agricultural tools (rippers and subsoilers).

The areas occupied by macropores were caused by relatively few large and short pores (1/7 total number of pores). This demonstrates that the macropores are not interconnected, i.e., the greater the number of pores found in the same area interval, the lesser the connectivity among them (PAGLIAI et al., 1984), explaining the low water flow imposed by such hardsetting horizons.

Most feeding roots require pores in the range of 0.01-0.02 mm^2 (100 μm ∅) to penetrate the soil (PAGLIAI; LA MARCA; LUCAMANTE, 1983). The reduced number of pores of adequate diameter for root development (Figure 3) explains why the hardsetting soils of Brazil restrict root growth (SANTANA et al., 2006), forcing a horizontal root distribution in the overlying horizons (CINTRA; LIBARDI, 1998). These findings agree with the morphological description of the soils studied, where the occurrence of roots is rare in hardsetting horizons.

Soil pores with areas smaller than 0.001 mm^2 (< 0.5 μm ∅) are classified as residual pores (GREENLAND, 1977), because they retain water to a degree which is unavailable for roots and not subject to drainage; pores with areas between 0.001-0.1 mm^2 (0.5-50 μm) are storage pores that hold the water necessary for the growth of plants and microorganisms; pores with areas between 0.1-1 mm^2 (50-500 μm) are transmission

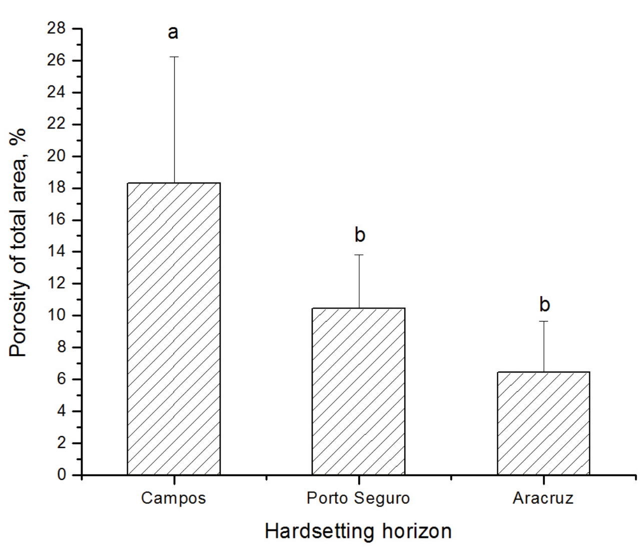

Figure 2. Total soil porosity of the studied horizons measured by image analysis. Different letters indicate significantly different values ($p < 0.05$, LSD test). Data are the mean ± SD of eight replicates.

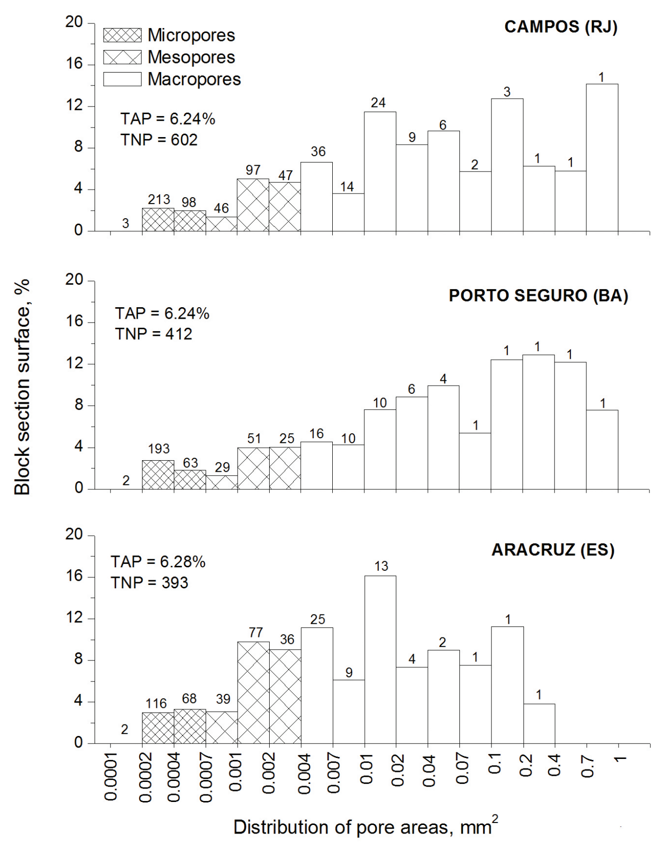

Figure 3. Distribution of pore areas as a function of block section surface in Brazilian hardsetting soil horizons. Numbers above the bars refer to the number of pores in each class and are the mean of eight replicates. TAP = total area of pores, TNP = total number of pores.

pores, which regulate the transmission of water and exchange of gases, allowing root development. Since residual and storage pores predominate in most hardsetting horizons (Figure 3), these properties allow interpretation and comprehension of the restrictive physical behavior of hardsetting horizons. The amount of water available for plants is very low in hardsetting horizons, but they retain more water than non-hardsetting horizons (GIAROLA et al., 2003; LIMA et al., 2004). The data presented herein suggest that the number of pores in hardsetting soils decreases with the disappearance of storage and transmission pores, leading to complete predominance of residual pores in the denser areas (AJMONE-MARSAN; PAGLIAI; PINI, 1994). This characteristic is a clear symptom of structural degradation (PAGLIAI; LA MARCA; LUCAMANTE, 1983).

There were no significant differences between the different pore classes (Table 2), showing that, although hardsetting soils present differences in the distribution of the total area of pores (TAP) and total number of pores (TNP) (Figure 3), their physical limitations are similar. Recent studies (PAGLIAI; VIGNOZZI; PELLEGRINI, 2004) have shown that a soil is considered dense when its macropores, i.e., pores larger than 0.08 mm, constitute < 10% of all pores. Thus, the smaller the average macropore size, the greater the density observed.

Table 2. Distribution of pore size classes in hardsetting soil horizons in three localities in the Brazilian Coastal Tablelands. Data are the mean ± standard deviation.

Local	Distribution of pores classes		
	Micropores	Mesopores	Macropores
		%	
Campos	1.41 ± 1.2	3.72 ± 2.0	8.45 ± 3.4
Porto	1.53 ± 1.4	3.12 ± 1.6	8.59 ± 3.3
Aracruz	2.11 ± 1.8	7.31 ± 3.7	7.23 ± 5.1
LSD test (5%)	*ns*	*ns*	*ns*

Micromorphological observations on hardsetting soils have revealed that macropores decrease expressively under conditions of fast wetting due to physical dispersion, i.e., crumbling of the structure into primary particles, leading to the collapse of aggregates (BRESSON; MORAN, 2004). However, further information is necessary to understand the dry and humid behaviors of Brazilian hardsetting soils.

The macropore class presents three distinct pore shapes depending on the area they occupy (>0.01 mm^2): rounded, elongate, or complex (Figure 4). Mesopores and micropores occur only as rounded pores of medium and small sizes.

The main difference between the hardsetting horizons concerns the percentage of rounded (regular) and complex (irregular) pores. The rounded pore class was significantly greater in the Aracruz horizon, in the three size classes analyzed with the exception of the small pores (< 0.001 mm^2), in which the Aracruz hardsetting horizon did not differ from that of Porto Seguro. The areas occupied by elongated pores, represented by fissures and microfissures (< 1 mm ∅) in the soils in Campos and Aracruz, and by chambers connected by channels and fissures (orthovughs) in the soil in Porto Seguro, showed no significant differences (p = 0.81).

Large complex pores (irregular) (> 0.01 mm^2) occurred in significantly greater number in the soils in Campos and Porto Seguro (41.43 and 38.64%, respectively), differing statically from the soil in Aracruz (8.3%). Such pores are characterized by their undefined shape and consist of randomly distributed, complex, packing pores; they are not connected to other similar pores.

Alterations in the distribution of pore shape and size classes as a result of the densification process lead to an increase in the number of rounded pores as a function of the destruction

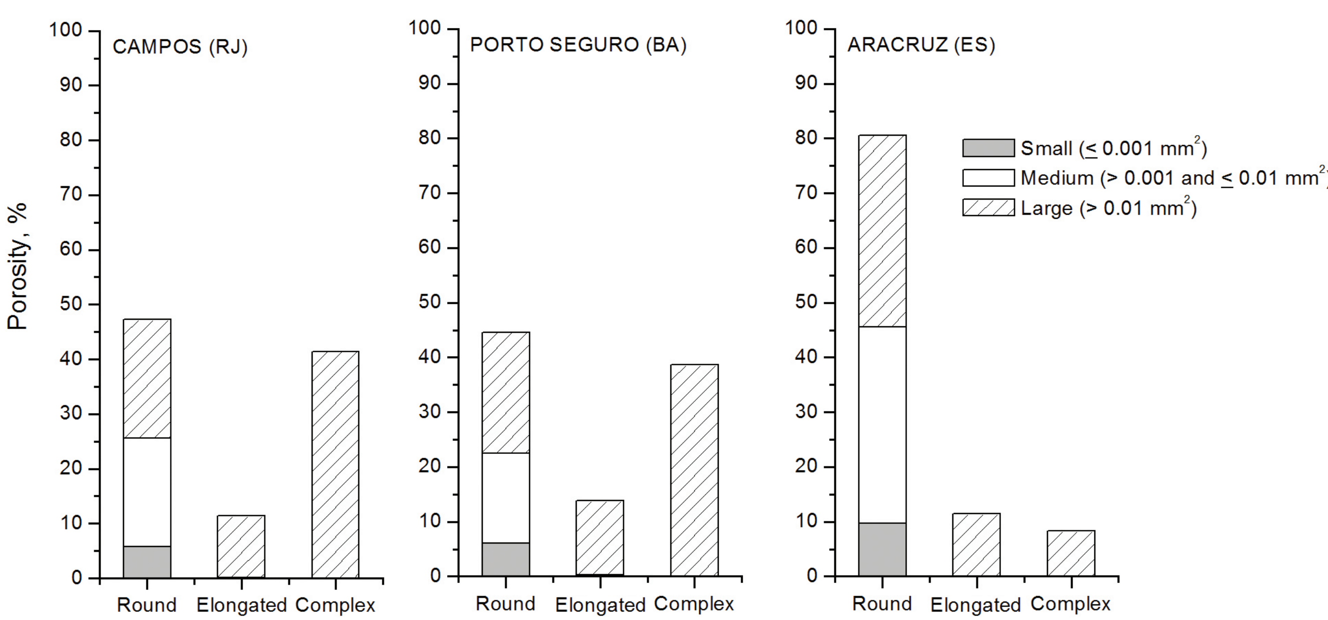

Figure 4. Shape and pore size distribution in Brazilian hardsetting soil horizons.

of elongated and complex pores (FOX; BRYAN; FOX, 2004). Such alterations promote a reduction in soil hydraulic conductivity, because rounded pores are less effective in water transmission than are irregular and elongated pores (VALENTIN, 1991). This can have a negative effect on the processes of water infiltration in hardsetting horizons.

Knowledge of the shape and size of the different pore classes aids in establishing the evolution of densification in hardsetting soils. The porosity of the soils in Campos and Porto Seguro under pasture and tropical forest exhibited similar characteristics. However, the larger pores disappear in the Aracruz horizon under eucalyptus plantation, probably due to the passage of heavy machines and equipment, which may have led to an increase in the number of rounded pores, confirming the hypothesis that densification in hardsetting soils can be aggravated by agricultural use.

Elongated pores are mainly oriented between 90 and 180°. The Campos horizon presented maximum orientation around 90°, while the Porto Seguro and Aracruz horizons showed 140 and 110°, respectively (Figure 5). The ratio between the Feret diameters, for all horizons, was very close to zero, i.e., Fv = Fh; the largest value (0.26) was found in the Aracruz horizon, justifying the low degree of orientation of elongated pores. A tendency to a horizontal orientation was observed in a hardsetting soil located in Ceará state, with Feret diameter values around 0.86 (LIMA et al., 2006). When this ratio is close to zero, the pores are less oriented. Thus, when Fv = Fh, there is no preferential pore orientation (MURPHY; BULLOCK; BISWELL, 1977).

Microscopic observations revealed that the pore network in hardsetting soils exhibits random distribution, and that the elongated pores are reduced in length owing to their low interconnectivity (Figure 4). This explains the absence of a strong preferential orientation; Figure 5 shows a small trend towards horizontal orientation only in the Porto Seguro horizon.

Even in the horizon under preserved forest (Porto Seguro), very few pores derived from biological activity were found. This occurs probably because of the inexistence of pore space compatible with the activity and the size of the soil fauna. The low organic matter content (< 1%) (Table 1) also contributes to the absence of a visible organizational structure.

The shape and distribution of pore size class reflect the absence of structure observed in hardsetting horizons. Microscopic examinations of thin sections reveal that hardsetting soils present a dense, porphyritic matrix (≈85% of the thin section surface) in which quartz grains are embedded in a fine fraction (< 0.002 mm), reflecting the massive structure observed in the field. Some hardsetting soils present a tendency to block formation when humid, which may be caused by less dense areas (LIMA et al., 2006). However, in physical terms, the percentage of less dense areas (≈15%) is insufficient to favor root development. Furthermore, when dry, or at low humidity level, hardsetting horizons do not show lines of weakness; they exhibit a completely massive structure. When subjected to different forms of wetting, hardsetting soils may display an association of complex factors that lead to structural collapse, such as slaking, slumping, material relocation, and compaction (BRESSON; MORAN, 2004).

The photomicrographs illustrate the bi-dimensional distribution of pore network in the hardsetting horizons studied (Figure 6). Visual inspection shows that the Campos horizon (Figure 6a) presents more pores of different sizes and shapes, distributed randomly, without exhibiting a visible structure. The Porto Seguro and Aracruz horizons contained a greater amount of dense areas, with a pore network composed mainly of chambers and vughs, occasionally isolated or showing little connectivity (Figure 6b) where the massive structure is sufficiently evident. The presence of vesicles and rounded pores, caused by physical stress, is constantly present throughout the horizons, confirming the low degree of structuring.

These findings emphasize the pedogenic origin of hardsetting horizons compared with mechanically compacted soils, which generally present flattened structure with horizontal pore distribution (PAGLIAI; VIGNOZZI; PELLEGRINI, 2004). Our micromorphological observations did not detect the presence of an amorphous composite or

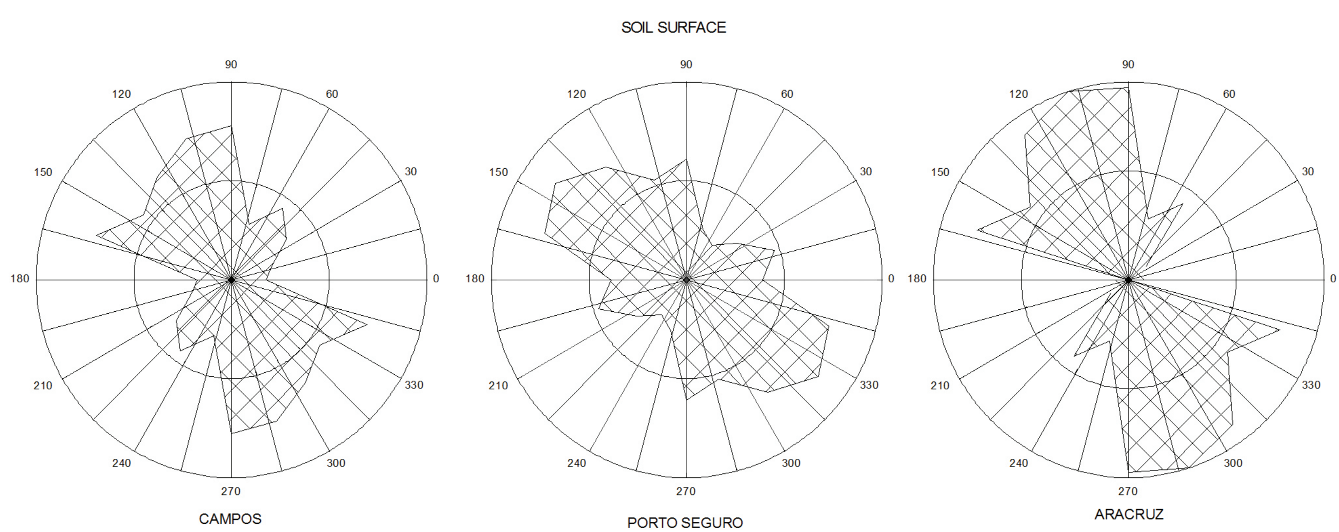

Figure 5. Mean orientation (ratio between horizontal and vertical Feret diameters) of elongated pores in Brazilian hardsetting soil horizons.

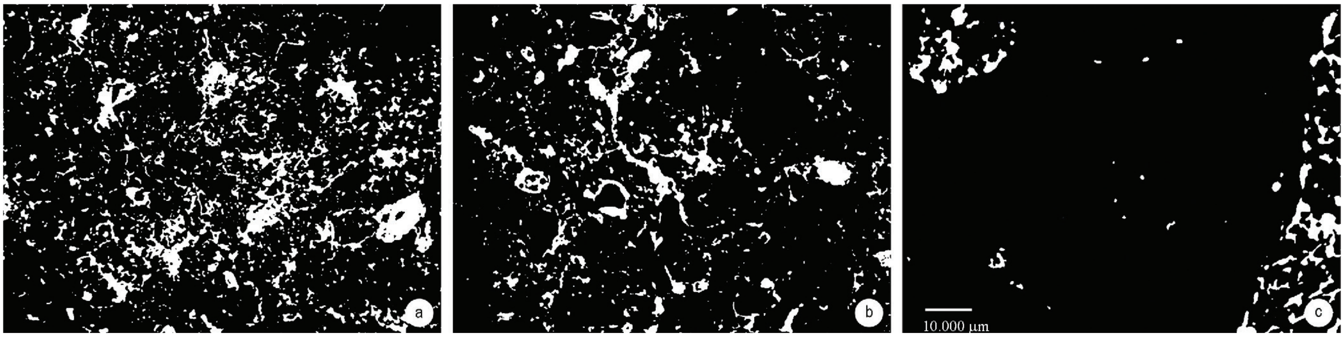

Figure 6. Binary images of vertical sections of the matrix of hardsetting soil horizons: (a) Campos, (b) Porto Seguro, (c) Aracruz. Pores are represented in white and soil matrix in black.

illuvial clay compatible with the constitution of the denser matrix of hardsetting horizons, corroborating the findings by Lima et al. (2006). Conversely, Chartres and Norton (1994) noted the influence of an amorphous composite on the constitution of Australian hardsetting soils.

The microscopic characterization herein presented allows a better understanding of pore space distribution in hardsetting horizons, and the water flow and strength offered by these horizons would be determined by pore network characteristics and soil structure.

4 Conclusions

The present study confirms the hypothesis that hardsetting soils along the Brazilian coast present similar characteristics in terms of structural organization (or organization of the soil matrix) and soil porosity.

The number and distribution of pore size classes revealed that the pore network in hardsetting soils exhibits random distribution and that the elongated pores are reduced in length owing to their low interconnectivity.

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