

## Soil moisture influences sorptivity and water repellency of topsoil aggregates in native grasslands



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### ABSTRACT

Water repellency is associated to coating of soil particles by hydrophobic substances, usually of organic origin, affecting water dynamics in soil matrix. We analyzed the effect of water repellency on water sorptivity of topsoil aggregates of six soil types under three initial moisture conditions (10 kPa, 100 kPa, and air-dried). Undisturbed soil samples were collected to evaluate sorptivity in the 0–5 cm soil layer at different locations in Pampa Biome in southern Brazil. Disturbed soil samples were also collected for soil particle size distribution, particle density and organic matter content. Sorptivity test was conducted in a tension micro-infiltrometer, using distilled water and ethanol (95% v/v). High values of repellency index R (13.43 in Hapludert, and 8.98 in Dystrudept) of soil aggregates reduced sorptivity and restricted infiltration properties. Repellency index decreased sharply with increase in soil moisture. Therefore, for hydrophobic soils an increase in soil moisture of original air-dry soil reduces hydrophobicity and enhances sorptivity and water infiltration into soil aggregates. High values of water repellency modifies water dynamics in soil aggregates, concealing the effects of matric potential and generating different patterns of conventional water infiltration behavior, especially in dry soil conditions.

### 1. Introduction

Soil water repellency is a widely documented phenomenon, with high spatial variability (Doerr et al., 2007; Madsen et al., 2011). For example, in Europe soil hydrophobicity in Mediterranean areas can cause serious problems in forest especially after intense forest fires (Mataix-Solera and Doerr, 2004; Jiménez-Morillo et al., 2014; Hewelke et al., 2015), while in South America and in Oceania (Deurer et al., 2011) soil hydrophobicity is also reported in native pastures under different soil classes (Vogelmann et al., 2010, 2013b). Soil water repellency can be defined as a reduction in soil wettability, usually due to coating of soil particles by hydrophobic organic soil substances (Cerdà and Doerr, 2007). Soil water repellency can affect soil use and management and directly the plant production (Müller and Deurer, 2011). As a primary effect, Cerdà and Doerr (2007) and González-Peñaloza et al. (2012) cited water infiltration reduction and hence the available water amount will be reduced thereby affecting seed germination, plant growth and development. Because of infiltration rate reduction the

runoff increase, especially in hilly areas, increasing soil erosion, especially in regions with heavy rains after prolonged droughts (Madsen et al., 2011). Soil water repellency can affect the services the soils offers due to the reduction of the infiltration rates (Brevik et al., 2015) and affect the sustainability such as the United Nations shown (Keesstra et al., 2016).

High temporal and spatial variability is a vital aspect of hydrophobicity (Benito Rueda et al., 2016; Alanís et al., 2016; Keesstra et al., 2017) but this phenomenon is not permanent; maximum persistence and severity occurs in driest seasons, and diminish or even vanish in wet seasons (Keizer et al., 2007). Long periods of soil desiccation might promote the increase in persistence and severity in water repellency restricting the soil re-wetting, thus requiring a long time for the soil recover its wettability (Bodí et al., 2013).

Buildup of hydrophobic compounds in soil may indirectly lead to drastic reduction in water content due to soil particles coating by such compounds (De Gryze et al., 2006). Thus, this phenomenon affect water infiltration, resulting in non-uniform preferential flow, interfere in soil

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water distribution and dynamics (Hallett and Young, 1999) and lead to solute loss by leaching in preferential flow paths (Cerdà and Doerr, 2007).

Hydrophobic compounds that promote changes of soil sorptivity indirectly clearly affect water infiltration processes (Vogelmann et al., 2013a). According to the definition of Philip (1957) the sorptivity expresses the tendency of an intrinsic material to absorb and transmit a liquid by capillarity. The sorptivity is a component of the flow processes and needs to be incorporated in any application where adsorption or desorption of a fluid, like water, from a porous media (soil) is occurring due to a potential change at a surface boundary. If water repellency is absent during infiltration of ponded water, an initially-dry soil exhibits high infiltration rate due to increased hydraulic gradient (highest potential difference in soil water potential), while infiltration rate tends to decrease with time, reaching a near-constant value in uniform soil (Cerdà, 1996; Hillel, 1998). This infiltration behavior is very variable through seasons and space, especially under irregular and highly seasonal contrasted climatic conditions, such as the Mediterranean (Cerdà, 1996).

For an understanding of water infiltration processes, soil porosity, initial soil water content, biological activity, vegetation cover, and soil surface roughness are key elements (Keizer et al., 2007). However, hydrophobicity is not yet recognized as a crucial factor in soil water infiltration, and in some studies and models it is neglected, even in cases where soil hydrophobicity is responsible for preferential flow (Ritsema et al., 1998).

Some studies have demonstrated that hydrophobicity is a much broader phenomenon than previously assumed (Hallett and Young, 1999; Vogelmann et al., 2012), and highlighted the need to study about its temporal and spatial properties, factors, and impacts of soil hydrophobicity on hydrological cycle. In this context, aggregate behavior in soil matrix is crucial to understanding changes in soil infiltration from fluctuating soil wettability (Ritsema et al., 1998; Vogelmann et al., 2013a).

The understanding of soil hydrophobicity as one factor possibly influencing soil water infiltration should be associated with soil moisture conditions that are directly related with the hydrophobicity severity and soil sorptivity. This goes in line with the described by Doerr et al. (2007) who reviewed several studies related to soil hydrophobicity and recommends, among other research needs, new studies to elucidate and understand the mechanisms involved in the hydrophobicity expression considering the moisture variation and its relation with soil structure in the microscale (as in soil aggregates for example).

The objective of this study was to analyze the impact of hydrophobicity and initial soil moisture conditions on soil aggregates sorptivity from a range of soils classes.

## 2. Materials and methods

### 2.1. Description of study site

A laboratory study was conducted on soil samples collected from different soil types (Table 1) from Rio Grande do Sul state, southern

**Table 1**  
Classification of the six soils according to Soil Taxonomy (Soil Survey Staff, 2014) and geographic coordinates of the sampling locations.

Soil class	Parental material	Latitude	Longitude
Dystrudept	Basalt	S 29° 38' 41.5"	W 53° 45' 19.6"
Hapludox	Basalt	S 28° 40' 30.8"	W 53° 35' 47.0"
Paleudalf	Sandstone	S 29° 43' 12.4"	W 53° 42' 10.8"
Haplaquent	Basalt sediments	S 29° 43' 08.7"	W 53° 42' 07.2"
Albaqualf	Basalt sediments	S 30° 02' 26.6"	W 53° 40' 42.7"
Hapludert	Basalt	S 30° 43' 14.7"	W 55° 47' 41.5"

Brazil. According to Köppen climatic classification, climate is Cfa, subtropical humid, consisting of four reasonably well-defined seasons, mild winters and hot summers, and well-distributed rains throughout the year. Average annual rainfall ranges from 1500 to 1700 mm, while mean annual temperature is 17 °C (Nimer, 1990).

In all sampled points the vegetation was composed solely by native grassland, composed mainly of *Andropogon lateralis* Nees, *Axonopus affinis* Chase, *Paspalum* spp. and *Aristida laevis* (Nees) Kunth. These grasslands had been used, historically, for beef cattle raising with moderate grazing, approximately one adult animal per hectare. Moreover, soil was not ploughed, and vegetation was not burned in the last 20 years before carrying out this experiment.

### 2.2. Sample collection

All soil samples were collected in grassland fields with no evidence of recent soil tillage. Undisturbed soil samples were collected as blocks, with dimensions of approximately 20 × 10 cm and 5 cm in height, in the 0–5 cm soil layer for sorptivity evaluation. To determine soil bulk density, twelve undisturbed samples were collected using metallic rings, 5.7-cm diameter and 4-cm height, in the middle of 0–5 cm soil layer in each soil type. Disturbed soil samples were also collected at same locations to determine soil particle-size distribution, particle density and organic matter content.

### 2.3. Soil physical characterization

Undisturbed soil samples (collected with metallic rings) were saturated by capillarity and then exposed to water tensions of 6 and 10 kPa, in a sand column (Reinert and Reichert, 2006) and the tension of 100 kPa using the pressure chambers (Klute, 1986). To obtain the soil bulk density, the samples were dried in an oven at 105 °C for 48 h to constant weight. Soil microporosity corresponds to the volumetric water content retained at 6-kPa water tension, while the macroporosity was obtained by the difference between total porosity and microporosity. Total porosity was obtained using Eq. (1):

$$f = \left( 1 - \frac{\rho_d}{\rho_p} \right) \quad (1)$$

where:  $f$  is total porosity ( $\text{cm}^3 \text{cm}^{-3}$ );  $\rho_d$  is soil bulk density ( $\text{g cm}^{-3}$ );  $\rho_p$  is particle density ( $\text{g cm}^{-3}$ ).

For the determination of soil particle-size distribution and particle density, disturbed soil samples were disaggregated and sieved (2 mm diameter). The soil particle-size distribution was determined using the pipette method (Gee and Bauder, 1986), after soil dispersion as described in Suzuki et al. (2015). Sand was sorted by sieving, clay was quantified by sedimentation based on Stoke's law, and silt was calculated as difference between total soil mass and sum of clay plus sand. Particle density was determined by volumetric flask (Flint and Flint, 2002), following the method described in Gubiani et al. (2006).

### 2.4. Determination of soil organic matter

Soil organic carbon was determined by oxidation with potassium dichromate solution ( $\text{K}_2\text{Cr}_2\text{O}_7$ ) at  $0.4 \text{ mol L}^{-1}$  in the presence of concentrated sulfuric acid ( $\text{H}_2\text{SO}_4$ ), with heating in a block digester (Nelson and Sommers, 1996). Organic matter was calculated assuming that 58% of the organic matter content is organic carbon (Nelson and Sommers, 1996).

### 2.5. Determination of soil sorptivities and water repellency index

Undisturbed soil samples were air dried, during approximately 2 weeks in laboratory, up to reaching brittleness consistency. Subsequently, aggregates were manually separated by means of traction

**Table 2**  
Particle size distribution, total porosity ( $\phi$ ), soil bulk density (Bd) and organic matter content (OM) at soil depth 0–5 cm of the six soil types.

Soil	$\phi$		Bd		OM		Sand <sup>a</sup>		Silt		Clay		Textural class
	(m <sup>3</sup> m <sup>-3</sup> )		(Mg m <sup>-3</sup> )		(%)		(g kg <sup>-1</sup> )						
Dystrudept	0.57	± 0.03	1.18	± 0.01	4.1	± 0.2	113	± 7	441	± 6	446	± 5	Silty clay
Hapludox	0.55	± 0.02	1.13	± 0.02	3.7	± 0.1	393	± 4	191	± 8	416	± 13	Loam
Paleudalf	0.42	± 0.01	1.42	± 0.03	2.7	± 0.1	643	± 17	253	± 10	100	± 4	Sand
Haplaquent	0.58	± 0.02	1.22	± 0.01	2.7	± 0.2	339	± 9	410	± 7	251	± 6	Sandy loam
Albaqualf	0.61	± 0.03	0.92	± 0.02	3.1	± 0.2	537	± 14	176	± 11	287	± 7	Sandy clay loam
Hapludert	0.54	± 0.02	1.06	± 0.02	5.6	± 0.2	164	± 5	435	± 10	401	± 15	Silty clay

<sup>a</sup> Sand = 2–0.05 mm; silt = 0.05–0.002 mm; clay ≤ 0.002 mm.

movement to individualize aggregates of approximately 20-mm diameter and of quasi-spheroidal shape. Ten soil aggregates of each soil class were saturated and equilibrated to three soil moisture conditions: 10 kPa tension in sand column (Reinert and Reichert, 2006); 100 kPa in pressure chamber (Klute, 1986), and air-dried. Subsequently, aggregates were tested for sorptivity using tension micro-infiltrometer, composed of a tube at one end, which is connected to a reservoir with liquid, and the other end has a small sponge in contact with soil aggregate (Hallett and Young, 1999). We used two different liquids in the trials: distilled water and ethanol (95% v/v).

During the test, the same hydraulic pressure difference was maintained which equals the height difference between the infiltrometer tip with sponge and the level of the liquid column in the reservoir. The liquid reservoir was a container with a diameter of 15 cm, where the volume consumed during the test caused a change in liquid level inside the reservoir of < 1 mm; thus the effect of this variation was considered negligible. Any bubbles present inside the micro-infiltrometer which could affect its performance were removed prior to commencement of the test. Evaporation losses was measured first and considered negligible during 120 s.

Aggregate was in contact with the infiltrometer tip (sponge of 0.79 mm<sup>2</sup>) for 120 s. Cumulative mass of water or of ethanol that infiltrated by capillary in soil aggregate was recorded as the difference between the initial and the final weight of the liquid reservoir using an analytical balance with a precision of 0.001 g. Temperature of liquids (water and ethanol) was recorded (approximately 20 °C ± 2 for all tests) to estimate liquids density.

Sorptivity ( $S$ ) was obtained by Eq. (2) (Leeds-Harrison et al., 1994):

$$S = \sqrt{\frac{Qf}{4br}} \quad (2)$$

where:  $Q$  corresponds to liquid flow in a circular area in central part of soil aggregate (mm<sup>3</sup> s<sup>-1</sup>);  $b$  is dependent on water diffusion in soil,  $b$  is in the range  $0.5 \leq b \leq \pi/4$  and is equal to 0.5 for Green-Ampt model. White and Sully (1987) suggest that a typical 'average' value for  $b$  is 0.55, value used in this case;  $r$  is infiltrometer tip radius (0.5 mm);  $f$  is fillable porosity (mm<sup>3</sup> mm<sup>-3</sup>). The value of  $f$  for air-dry soil condition was equal to total porosity value, while, the  $f$  values to 10 and 100 kPa tensions were equal to the total porosity value less water volume retained in the respective tension, determined with the soil water retention curve.

Water repellency index ( $R$ ) was obtained by Eq. (3) (Tillman et al., 1989):

$$R = 1.95 \left[ \frac{S_{\text{ethanol}}}{S_{\text{water}}} \right] \quad (3)$$

where:  $S_{\text{ethanol}}$  is sorptivity for ethanol (mm s<sup>-1/2</sup>), and  $S_{\text{water}}$  is sorptivity for water (mm s<sup>-1/2</sup>). Thus, a perfectly wettable soil has  $R$  equal to 1, as defined by the physical relationship shown in Eq. (3). To determine the  $R$  values first were used 10 pairs of sorptivities measurements for water and ethanol, to calculate first the  $R$  value from each pair of sorptivities. After was processed the set of  $R$  values and then

calculated the mean and standard deviation of  $R$ . From this set of 10 replicates of  $R$ , for each soil was determined coefficient of variation.

## 2.6. Statistical analysis

Water and ethanol sorptivity tests were conducted considering six soil types, with 10 replicates per treatment (soil type) for each moisture (air-dried, 10 and 100 kPa) for each sorptivities (water or ethanol) measurements; a total of 360 soil aggregates were tested.

Data were analyzed for normal distribution using Shapiro-Wilk procedure and all variables followed the normal distribution. All data were then submitted to ANOVA and, when F test was significant, means were compared and separated by Tukey test ( $p < 0.05$ ).

## 3. Results and discussion

### 3.1. Effects of soil organic matter in water repellency

Soils with higher sand contents (above 537 g kg<sup>-1</sup>) were Albaqualf and Paleudalf, whilst highest clay contents (above 401 g kg<sup>-1</sup>) were found in Hapludox, Dystrudept and Hapludert (Table 2). Dystrudept, Hapludox, Albaqualf and Hapludert soils had organic matter contents above 3.0%, with the highest value (5.6%) observed in Hapludert.

Soil organic matter substances usually cause increase in repellency especially when the soil shows low moisture. Hallett and Young (1999) and Doerr et al. (2007) suggested that soil organic substances form water repellent structures with hydrophobic and hydrophilic functional groups, which may change orientation depending on the degree of hydration (or soil water potential). If the hydrophobic groups are pointed outward, water repellency increases; when they are oriented toward each other or the interior, water repellency may decrease. This behavior was also verified in this study, in which the Hapludert and Dytrudept, which presented the highest organic matter content, also presented the highest values of  $R$  that increased in the air dry soil condition. Otherwise, Paleudalf and Hapludert were the ones with the lowest organic matter content and  $R$  values below 1.6. This behavior corroborates with De Gryze et al. (2006) and Vogelmann et al. (2013b), who observed the occurrence of more-severe hydrophobicity in air-dried soils with higher organic matter content, as shown by the positive correlation between water repellency and organic matter content.

According to Kleber and Johnson (2010), when the soil is highly wet, the ends of the polar hydrophobic compounds are attracted by free water and thus the compounds previously adhered to the soil are attracted to the soil solution. However, as the hydrophobic part of the compounds do not relate to water, they tend to cluster around, thereby reducing the direct contact area with water and exposed only to the outside of the hydrophilic face (Rezus and Bakker, 2007). Thus, in higher soil moisture there is reduction of organic matter influence, because hydrophobic compounds turn to the outside their hydrophilic faces, promoting the reduction of  $R$  values.

**Table 3**

Arithmetic mean values of ethanol and water sorptivity and water repellency index (R) of soil aggregates from 0 to 5 cm depth in the six soil types at different soil moisture conditions (water tension 10, 100 kPa and air-dried).

Acronym	Water tension 10 kPa			Water tension 100 kPa			Air-dried			CV (%)
Ethanol sorptivity ( $\text{mm s}^{-1/2}$ )										
Dystrudept	0.043	b*	$\pm 0.005^{**}$	0.055	ab	$\pm 0.009$	0.060	a	$\pm 0.011$	3.9
Hapludox	0.044	c	$\pm 0.011$	0.067	b	$\pm 0.007$	0.086	a	$\pm 0.012$	6.7
Paleudalf	0.029	b	$\pm 0.009$	0.036	b	$\pm 0.009$	0.061	a	$\pm 0.010$	8.2
Haplaquent	0.038	c	$\pm 0.010$	0.054	b	$\pm 0.010$	0.068	a	$\pm 0.010$	4.2
Albaqualf	0.046	c	$\pm 0.004$	0.062	b	$\pm 0.008$	0.082	a	$\pm 0.011$	3.7
Hapludert	0.051	b	$\pm 0.008$	0.054	b	$\pm 0.009$	0.062	a	$\pm 0.009$	4.4
Water sorptivity ( $\text{mm s}^{-1/2}$ )										
Dystrudept	0.037	b	$\pm 0.008$	0.046	a	$\pm 0.007$	0.013	c	$\pm 0.005$	8.2
Hapludox	0.029	c	$\pm 0.009$	0.039	b	$\pm 0.008$	0.053	a	$\pm 0.008$	9.4
Paleudalf	0.041	b	$\pm 0.005$	0.048	b	$\pm 0.009$	0.074	a	$\pm 0.007$	10.7
Haplaquent	0.058	b	$\pm 0.011$	0.060	b	$\pm 0.010$	0.087	a	$\pm 0.007$	7.9
Albaqualf	0.044	a	$\pm 0.008$	0.052	a	$\pm 0.010$	0.034	b	$\pm 0.009$	8.0
Hapludert	0.084	a	$\pm 0.010$	0.011	b	$\pm 0.006$	0.009	b	$\pm 0.008$	5.5
Water repellency index (R)										
Dystrudept	2.27	b	$\pm 0.10$	2.33	b	$\pm 0.19$	8.98	a	$\pm 0.48$	6.5
Hapludox	2.94	a	$\pm 0.21$	3.36	a	$\pm 0.24$	3.17	a	$\pm 0.20$	8.1
Paleudalf	1.39	a	$\pm 0.19$	1.46	a	$\pm 0.21$	1.60	a	$\pm 0.24$	9.8
Haplaquent	1.29	b	$\pm 0.20$	1.76	a	$\pm 0.28$	1.53	ab	$\pm 0.24$	7.8
Albaqualf	2.04	b	$\pm 0.20$	2.33	b	$\pm 0.13$	4.70	a	$\pm 0.31$	6.4
Hapludert	1.19	c	$\pm 0.28$	9.57	b	$\pm 0.56$	13.43	a	$\pm 0.69$	6.7

\* Means followed by the same letter in the line do not differ by Tukey test ( $p < 0,05$ ).

\*\* Standard deviation. CV – Coefficient of variation.

### 3.2. Effects of soil moisture in sorptivity and water repellency of soil

Ethanol sorptivity was highest in air-dried soil aggregates, due to low soil water content (Table 3). Higher sorptivity in dry condition occurred because ethanol infiltration is influenced mainly by soil matric potential (Philip, 1957). Capillary forces and water-solid molecular adhesion are high in initial infiltration of dry soil. As ethanol begins to percolate, the surface layer is being semi-saturated, while at the same time capillary forces tend to decrease, reducing ethanol infiltration into soil, which tends to a constant value close to saturation condition (Feng et al., 2001; Culligan et al., 2005).

In soil aggregates equilibrated to 10-kPa and 100-kPa water tension (higher water content), ethanol sorptivity was lower than in air-dried aggregates even in early stage (Table 3), indicating a decrease of ethanol sorptivity with an increase of moisture in soil aggregates. In some soil types water sorptivity was higher in aggregates with very low water content (air-dried), which can be explained by the fact that, just as ethanol, water infiltration into soil with low moisture is influenced primarily by soil matric potential gradient.

Thus, in Hapludox, higher water sorptivity was observed in samples with higher moisture, and then reducing with increasing water content. Among the analyzed soils, only in Paleudalf and Haplaquents R was below the critical limit described by Tillman et al. (1989), i.e., R of 1.95 as critical water repellency index.

Dystrudept, Albaqualf and Hapludert showed a different behavior, in which water sorptivity of air-dried soil aggregates was lower than for moist soil; thus, water flux through soil surface was lower in dry soil than in moist soil. Further, there was reduction in water sorptivity calculated according to Eq. (2), where in the parameters  $b$  (physical diffusion into soil) and  $r$  (radius of infiltrometer tip) are intrinsic physical properties of soil samples and equipment. These parameters show no significant change during the test, so that  $Q$  (liquid flow), i.e. fluid infiltration rate into soil aggregates, is the only varying parameter. Hence, reduction in sorptivity is directly proportional to square root of the liquid flow rate, probably from the action of hydrophobic compounds controlling water infiltration (Hallett et al., 2004; Lichner et al., 2007). This corroborates to the hypothesis acceptance of this study, because the correlation of R values, considering the different soils, with the water sorptivity evidences the inverse relationship between these properties (Fig. 3). From this, it is possible to verify that the high

hydrophobicity promotes soil wetting reduction, which is expressed by water sorptivity, that is significantly reduced with hydrophobicity increase.

Maximum water sorptivity in Dystrudept was quantified for intermediate moisture condition (water tension of 100 kPa). Thus, reduction in hydrophobic compounds effect occurs only after the soil reaches 100 kPa water tension, indicating a higher persistence and action of these compounds in the soil, differently from the behavior observed in Paleudalf, Haplaquent and Hapludox where soil hydrophobicity drastically reduced shortly after soil moistening. Thus, sorptivity becomes dependent only of soil water potential, although it may be affected by reducing water flow with low matric potential in wet soil, as observed in samples equilibrated at 10 kPa water tension (Jasinska et al., 2006).

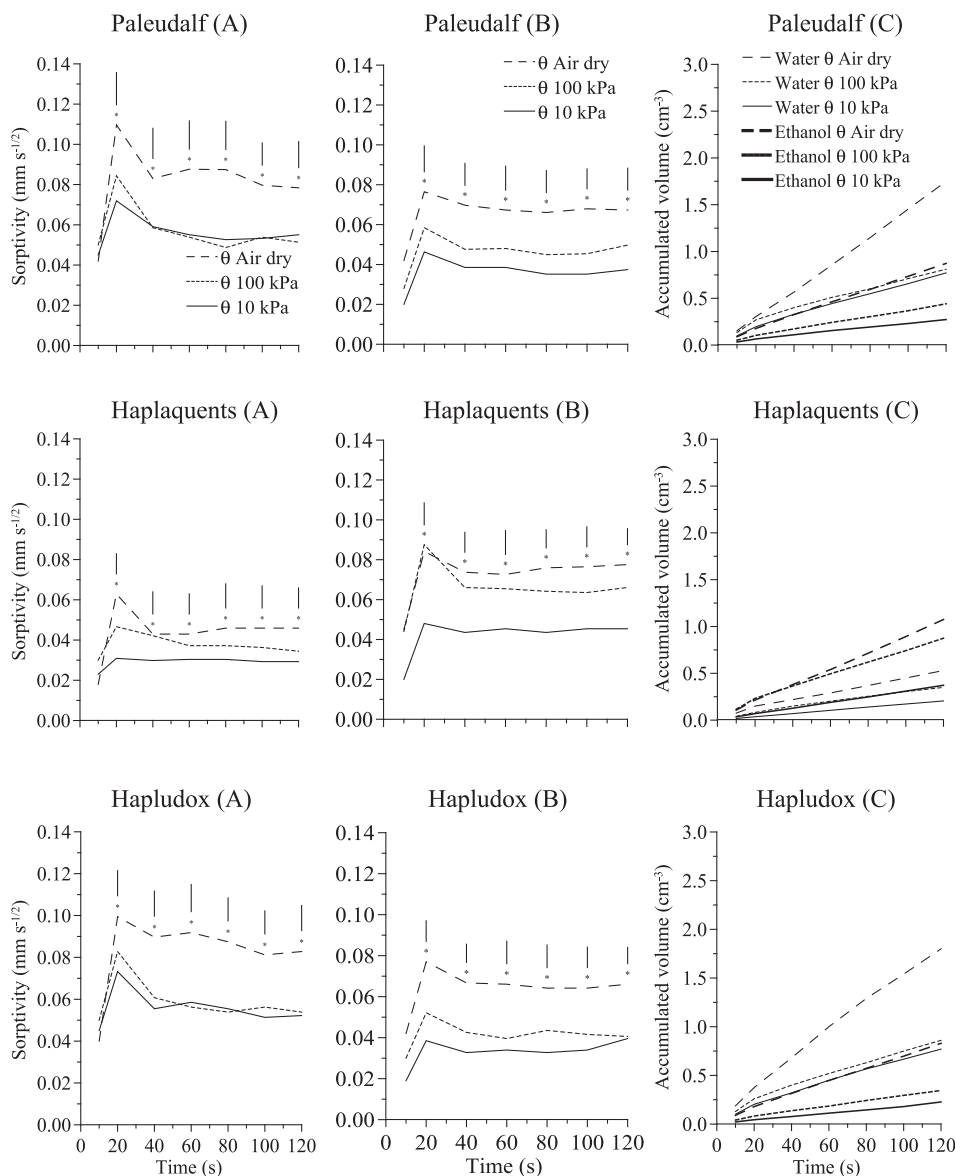
Except for Hapludert, all soils had maximum water sorptivity at intermediate moisture condition (water tension of 100 kPa) and decreased at higher moisture (water tension of 10 kPa). In Hapludert, however, the maximum water sorptivity occurred at higher soil moisture condition (water tension of 10 kPa). This shows that hydrophobic compounds reduced water infiltration over a wide range of soil moisture. For instance, in initially air-dry Hapludert, sorptivity was maximal when soil water content reached near-saturation condition (10 kPa).

For low soil moisture (air-dried soil), Dystrudept, Albaqualf and Hapludert showed high R, which differed significantly among these and other soils. For Hapludert there was a significant decrease in sorptivity, that is, in soil wetting rate. Doerr et al. (2007) and Vogelmann et al. (2013b) state that diverse hydrophobicity behavior may be associated with different concentrations of hydrophobic substances responsible for water sorptivity decrease. Hallett and Young (1999) and Czarnes et al. (2000) assert that higher water repellency is observed with higher biological activity on surface aggregate, by produces organic biofilms.

Further, the variation in sorptivity was correlated to total time of water and ethanol sorptivity tests for the studied soils (Figs. 1 and 2). Paleudalf, Haplaquents and Hapludox soils presented “typical” behavior of water sorptivity by showing greater values at lower soil moisture, and then reduces with increasing moisture (Fig. 1).

Three stages in time of sorptivity may be defined:

- (i) initial stage in sorptivity increase (0–20 s), indicating unsaturated flow in which hydraulic gradient is determined mainly by matrix



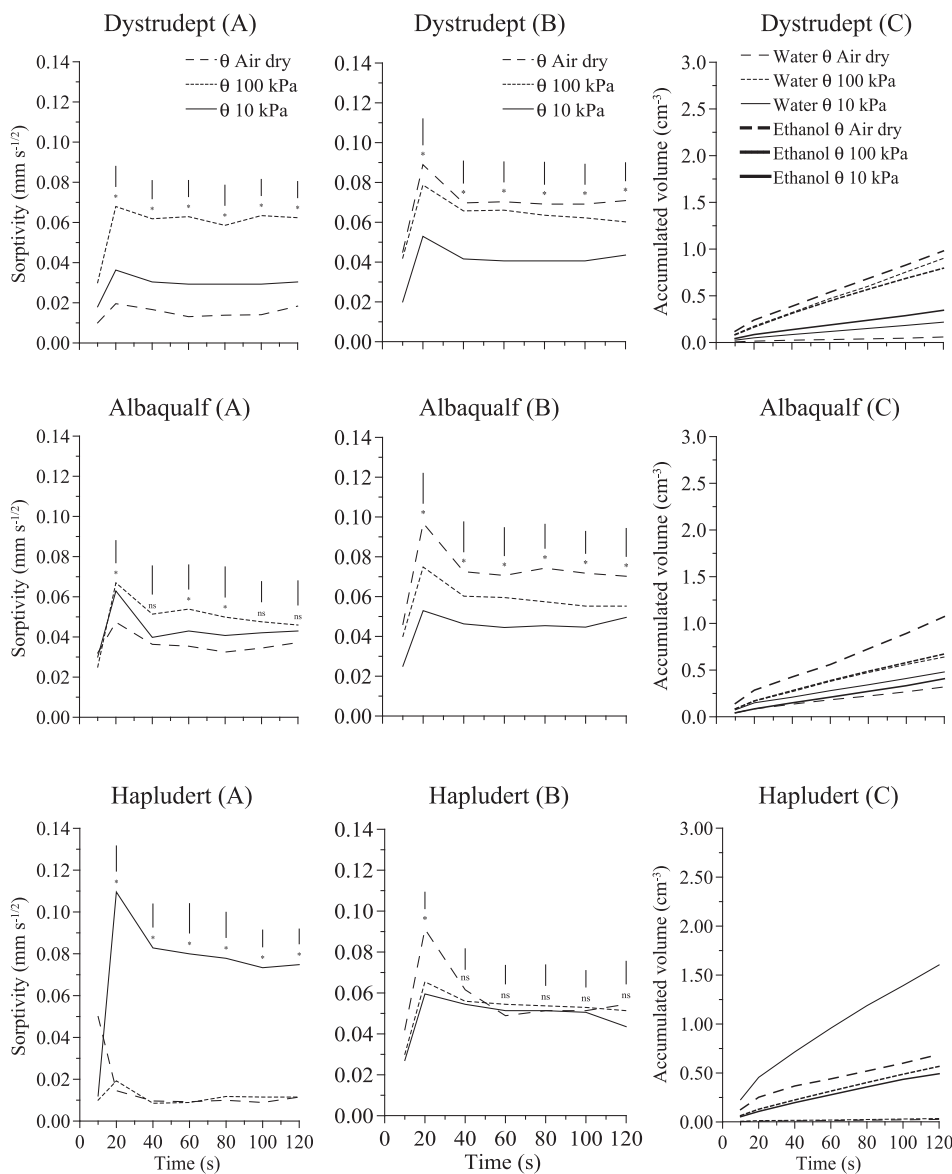
**Fig. 1.** Water sorptivity (A), ethanol sorptivity (B) and (C) the accumulated water and ethanol infiltration during the sorptivity test of soil aggregates from 0 to 5 cm depth of the soil types, equilibrated to three initial conditions in the pressure head representing relatively moist, medium, and air dry soil aggregates. Vertical bar represents the minimum significant difference from Tukey test ( $p < 0,05$ ). \* Significant ( $p < 0,05$ ).

- potential;
- (ii) transition stage where, after reaching its maximum, sorptivity begins to decrease significantly (20–60 s), and hydraulic gradient is determined mainly by liquid wettability and space geometry, at the expense of matric potential which will be reduced with increased soil moisture (Culligan et al., 2005);
  - (iii) near-saturation stage in which sorptivity varies little, reaching a quasi steady-state (> 60 s), indicating saturated flow where the soil saturated hydraulic conductivity determines the water flow (Hallett et al., 2004; De Gryze et al., 2006).

In soils with this “typical” behavior, variation in sorptivity at different stages can be explained by Richards’s equation, which describes water flow in unsaturated soil (Hillel, 1998). At the onset of the process, in dry soil conditions, the depth of wetting front is small and hydraulic gradient is not very important, but soil matric potential ( $\Psi_m$ ) is highly negative, promoting the increases in water sorptivity. As the soil absorbs water the  $\Psi_m$  increases, approaching zero at soil water saturation interfering insignificantly in infiltration. Close to this moisture condition, flow tends to be preferentially determined by the gravitational component ( $\Psi_g$ ), which is directly proportional to vertical distance from soil surface toward subsurface layers. Thus, under saturated

conditions hydraulic gradient  $[(\Psi_m + \Psi_g) / \Psi_g]$  is equal to 1 and hence the infiltration rate will be approximately equal to saturated hydraulic conductivity, which corresponds to stage (iii), in which sorptivity is alleviated. Consequently, a relatively-wet soil will have an initial low infiltration rate due to low hydraulic gradient (lower gradient in soil matric potential) and infiltration rate rapidly becomes steady, as described by Culligan et al. (2005).

This behavior is illustrated in Fig. 1A for water and in Fig. 1B for ethanol sorptivity, where the lower moisture the higher the sorptivity, which in this case was attributed to higher water flux. Therefore, it follows that in soil aggregates with low moisture, accumulated infiltration is greater since infiltration rate is higher, resulting in greater volume of infiltrated water into aggregates (Fig. 1C). However, ethanol infiltrates more easily compared to water, due to difference in their physical properties, i.e., ethanol has lower viscosity and surface tension than water (Tillman et al., 1989; Lichner et al., 2007). Thus, simple analysis of water and ethanol sorptivity does not demonstrate the hydrophobic character of soil, since water repellency index  $R$  compares volumes of water and ethanol infiltrated after correction by differences in physical properties of liquids. This is supported by Feng et al. (2001) who analyzed absolute infiltration rate in artificially produced water-repellent sand, in which infiltration rate for aqueous ethanol solution



**Fig. 2.** Water sorptivity (A), ethanol sorptivity (B) and (C) the accumulated water and ethanol infiltration during the sorptivity test of soil aggregates from 0 to 5 cm depth of the soil types, equilibrated to three initial conditions in the pressure head representing relatively moist, medium, and air dry soil aggregates. Vertical bar represents the minimum significant difference from Tukey test ( $p < 0,05$ ). \*Significant ( $p < 0,05$ ).

differed from water (lower infiltration rate).

Soil aggregates of Hapludert, Albaqualf and Dystrudept exhibited typical behavior for ethanol sorptivity, which was very similar to the obtained for Paleudalf, Haplaquents and Hapludox (Fig. 2B). However, for water sorptivity the behavior was “atypical”, because sorptivity of aggregates at low moisture was lower than those for moist soil (water tension of 10 kPa and 100 kPa), leading to small increase in water infiltration in air-dried soil aggregates in the first seconds, followed by a linear relationship with little variation after maximum sorptivity was reached (Fig. 2A). However, ethanol sorptivity and, consequently, ethanol flux in Hapludert, Dystrudept and Albaqualf air-dried soil aggregates did not show such behavior, and most high-ethanol sorptivities were observed at low moisture condition (air-dried soil), unlike water, which gave small sorptivity due to reduced flux in aggregates of these soils. In Fig. 2C, Hapludert, Dystrudept and Albaqualf show reduced water infiltration in air-dried soil condition as compared with wet soil (water tension of 10 kPa) at the end of test period (2 min). This agrees with Hallett et al. (2004), Culligan et al. (2005), and Vogelmann et al. (2013b), who observed that soil sorptivity and consequently water infiltration are directly influenced by soil moisture.

This atypical behavior also reflected in cumulative infiltration, where ethanol infiltration was higher in air-dried soil samples, followed

by samples equilibrated at 10 and 100 kPa. In contrast, cumulative water infiltration was greater in samples with higher water content, mainly due to reduced water flux in air-dried soil aggregates caused by hydrophobic compounds. Furthermore, high accumulated infiltration for both liquids is associated with high sorptivity and hence with greater fluid flow, and is variable depending on initial moisture that may be considered a factor regulating initial infiltration rate. Dekker et al. (2001) and Deurer et al. (2011) also identified the existence of threshold water content for hydrophobicity expression, which was associated to soil organic matter and particles surface area. Other relevant aspect is showed in Bauters et al. (2000), who comment that soil hydrophobicity can affect the matric potential through the contact angle. For instance, for contact angles  $< 90^\circ$  water infiltrates under negative pressure, where small pores fill up first, followed by successively larger pores. For contact angles  $> 90^\circ$ , the matric potential of the infiltrating water in dry soils becomes positive, and thus large pores fill up first followed by smaller pores. When the contact angle is  $90^\circ$ , all the pores will fill up simultaneously.

As recently discussed in the literature (Horn and Kutilek, 2009; Mentges et al., 2016; Reichert et al., 2016), the dynamics of soil behavior is better understood by using the concept of intensity and capacity (or composition) soil properties and their interrelationships.

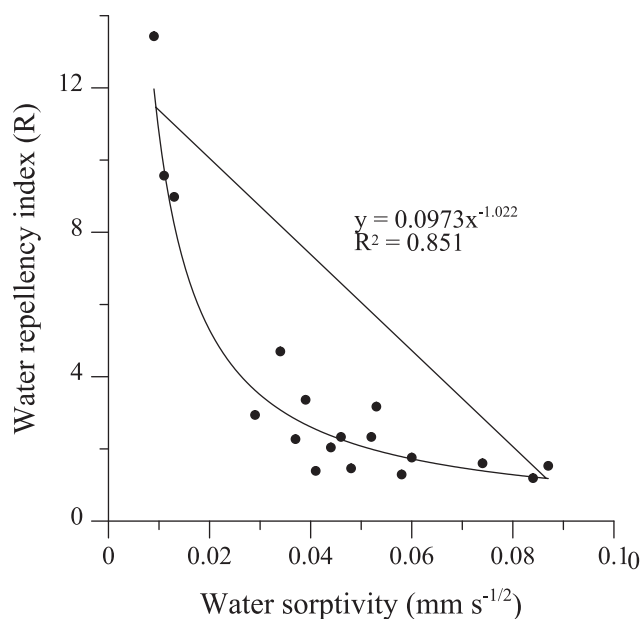


Fig. 3. Graphical representation of correlation between water sorptivity and water repellency index (R) of topsoil aggregates of six soil types under three initial moisture conditions (10 kPa, 100 kPa and air-dried).

Thus, soil properties related to hydrophobicity, an intensity (or functioning) property is fundamental in the understanding of water infiltration, retention, and runoff at the plot, landscape, and watershed scales.

#### 4. Conclusions

Water repellency index and water sorptivity are inversely associated, and drastically affect water infiltration and water dynamics in soil aggregates in soils under native grasslands. With decreasing water content, water repellency index increases sharply. Despite the evident hydrophobicity decrease with soil moistening in the case of Haplodux, this decrease represents only a decrease in intensity but not the hydrophobic condition suppression, resulting in the hydrophobicity occurrence with high soil moisture content and indicating the existence of different phenomenon persistence in function of soil classes. A decrease in soil moisture increases the intensity of water repellency phenomenon, and decreases water sorptivity and infiltration into soil aggregates in soils under native grasslands. High water repellency modifies water dynamics in soil aggregates, concealing the effects of matric potential and generating different patterns of conventional water infiltration behavior, especially in dry soil conditions. Thus, water repellency should be considered in water infiltration models for soils under native grasslands.

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