Water repellency in soils of humid subtropical climate of Rio Grande do Sul, Brazil

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ABSTRACT

In this study, the effects of soil bulk density, total porosity, organic matter content, aluminium saturation and cation exchange capacity (CEC) on water and ethanol sorptivity and hydro-repellency index of various sized aggregates of horizons A and B were investigated. Soil samples were taken from horizons A and B in 17 different locations of Rio Grande do Sul, Brazil. Three samples were collected from each of the horizons for the determination of soil sorptivity in water and ethanol. Soil sorptivity was determined by a steady-state flow using a mini-infiltrometer. Hydro-repellency of samples was estimated from the ethanol/water sorptivity values. Aggregates from most soil samples exhibited low hydro-repellency index, R (1.24–3.12), except for luvisol and vertisol, which had $R \geq 5.79$. The very low coefficients of determination, $r^2 = 0.18$ and 0.22 at $p = 0.01$ between hydro-repellency index and organic matter content, and between angle of contact and organic matter content, respectively is an indication that the quantity of organic matter have little influence on hydro-repellency, but the composition of organic matter and other soil properties. The mean pH of sampled soils ranged from 3.90 and 5.50 in both horizons A and B but presents no significant effect on the hydro-repellency of soil at $p = 0.01$. The results show that soil hydraulic and sorptivity properties are dependent on interaction between aggregate sizes, which is mainly a function of the soil clay minerals.

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1. Introduction

Assessment of the hydraulic properties of soil, such as infiltration and sorptivity, is very important component for the interpretation of the physical characteristics of soil and the management of agricultural practices (Green et al., 2003). These properties of soil affect water and solute movement in soil aggregates (Gerke and Köhne, 2002). Therefore, water dynamic and solution transport in the soil matrix requires investigation of the soil hydraulic properties. Severe variability of soil texture, soil structure and other physical and chemical properties in agricultural lands has been reported. However, these variabilities have appreciable effects on infiltration process and its related parameters (Gupta et al., 1994; Russo and Bresler, 1981).

The importance of the hydraulic properties is mostly significant by the fact that large inter-aggregate pores are drained off first under prevalent field conditions, and water and solutes transports are influenced by the properties of the individual aggregates and contacts between them (Horn and Smucker, 2005). Several studies

have established different spatial correlation structures for soil hydraulic properties such as saturated and unsaturated hydraulic conductivity, saturated and residual soil water content, sorptivity and pore-size distribution parameters (Gajem et al., 1981; Russo and Bresler, 1981; Jury, 1985; Saddiq et al., 1985; Mohanty et al., 1994). The hydraulic properties can differ in various parts of aggregates as reported in Gerke and Köhne (2002), and in some situations the hydraulic conductivity/water retention curves show a substantially different pattern between the inner and the outer skins of aggregates, which also can result in enhanced anoxic conditions inside at less negative pore water pressure.

Pore structures affects the hydraulic properties of soil aggregates (Horn and Smucker, 2005; Lipiec et al., 2007) and are modified by soil compression and tillage practices (Kutílek et al., 2005; Lipiec et al., 2006). Compacted aggregates characterized with increased contribution of finer pores reduces the accessibility of water for roots due to its availability only at more negative pore water pressures (Horn and Smucker, 2005).

Other authors acknowledge the influence of high pH values, particularly above 6.5 on the reduction of water repellency of some soils (Bayer and Schaumann, 2007; Mataix-Solera and Doerr, 2004), which may be indirectly linked to the specific surface area and texture of the soil (Doerr et al., 2006; Woche et al., 2005). Generally, the existence of hydro-repellency necessitates adequate

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attention to the different aspects of soil use and management. Hallett (2008) reported the reduction in infiltration of water into the soil and the resulting reduction in available water for seed germination as well as growth and development of the plant. Furthermore, increase in surface water may reduce the rate of infiltration, especially in slope, and increase the risk of erosion as observed by Shakesby et al. (2000). Also, the main problems of the water repellency of soils are those related to water flow in vertical and lateral soil, causing loss of solutes by leaching, erosion by wind, less infiltration of water into the soil (Shakesby et al., 2000), and inactivity of pesticides and fertilizers (Blackwell, 2000).

Some recent studies indicated that increased soil stability and water infiltration can be a result of the combined effect of internal aggregate strength and wettability (opposite to repellency) (Czarnes et al., 2000; Goebel et al., 2004; Eynard et al., 2006). Therefore, soil compaction which increased the contact points or forces among soil aggregates must have been responsible for internal aggregate strength and stability (Horn et al., 1994a,b; Chenu et al., 2000; Ferrero et al., 2007) and lower wettability (Goebel et al., 2004; Eynard et al., 2006). Jasínska et al. (2006) showed that the degree of water repellency is a function of aggregate sizes and as well reported that the hydrophobicity is mostly concentrated at the outer skin while the inner part of the aggregates is less hydrophobic (Urbanek et al., 2007).

Despite the emphasized importance of the study of soil matrix potential, little information is available on the water repellency of predominant subtropical and tropical soils in southern Brazil. The objective of the research was to identify and determine the hydro-repellency of soils of Rio Grande do Sul, Southern Brazil.

2. Materials and methods

2.1. Site description and soil sampling

Soil samples were collected during the wet season of 2009 from southernmost state of Brazil, called Rio Grande do Sul (32°02′06″S, 52°05′55″W, altitude 460 m m.a.s.l). The state is 2814 km^2 in area and climatologically belongs to the subtropical climate with an annual average maximum temperature of 17.5 °C and lowest minimum temperature of 6 °C during the wet season (October–March). The mean annual rainfall ranges between 1417 and 1500 mm.

Undisturbed soil samples were collected in soil profiles at depths up to 1 m, from 17 different locations mainly from horizons A and B. Three samples were collected from each horizon, packed in plastic bags, placed in wooden box and transferred to the laboratory. The samples were allowed to dry in the open air until reaching friability. Subsequently, the aggregates were separated manually into fractions to obtaining moulds of approximately 15 mm in diameter. The code, Brazilian classification and the USDA classification of soils of the experimental site is presented in Table 1.

2.2. Measurements

2.2.1. Physico-chemical characterization of soils

The chemical characterization includes the analysis of organic carbon, active acidity, potential acidity, Al^{3+} saturation, CEC at pH 7.0 and base saturation, whereas the physical characterization consisted of particle size analysis, clay dispersion, particle density and bulk density determination. The soil organic carbon was determined by the method described in EMBRAPA (1997). The active acidity of the soil was inferred by pH determined in distilled water in soil: water ratio of 1:2.5. The exchangeable Ca^{2+} and Mg^{2+} were determined by atomic absorption spectroscopy after extraction with KCl 1.0 mol l^{-1}. The exchangeable Al^{3+}, Na^+ and

Table 1
Codes and classifications of soil of the experimental sites.

Code	Brazilian classification (EMBRAPA, 2006)	Soil taxonomy (USDA, 1999)
CHa	Cambissolo Húmico Alumínico típico	Dystrudept
LBaf	Latossolo Bruno Aluminoférrico típico	Hapludox
LVd1	Latossolo Vermelho Distrófico típico	Hapludox
LVd2	Latossolo Vermelho Distrófico húmico	Hapludox
LVdf	Latossolo Vermelho Distroférrico húmico	Hapludox
NVdf	Nitossolo Vermelho Distroférrico latossólico	Paleodult
PBACal	Argissolo Bruno-Acinzentado Alítico úmbrico	Hapludalf
PVAa	Argissolo Vermelho-Amarelo Alumínico úmbrico	Haplohumult
PVd1	Argissolo Vermelho Distrófico arênico	Paleudalf
PVd2	Argissolo Vermelho Distrófico típico	Paleudult
PVd3	Argissolo Vermelho Distrófico latossólico	Paleudalf
RLd	Neossolo Litólico Distrófico típico	Udorthent
SXe1	Planossolo Háplico Eutrófico arênico	Albaqualf
SXe2	Planossolo Háplico Eutrófico típico	Endoaqualf
TCp	Luvissolo Crômico Pálico saprolítico	Argiudoll
TXo	Luvissolo Háplico Órtico típico	Endoaqualf
VEo	Vertissolo Ebânico Órtico típico	Hapludert

exchangeable K were extracted with HCl solution and their levels determined by flame photometry. The potential acidity ($H^+ + Al^{3+}$) was determined in extracts of Ca $(OAc)_2$ (1.0 mol l^{-1}) at pH 7.0 titrated with NaOH (0.0606 mol l^{-1}). The cation exchange capacity (CEC) at pH 7.0 and percent of base saturation were determined following the procedure described in EMBRAPA (1997).

Soil particle sizes were determined by the pipette method. Textural classification was carried out using the USDA classification system. The particle density (Dp) was determined following the method describe in Gubiani et al. (2006) and the bulk density was obtained by the paraffin clod method described by Blake and Hartge (1986). The total porosity (Pt) was calculated from Ds and Dp.

Soil sorptivity test was conducted using a micro-infiltrometer, which consists of a tube connected to a tank with a small sponge making contact with the narrow tip of the tube. Two different liquids (distilled water and ethanol) with different angles of contact, densities and viscosities were used to conduct the soil sorptivity test.

Hydraulic pressure differences within the column of fluid in the reservoir and the infiltrometer, which could affect flow, were eliminated. The soil samples were held in contact with the tip of the infiltrometer (sponge) for 2 min, and the cumulative mass of water or ethanol, which infiltrates the soil by capillary, was recorded by analytical balance to accuracy of 0.0001 g, from the difference in initial and final weight of the reservoir of liquid. The sorptivity (S) of soil in water and ethanol was estimated by Eq. (1) (Leeds-Harrison et al., 1994):

$$S = \sqrt{\frac{Q\,f}{4br}} \qquad (1)$$

where Q is the measure of the flow of liquid (m s^{-1}), b is a parameter dependent on the function of diffusion of water in the soil and the value of 0.55 was adopted (White and Sully, 1987), r is the radius of the tip of infiltrometer (0.5 mm), f is the total porosity (m^3 m^{-3}). The flow of liquid (Q) was obtained by the infiltration rate in a small circular area on the surface of the soil aggregate (Leeds-Harrison et al., 1994). The density of liquids (water and ethanol) was determined using the mass per unit volume method at temperature of approximately 20 °C in all tests (this value was adopted as standard temperature to estimate the density of liquids).

The hydrophobicity influence of the particles was measured separately by sorptivity of ethanol, which, due to its polar nature and smaller angle of contact with hydrophobic surfaces, provides a

measure of transport of liquid, with no influence by repellency. The hydro-repellency was assessed by comparing values of soil sorptivity to water and ethanol. This parameter describes the extent to which sorptivity water can be altered by the layer of particles of soil with minerals or organic hydrophobic constituents.

An index of hydro-repellency, R, was evaluated following the suggestion of Tillman et al. (1989), relating soil sorptivity in water (Swater) and ethanol (Sethanol) as shown in Eq. (2):

$$R = 1.95 \left[\frac{Sethanol}{Swater} \right]$$

The constant (1.95) accounts for the difference in surface tension and the viscosity of ethanol and water. Ignoring the influence of liquid properties, a measure of intrinsic sorptivity was obtained so that Swater can be directly compared with Sethanol. The angle of soil–water contact was obtained from the formula of Gryze et al. (2006) as shown in Eq. (5).

$$\theta = \arccos \frac{1}{R} \qquad (5)$$

where θ is the angle of soil–water contact, R is the index of repellency.

2.3. Statistical analysis

Sorptivity data were subjected to the Tukey test at 5% level of significance. Student t test was used to compare each soil property and the hydro-repellence index for the A and B horizons and the existence of inter-relationships between data set was tested by linear correlation and the correlation coefficients determined at the 5% level significance.

3. Results and discussion

3.1. Physical and chemical properties of soil

The result of particle size composition of the collected soil samples is presented in Table 2. There were wide variations in the particle size composition of the collected soil samples. The Hapludox (LVd1), Hapludalf (PBACal), Paleudalf (PVd1 and PVd3) and Albaqualf (SXe1) were characterized by high sand content of above 592 g kg^{-1} in the horizon A, while Hapludox (LVd1) and Argiudoll (TCp) showed sand levels of over 514 g kg^{-1} in the B horizon. Hapludox (LBaf) showed higher level of clay, with quantity 594 g kg^{-1} in the A horizon, while the Dystrudept (Cha), Hapludox (LBaf and LVd2), Paleodult (NVdf), Hapludert (VE$_O$) and Haplohumult (PVAa) were high in clay content (>597 g kg^{-1}) in the subsurface soil horizon. Similar observation was reported by Streck et al. (2008) that a high level of clay is characteristic of Oxisol and Alfisol. The Hapludalf (PBACal), Haplohumult (PVAa), Paleudalf (PVd1, PVd2 and PVd3), and Endoaqualf (TXo) samples showed wide variation in clay content between the horizons A and B, with an increase in clay content in the B horizon comparatively to horizon A. This agrees with the findings of Zalamena (2008) and Streck et al. (2008) who reported that the feature is specific to Argisols and Luvisols, which present a profile with textural gradient. The highest values of dispersed clay were in B horizon. However, Hapludox (LVd2), Hapludert (VEo) and Paleodult (NVdf) also had high levels of clay dispersion in the A horizon.

The results of particle density, bulk density and total porosity are shown in Table 3. The density of particles ranged from 2.39 Mg m^{-3} in the A horizon to 2.59 Mg m^{-3} in the B horizon. The total porosity varies from 0.6078 to 0.3356 m^3 m^{-3} in the B horizon. The total porosity showed an inverse relationship with the

Table 2
Means of particle size distribution, dispersed clay and silt/clay relationship in horizons A and B of the 17 soils.

Soil	Horizon	Granulometric composition (g kg^{-1})			Dispersible clay (g kg^{-1})	Silt/clay
		Sand	Silt	Clay		
CHa	A	294.51 ± 40.36	267.70 ± 33.85	437.79 ± 10.03	293.73	0.61
CHa	B	165.35 ± 42.26	205.66 ± 56.33	628.99 ± 87.35	298.55	0.33
LBaf	A	55.71 ± 6.19	349.49 ± 74.52	594.80 ± 26.34	221.72	0.59
LBaf	B	37.59 ± 6.19	172.44 ± 108.17	789.69 ± 100.47	8.37	0.22
LVd1	A	736.39 ± 20.35	63.24 ± 24.15	200.37 ± 99.76	82.56	0.32
LVd1	B	646.90 ± 54.09	63.77 ± 11.45	289.33 ± 67.54	95.19	0.22
LVd2	A	429.76 ± 65.23	167.51 ± 26.98	402.74 ± 19.66	153.84	0.42
LVd2	B	306.21 ± 91.52	108.47 ± 17.98	585.33 ± 56.34	72.1	0.19
LVdf	A	42.10 ± 26.53	337.69 ± 33.57	620.21 ± 54.55	231.57	0.54
LVdf	B	22.37 ± 7.48	161.23 ± 27.05	816.40 ± 59.69	6.55	0.20
NVdf	A	306.96 ± 85.74	196.35 ± 89.59	496.70 ± 21.53	166.35	0.40
NVdf	B	225.42 ± 72.02	149.16 ± 43.99	625.42 ± 76.80	11.59	0.24
PBACal	A	664.99 ± 76.48	196.35 ± 14.05	138.66 ± 65.51	39.69	1.42
PBACal	B	470.59 ± 86.33	247.49 ± 53.86	281.93 ± 82.32	257.02	0.88
PVAa	A	256.60 ± 113.28	387.40 ± 90.59	356.00 ± 112.55	131.50	1.09
PVAa	B	143.00 ± 40.74	251.20 ± 103.26	605.80 ± 73.07	342.60	0.41
PVd1	A	680.48 ± 173.61	119.80 ± 31.72	199.72 ± 57.52	65.92	0.60
PVd1	B	452.69 ± 142.43	114.90 ± 77.06	432.40 ± 47.68	162.69	0.27
PVd2	A	394.59 ± 137.88	336.72 ± 46.01	268.69 ± 143.19	96.96	1.25
PVd2	B	266.69 ± 60.87	267.74 ± 88.67	485.57 ± 161.15	190.98	0.55
PVd3	A	592.16 ± 121.93	237.34 ± 29.03	170.49 ± 105.10	121.88	1.39
PVd3	B	373.77 ± 95.52	194.13 ± 49.30	432.11 ± 44.67	276.43	0.45
RLd	A	194.20 ± 78.08	563.70 ± 87.25	242.10 ± 87.26	182.50	2.33
SXe1	A	653.94 ± 73.28	239.52 ± 50.31	106.54 ± 26.60	46.56	2.25
SXe1	B	437.00 ± 37.95	240.57 ± 11.13	322.42 ± 45.60	253.16	0.75
SXe2	A	290.53 ± 91.42	527.08 ± 66.56	182.39 ± 78.41	72.66	2.89
SXe2	B	284.21 ± 105.75	419.23 ± 49.73	296.56 ± 72.90	217.15	1.41
TCp	A	447.27 ± 138.01	248.41 ± 110.85	304.33 ± 54.83	125.80	0.82
TCp	B	514.47 ± 162.14	258.79 ± 57.81	226.74 ± 47.76	176.56	1.14
TXo	A	312.70 ± 32.28	403.83 ± 16.62	283.47 ± 61.51	118.48	1.42
TXo	B	207.24 ± 42.78	350.02 ± 59.96	442.74 ± 76.11	280.63	0.79
VEo	A	102.95 ± 25.92	438.65 ± 49.45	458.40 ± 184.77	266.04	0.96
VEo	B	70.47 ± 8.64	331.60 ± 48.39	597.92 ± 77.52	395.73	0.55

Table 3
Means of particle density (Dp), bulk density (Ds) and total porosity (Pt) in A and B horizons of sampled soils.

Soil	Horizon	Ds (Mg m^{-3})	Dp (Mg m^{-3})	Pt (m^3 m^{-3})
CHa	A	1.33 ± 0.05	2.54 ± 0.03	0.4764 ± 0.10
CHa	B	1.46 ± 0.12	2.52 ± 0.02	0.4206 ± 0.20
LBaf	A	1.29 ± 0.01	2.55 ± 0.01	0.4941 ± 0.10
LBaf	B	1.65 ± 0.05	2.55 ± 0.22	0.3529 ± 0.10
LVd1	A	1.35 ± 0.03	2.52 ± 0.02	0.4646 ± 0.10
LVd1	B	1.41 ± 0.03	2.59 ± 0.04	0.4572 ± 0.17
LVd2	A	1.21 ± 0.01	2.57 ± 0.01	0.5306 ± 0.10
LVd2	B	1.56 ± 0.01	2.55 ± 0.01	0.3887 ± 0.10
LVdf	A	1.10 ± 0.01	2.55 ± 0.01	0.6078 ± 0.10
LVdf	B	1.15 ± 0.04	2.55 ± 0.01	0.5492 ± 0.11
NVdf	A	1.38 ± 0.03	2.48 ± 0.01	0.4435 ± 0.10
NVdf	B	1.31 ± 0.02	2.55 ± 0.02	0.4863 ± 0.10
PBACal	A	1.34 ± 0.01	2.51 ± 0.03	0.4673 ± 0.10
PBACal	B	1.62 ± 0.02	2.53 ± 0.01	0.3623 ± 0.10
PVAa	A	1.49 ± 0.03	2.46 ± 0.02	0.3933 ± 0.10
PVAa	B	1.37 ± 0.01	2.53 ± 0.03	0.4576 ± 0.10
PVd1	A	1.42 ± 0.03	2.49 ± 0.01	0.4294 ± 0.01
PVd1	B	1.48 ± 0.03	2.52 ± 0.04	0.4126 ± 0.09
PVd2	A	1.25 ± 0.02	2.55 ± 0.03	0.5098 ± 0.10
PVd2	B	1.43 ± 0.03	2.54 ± 0.04	0.4370 ± 0.02
PVd3	A	1.11 ± 0.02	2.56 ± 0.04	0.5676 ± 0.02
PVd3	B	1.48 ± 0.01	2.48 ± 0.02	0.4012 ± 0.10
RLd	A	1.40 ± 0.01	2.55 ± 0.05	0.4510 ± 0.10
SXe1	A	1.42 ± 0.01	2.55 ± 0.04	0.4417 ± 0.04
SXe1	B	1.56 ± 0.02	2.55 ± 0.02	0.3870 ± 0.10
SXe2	A	1.36 ± 0.01	2.39 ± 0.59	0.4339 ± 0.10
SXe2	B	1.61 ± 0.01	2.43 ± 0.04	0.3356 ± 0.02
TCp	A	1.39 ± 0.02	2.50 ± 0.06	0.4443 ± 0.04
TCp	B	1.67 ± 0.03	2.53 ± 0.04	0.3398 ± 0.03
TXo	A	1.31 ± 0.02	2.40 ± 0.04	0.4531 ± 0.02
TXo	B	1.40 ± 0.02	2.54 ± 0.03	0.4485 ± 0.01
VEo	A	1.35 ± 0.04	2.55 ± 0.03	0.4707 ± 0.02
VEo	B	1.30 ± 0.03	2.55 ± 0.03	0.4913 ± 0.09

density of the soil an observation which was reported in Kay and Angers (2002), Gantzer and Anderson (2002) and Ringrose-Voase (1996). The values of bulk density found in the soil are not restrictive. This observation was in line with the findings of Reichert et al. (2007).

The organic matter contents of sampled Argiudoll, Udorthent, Haplohumult, Dystrudept and Hapludox were above 3%, whereas the Hapludert sample had the highest values of organic matter in the A and B horizons with values 7.3% and 4.0%, respectively. Generally, soil organic matter content in the subsurface horizon was below the observed values in all top horizons examined (Table 4) but the difference of organic matter contents between horizons A and B were only significant at $p < 0.001$ (Table 8). This observation agrees with that described in Streck et al. (2008), which reported a high base saturation and CEC, and the presence of high organic carbon in Vertisols.

The lowest soil pH value of 3.9 was observed in the A horizon of Paleudult and Albaqualf and in horizon B of Hapludox sample (LBaf), while the highest pH of 5.5 was obtained in the horizon B of Endoaqualf and Hapludert. This agrees with the findings of Streck et al. (2008), which reported that Argisols and Oxisols have low natural fertility, high acidity and, in general, high aluminum saturation. The lower aluminum saturation values in the A horizon must have been caused by high pH. Menezes (2008) reported similar observation in typic Cambisol. The CEC at pH 7.0 vary from 8.1 to 52.8 cmolc kg^{-1}. Samples with higher values of CEC were found having high levels of organic matter and pH, as observed by Bayer and Bertol (1999). The CECpH7 was higher mostly in the samples collected from A horizon than in B by about 59%. Similar behavior was reported by Souza and Alves (2003) and Menezes (2008).

The values of base saturation range from 1% to 88%, demonstrating the wide variation of this feature in the sampled

Table 4
Means of organic matter content, pH in water, Al saturation, saturation of bases, CEC at pH in A and B horizons of 17 soils.

Soil	Horizon	Organic matter (%)	pH	Saturation by Al (%)	Bases saturation (%)	CEC$_{pH\ 7}$ (cmol$_c$ kg^{-1})
CHa	A	3.00 ± 0.13	4.30	75.00	9.00	22.30 ± 5.02
CHa	B	0.80 ± 0.09	4.50	96.00	4.00	12.10 ± 3.99
LBaf	A	3.70 ± 0.11	4.10	68.00	8.00	26.50 ± 4.99
LBaf	B	1.50 ± 0.02	3.90	86.00	3.00	17.80 ± 3.04
LVd1	A	1.30 ± 0.03	4.10	82.00	5.00	8.10 ± 0.04
LVd1	B	0.90 ± 0.02	4.40	80.00	2.00	9.90 ± 3.00
LVd2	A	2.80 ± 0.04	4.40	71.00	7.00	20.80 ± 5.02
LVd2	B	1.00 ± 0.09	4.10	93.00	1.00	17.60 ± 2.03
LVdf	A	3.50 ± 1.13	4.40	71.00	7.00	18.50 ± 1.04
LVdf	B	1.10 ± 0.06	4.80	89.00	2.00	12.50 ± 0.04
NVdf	A	2.60 ± 0.11	4.00	62.00	7.00	18.00 ± 1.00
NVdf	B	1.00 ± 0.10	4.00	96.00	1.00	11.60 ± 3.00
PBACal	A	2.40 ± 0.03	4.20	29.00	27.00	14.90 ± 1.98
PBACal	B	0.80 ± 0.09	5.30	4.00	80.00	24.70 ± 1.01
PVAa	A	3.10 ± 0.05	5.00	16.00	42.00	13.20 ± 1.98
PVAa	B	1.15 ± 0.07	4.80	82.00	12.00	11.00 ± 0.04
PVd1	A	1.90 ± 0.04	4.00	39.00	19.00	11.90 ± 1.98
PVd1	B	0.80 ± 0.04	4.50	47.00	13.00	17.70 ± 0.05
PVd2	A	2.10 ± 0.09	3.90	43.00	20.00	9.50 ± 1.05
PVd2	B	1.10 ± 0.03	4.70	24.00	31.00	8.40 ± 0.97
PVd3	A	1.30 ± 0.03	4.20	42.00	19.00	9.50 ± 1.00
PVd3	B	1.00 ± 0.03	4.20	56.00	8.00	26.40 ± 4.01
RLd	A	3.45 ± 0.10	5.00	16.00	41.00	12.50 ± 0.99
SXe1	A	1.80 ± 0.01	3.90	35.00	19.00	12.10 ± 0.02
SXe1	B	0.40 ± 0.03	5.30	22.00	45.00	19.90 ± 2.98
SXe2	A	2.10 ± 0.06	4.60	19.00	48.00	11.90 ± 0.03
SXe2	B	0.70 ± 0.10	5.20	42.00	22.00	31.40 ± 2.98
TCp	A	4.10 ± 0.04	4.80	5.00	45.00	25.10 ± 5.02
TCp	B	1.50 ± 0.02	5.00	14.00	63.00	16.80 ± 3.99
TXo	A	1.80 ± 0.02	4.40	44.00	29.00	21.70 ± 5.03
TXo	B	1.70 ± 0.03	5.50	11,00	58.00	45.70 ± 9.98
VEo	A	7.30 ± 0.08	5.30	0.00	81.00	40.30 ± 10.01
VEo	B	4.00 ± 0.57	5.50	0.00	88.00	52.80 ± 9.97

Table 5
Means of soil sorptivity to water (Swater), sortivity to ethanol (Sethanol), hydro-repellency index (R) and angle of contact with the drop of water in the soil horizons A and B for 17 soils.

Soil	Horizon	Swater (mm s$^{-1/2}$)	Sethanol (mm s$^{-1/2}$)	R	Contact angle θ (degree)
CHa	A	0.0616	0.0628	2.06 ± 0.02	60.65 ± 10.08
CHa	B	0.0401	0.0421	2.38 ± 0.02	59.70 ± 10.04
LBaf	A	0.0493	0.0647	2.70 ± 0.03	65.79 ± 4.95
LBaf	B	0.0350	0.0385	2.18 ± 0.03	60.92 ± 5.00
LVd1	A	0.0418	0.0642	3.04 ± 0.03	70.24 ± 2.95
LVd1	B	0.0504	0.0402	1.63 ± 0.02	48.16 ± 8.01
LVd2	A	0.0553	0.0622	2.23 ± 0.03	61.51 ± 10.05
LVd2	B	0.0683	0.0650	1.85 ± 0.03	55.70 ± 2.01
LVdf	A	0.0857	0.0790	1.81 ± 0.04	55.47 ± 8.70
LVdf	B	0.0698	0.0709	1.97 ± 0.01	56.25 ± 2.99
NVdf	A	0.0629	0.0579	1.84 ± 0.02	54.27 ± 4.99
NVdf	B	0.0670	0.0388	1.24 ± 0.03	32.45 ± 2.03
PBACal	A	0.0520	0.0596	2.23 ± 0.04	63.36 ± 5.20
PBACal	B	0.0458	0.0309	1.40 ± 0.03	38.48 ± 7.98
PVAa	A	0.0535	0.0466	1.77 ± 0.02	50.13 ± 5.01
PVAa	B	0.0570	0.0548	1.93 ± 0.03	56.87 ± 5.98
PVd1	A	0.0551	0.0630	2.29 ± 0.01	60.47 ± 4.97
PVd1	B	0.0537	0.0543	2.05 ± 0.05	58.81 ± 4.98
PVd2	A	0.0551	0.0635	2.33 ± 0.03	64.70 ± 3.99
PVd2	B	0.0567	0.0507	1.77 ± 0.03	50.73 ± 8.63
PVd3	A	0.0340	0.0469	2.92 ± 0.05	65.26 ± 5.01
PVd3	B	0.0421	0.0412	2.00 ± 0.05	58.14 ± 3.01
RLd	A	0.0680	0.0755	2.34 ± 0.03	60.34 ± 2.01
SXe1	A	0.0582	0.0557	1.97 ± 0.03	54.05 ± 4.02
SXe1	B	0.0387	0.0375	1.98 ± 0.01	54.46 ± 2.00
SXe2	A	0.0427	0.0473	2.48 ± 0.06	56.95 ± 2.98
SXe2	B	0.0313	0.0481	3.12 ± 0.17	68.49 ± 4.02
TCp	A	0.0191	0.0723	8.65 ± 0.13	81.99 ± 5.00
TCp	B	0.0343	0.0376	2.30 ± 0.03	61.23 ± 2.03
TXo	A	0.0151	0.0667	9.70 ± 0.05	82.82 ± 3.48
TXo	B	0.0384	0.0564	2.92 ± 0.03	68.82 ± 7.98
VEo	A	0.0140	0.0399	5.79 ± 0.28	79.01 ± 4.02
VEo	B	0.0214	0.0455	5.26 ± 0.04	72.07 ± 3.45
Cv				31.03	17.47

soils. The soils that had the lowest base saturation (1%) were Paleodult and Hapludox (LVd2), which together had low pH and high Al saturation. This observation is in agreement with Streck et al. (2008), who reported that low saturation of bases could be traced to high Al saturation and low pH in Oxisols and Alfisol. The base saturation showed a direct relationship with the levels of organic matter, pH and CEC, and an inverse relationship with aluminum saturation. This agrees with Souza and Alves (2003), who reported high bases saturation in soils with high CEC. Zalamena (2008) also found higher CEC in the areas associated with higher base saturation especially in the lower horizons.

3.2. Soil sorptivity, hydro-repellency and angle of contact

The hydrophobicity of soils decreased with increasing depth, except for Dystrudept, Hapludox, Haplohumult and Endoaqualf, which had higher hydro-repellency (R) in horizon B (Table 5). Doerr et al. (2000) documented a similar situation in which the decrease in water repellency with increased soil depth was caused by the decrease in organic matter content (OMC) down the soil profile.

There was no relationship between particle sizes and the occurrence of hydro-repellency (R), in agreement with Scott (2000). However, Wallis and Horne (1992) found cases of extreme water repellence in sandy soils due to the low specific surface of soils and the ease of coating of sand by hydrophobic substances. De Jong et al. (1999) and Gryze et al. (2006) reported that smaller fractions of the sandy soil showed the highest degree of hydro-repellency and this is behavior which he adduced to the higher organic material content in these fractions. However, there was

high hydro-repellency in Hapludert sample, which has expansive clays, and this agrees with Lichner et al. (2006), who established that the type of clay mineral can influence hydro-repellency, being higher in clay-type 2:1 (Table 6).

Generally, water repellency was more pronounced in soils with higher organic matter content, except for the Endoaqualf (horizon A) which had low organic matter content and higher value of hydro-repellency, an indication that the occurrence of water repellency in the soil is dependent of the amount of organic material (r = 0.44) at p = 0.01, even where there are

Table 6
Pearson correlation coefficients and significance of coefficients between the means of sorptivity to water (Swater), sorptivity to ethanol (Sethanol), index of hydro-repellency (R), angle of contact and other soil properties.

Property	Swater	Sethanol	R	Contact angle
Sand	ns	ns	ns	ns
Silt	ns	ns	ns	ns
Clay	ns	ns	ns	ns
Clay disperse	ns	ns	ns	ns
Relation silt/clay	ns	ns	ns	ns
Bulk density	ns	ns	ns	ns
Particle density	ns	ns	ns	ns
Total porosity	ns	0.52[*]	ns	ns
Organic matter	ns	ns	0.44[*]	0.47[*]
pH	ns	ns	ns	ns
Saturation by Al	0.50[*]	ns	ns	ns
Bases saturation	−0.53[*]	ns	ns	ns
CEC$_{pH\ 7}$	−0.47[*]	ns	ns	ns

ns, not significant.
[*] Significant at p = 0.01.

Table 7
Pearson correlation of hydro-repellency and organic matter content of sampled soils.

	R1 and OMC1	R1 and OMC2	R1 and OMC3	R2 and OMC1	R2 and OMC2	R2 and OMC3	R3 and OMC1	R3 and OMC2	R3 and OMC3
n (pares)	33	33	33	33	33	33	33	33	33
r (Pearson)	0.40[*]	0.43[*]	0.44[*]	0.42[*]	0.45[**]	0.45[**]	0.42[*]	0.45[**]	0.45[**]
r²	0.16	0.18	0.19	0.17	0.20	0.20	0.17	0.19	0.20
t	2.42	2.64	2.70	2.55	2.77	2.83	2.54	2.78	2.83
(p)	0.0213	0.0127	0.011	0.016	0.009	0.008	0.016	0.0091	0.0079
STE	1.74	1.72	1.71	1.76	1.73	1.72	1.74	1.72	1.71

STE, standard error of estimates; R1, hydro-repellency replicate 1; R2, hydro-repellency replicate 2; R3, hydro-repellency replicate 3; OMC1, organic matter content replicate 1; OMC2, organic matter content replicate 2; OMC3, organic matter content replicate 3.

[*] Correlation is significant at $p = 0.05$.
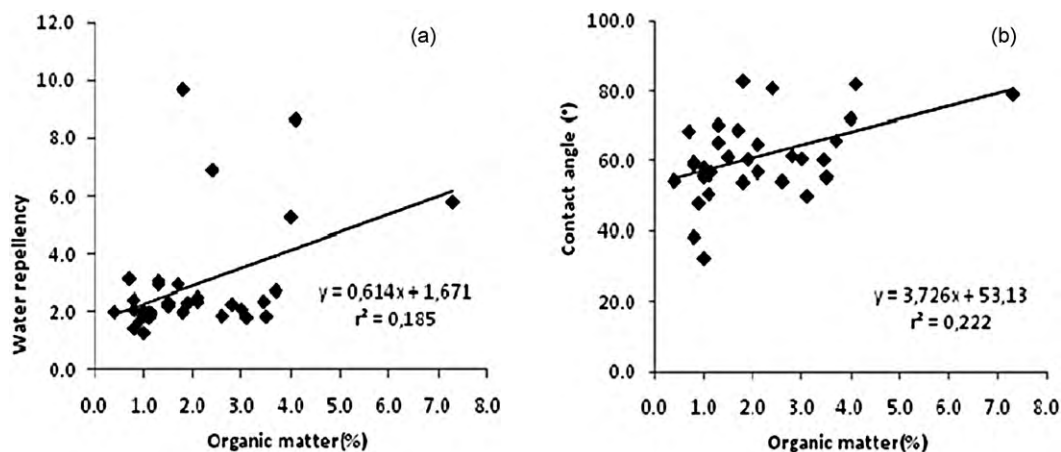
[**] Correlation is significant at $p = 0.01$.

Fig. 1. Relationship between the water repellency index and organic matter content (a) the angle of contact and the organic matter content (b).

other factors responsible for hydro-repellency (See Table 7). Also, the highest Pearson correlation coefficient (r) between R and OMC was 0.45 with a t- value of 2.83 at $p = 0.01$ (Table 7). The exception observed in Endoaqualf (horizon A) may have occurred due to the high quantity of organic matter in the sample (Dekker et al., 1998; Mataix-Solera et al., 2007; Rodríguez-Alleres et al., 2007).

The soil pH in water did not present significant effect on the hydro-repellency of soil at the $p = 0.01$. This observation was in line with the work of Pérez et al. (1999) and must have been caused by some location specific factors, like number of pH active functional group, which may be necessary to define hydro-repellency of soil (Bayer and Schaumann, 2007). Conversely, Mataix-Solera et al. (2007) found a negative relationship between the pH and water repellency in soils of Spain.

The value of hydro-repellency index (R) in most of the sampled soils was low showing a small degree of repellency, especially in the A horizon, probably due to the presence of higher organic matter. Argiudoll, Hapludert and Endoaqualf samples showed hydro-repellency index (R) values of 8.65, 5.79 and 9.70, respectively and which differ significantly from other soils, indicating the presence of high hydro-repellency. It was observed that horizon A of Endoaqualf, which had the highest R value of 9.70, had lower sorptivity comparatively with other sampled soils. The horizon B of Hapludert showed high hydro-repellency, which did not differ significantly from the value found in horizon A. This can be explained by the presence of expansive clay minerals, which produced significant changes in volume with variation of moisture content and result to deep cracks (Streck et al., 2008). This hypothesis justifies the higher degree of repellence found in the B horizon. Pérez et al. (1999), also found higher hydro-repellency in the subsurface horizons.

The angle of contact of the drop of water with the soil surface had a significant impact on the occurrence of hydro-repellency. Argiudoll, Hapludox and Endoaqualf showed high angles of contact in the horizon A, while Endoaqualf and Hapludert had high angle of contact in the B horizon. They also had similar relationships with the hydro-repellency index since the high angle of contact was associated with high levels of organic matter. The organic matter content differ significantly among samples but resulted to a positive correlation coefficient, $r = 0.47$, $p = 0.05$ with the angle of contact. According to Ellerbrock et al. (2005), the more decomposed organic substance is, the greater the angle of wetting, showing the interrelationship of the angle of contact with organic matter.

Table 8
Least significant difference and t test of organic matter content of horizons A and B.

Horizon	LSD (<0.001)	t	(p)
A1 and A2	0.1313	0.3163	ns
A1 and A3	0.0894	0.2154	ns
A1 and B1	1.6363	3.9437	<0.001
A1 and B2	1.7344	4.1802	<0.001
A1 and B3	1.6563	3.9919	<0.001
A2 and A3	0.0419	0.1009	ns
A2 and B1	1.5050	3.6273	<0.001
A2 and B2	1.6031	3.8638	<0.001
A2 and B3	1.5250	3.6755	<0.001
A3 and B1	1.5469	3.7282	<0.001
A3 and B2	1.6450	3.9647	<0.001
A3 and B3	1.5669	3.7764	<0.001
B1 and B2	0.0981	0.2365	ns
B1 and B3	0.0200	0.0482	ns
B2 and B3	0.0781	0.1883	ns

A, B, horizons; 1, 2, 3, sample replicates; ns, not significant at $p < 0.001$.

Table 9

Pearson correlation of hydro-repellency and cation exchange capacity of sampled soils.

	R1 and CEC1	R1 and CEC2	R1 and CEC3	R2 and CEC1	R2 and CEC2	R2 and CEC3	R3 and CEC1	R3 and CEC2	R3 and CEC3
n (pares)	33	33	33	33	33	33	33	33	33
r (Pearson)	0.40[*]	0.39[*]	0.40[*]	0.40[*]	0.40[*]	0.41[*]	0.40[*]	0.41[*]	0.42[*]
r^2	0.16	0.15	0.16	0.16	0.16	0.17	0.16	0.16	0.17
t	2.41	2.34	2.46	2.42	2.43	2.52	2.45	2.48	2.54
(p)	0.022	0.0257	0.019	0.021	0.021	0.017	0.02	0.018	0.016
STE	1.74	1.75	1.74	1.77	1.77	1.76	1.76	1.75	1.75

STE, standard error of estimates; R1, hydro-repellency replicate 1; R2, hydro-repellency replicate 2; R3, hydro-repellency replicate 3; CEC1, cation exchange capacity replicate 1; CEC2, cation exchange capacity replicate 2; CEC3, cation exchange capacity replicate 3.

[*] Correlation is significant at $p = 0.05$.

Soil sorptivity to water showed positive correlation with the aluminum saturation ($r = 0.50$) and negative with bases saturation (-0.53) and CEC at pH 7 (-0.47) as shown in Table 6, which are surrogates for high and low weathering status and are represented by 1:1 and 2:1 in oxidic clay minerals and clay minerals, respectively. The sorptivity to ethanol correlated positively with total porosity ($r = 0.52$), which is explained by the fact that ethanol has high affinity in the soil, thus, its infiltration is governed mainly by the porosity of the soil, irrespective of the existence of hydrophobicity.

The angle of contact and hydro-repellency showed positive correlation with the organic matter content in soil. Previous studies have also found positive relationships between water repellency and organic matter content (Dekker et al., 1998; Mataix-Solera et al., 2007; Rodríguez-Alleres et al., 2007; De Jong et al., 1999 and Gryze et al., 2006). However, low coefficients of determination of 0.18 and 0.22 were obtained for both the hydro-repellency index and the angle of contact, respectively with the organic matter (Fig. 1). This behavior was also observed by Jaramillo (2006), which concluded that it is not the quantity but the composition of soil organic matter which induces the expression of hydro-repellency (Tables 8 and 9).

A relatively high coefficient of variation (31.03) was obtained among hydro-repellency values of all samples in this study, as also observed by Keizer et al. (2007) and Rodríguez-Alleres et al., 2007. These authors pointed out that water repellency in soils is dependent on seasonal variability and spatial variability. Thus, soils that had high rates of hydro-repellency require different strategies to reduce the occurrence of high surface runoff and possibility of soil erosion especially in areas with steep slopes (Shakesby et al., 2000). Hallett (2008) pointed out that reduction in infiltration of water into the soil will reduce the amount of soil available water, and this can affect the process of seed germination, growth and development.

4. Conclusion

In this research, we determined the variability of water and ethanol sorptivity and the resultant hydro-repellency in soils specifically from A and B horizons. Hydrophilic components of organic matter were able to both increase or decrease aggregate sorptivity depending on aggregate structure, pore-size distribution and bulk density. Soil sorptivity to water showed positive correlation with the aluminum saturation and negative correlation with bases saturation and CEC at pH 7. High hydro-repellency index is typical to soils high in clay content, which is predominant to soils of horizon B.

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