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Evaluating soil water matric pressure and sorptivity relationship as affected by some properties of a clay soil

Gülay Karahan

Abstract: Sorptivity (S) is the fundamental variable controlling the early infiltration process. Besides soil properties, soil initial water content (θ_i) and (or) matric pressure (h_i) are key factors determining extent of S. Assessment of interrelationship among S, h_i, and soil properties can provide a considerable insight into understanding the behaviour of dry soils to rainfall or irrigation water. This study was conducted to evaluate relationship between S and some selected soil parametric and morphometric properties within a range of h_i. Sixteen undisturbed soil samples (5 cm id, 5 cm length) were taken from the topsoil (0–15 cm) of a paddy soil with clay texture. Sorptivity was measured with a mini-disc infiltrometer on the samples equilibrated at h, ranging from −20 to −1500 kPa. A parameter (η), representing the relationship between S and h_i, was introduced. Correlation analysis was conducted between η and selected soil morphometric and parametric properties. Soil structure and clay content appeared the most important soil attributes influencing S–h_i relation between −200 and −1500 kPa. The results provided a fundamental understanding on S–h_i–soil properties interrelations in a clay soil. The methodology developed in this study can be used to evaluate S–h_i relationship across different soils and scales.

Key words: sorptivity, soil structure, soil water content, matric pressure, hydrophobicity.

Résumé : La sorptivité (S) est la variable fondamentale qui commande le début de l’infiltration. Outre les propriétés du sol, la concentration d’eau initiale dans le sol (θ_i) et la pression capillaire (h_i) jouent un rôle déterminant dans l’ampleur de la sorptivité. En évaluant les relations entre S, h_i et les propriétés du sol, on parvient à se faire une très bonne idée du comportement des sols arides en présence d’eau, qu’elle vienne de précipitations naturelles ou de l’irrigation. Dans le cadre de leur étude, les auteurs ont évalué les liens entre S et quelques propriétés paramétriques et morphométriques du sol à l’intérieur d’une plage de valeurs de h_i. Pour cela, ils ont prélevé seize carottes (5 cm de diamètre intérieur et 5 cm de longueur) dans le sol de surface intact (0–15 cm) à texture argileuse d’une rizière. Ils ont mesuré la sorptivité des échantillons équilibrés à h, soit de −20 à −1500 kPa, avec un infiltromètre à minidisque. Les auteurs ont créé un paramètre (η) qui illustre le lien entre S et h_i. Ensuite, ils ont analysé la corrélation entre ce nouveau paramètre et certaines propriétés morphométriques et paramétriques du sol. La structure du sol et sa teneur en argile semblent influencer le plus la relation S–h_i entre −200 et −1500 kPa. Les résultats de l’étude nous aident à comprendre les bases de la relation entre les propriétés S et h_i d’un sol argileux. La méthode élaborée par les auteurs pourrait servir à évaluer les liens S–h_i entre différentes sortes de sols à diverses échelles. [Traduit par la Rédaction]

Mots-clés : sorptivité, structure du sol, teneur en eau du sol, pression capillaire, hydrophobicité.

Introduction

Sorptivity (S) specifies soil’s capacity to absorb water when capillary forces dominate over gravity (Chong and Green 1983; Radcliffe 1999; Angulo-Jaramillo et al. 2016; Moret-Fernández and Latorre 2017); it is used to express the early infiltration rate as a function of time and water content and to predict related soil hydraulic properties (Moldrulp et al. 1994; Moret-Fernández and Latorre 2017). The variable S has a great importance to characterize water loss from runoff and evaporation (Shaver et al. 2013). Also, an inherent relationship exists between S and other soil hydraulic properties such as hydraulic conductivity ($K(\theta)$), soil water diffusivity (D), as well as with soil water matric pressure (Ψ) (Gerke and Köhne 2002; Moret-Fernández and Latorre 2017; Villarreal et al. 2019). Therefore, understanding of S–soil water matric

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pressure relationship for the surface soil layer is critical for understanding the water dynamics in response to rainfall or irrigation (Cook and Broeren 1994; Carrick et al. 2011).

Soil sorptivity depends on supply soil water matric pressure and initial soil water matric pressure (Carrick et al. 2011; Vogelmann et al. 2017; Bagarello et al. 2020). Studies (Carrick et al. 2011) showed that S decreases with increasing initial water content θ_i due to increased soil water storage capacity and soil water matric pressure gradient. Matric pressure of air-filled portion of pore network has a fundamental influence on sorptivity (Carrick et al. 2011). Sorptivity is governed by surface soil physical properties such as aggregate stability and degree of aggregation (Lipiec et al. 2009), soil texture, total porosity, and bulk density (Ferrero et al. 2007; Shaver et al. 2013; Raut et al. 2014). Hydrophobicity is a fundamental factor affecting S, especially below a critical initial water content (Vogelmann et al. 2017). The critical soil water content is the soil water value below which a wettable soil becomes water repellent; the value may depend on the type and amount of organic matter content besides other interacting soil variables (Dekker and Ritsema 1994; Dekker et al. 2001; Vogelmann et al. 2017). Number of studies conducted for evaluating S–soil attributes relationships at different h_i values is low. Point values of S (h_i) were correlated with soil attributes to understand relationship between S and soil properties across different h_i values in those studies. For example, Yusuf et al. (2018) evaluated sorptivity, infiltration rate, hydraulic conductivity, and diffusivity of the soils at different soil water matric pressures (−0.02, −0.05, −0.10, and −0.15 m) in a loamy sand in Nigeria and noted that soils with the loose structure had greater sorptivity. Shaver et al. (2013) studied the effect of total and effective porosity on sorptivity and found a significant correlation between S and total porosity. A thorough evaluation of soil properties–S–h_i interactions needs considering S–h_i or S–θ_i relations within a range of h_i or θ_i. However, the literature research conducted for this study has shown that no such study has been conducted to date. The objective of this study was to develop a procedure to evaluate relationship between soil properties and S–h_i relations within a range of h_i. In this regard, a parameter (η) representing S–h_i relations between −200 and −1500 kPa was introduced, and then correlation coefficients between η and some selected soil properties were calculated on the soil samples representing the study soils.

Materials and Methods

This study was carried out on a paddy clay soil in Kızılırmak Township in Çankırı Province (40°21′03″N, 33°59′12″E) in the Central Anatolia Region of Turkey (Fig. 1). Kızılırmak has a semiarid climate, 11 °C annual temperature, 64% humidity, and 418 mm rainfall (Anonyoumus 2011). Studied soils have been developed gypsum, andesite, spilite, basalt, marl, clay, and limestone parent materials are classified as Gypsic Ustorthends. The topsoil texture is mostly clay.

Sixteen undisturbed soil samples (5 cm id, 5 cm length) were taken for measuring S. In addition, 15 undisturbed soil samples (8 cm inner id, 15 cm length) were taken for the determination of saturated hydraulic conductivity. Soil cores were placed in vapour-proof plastic bags, moved to the laboratory, and stored there until analyzed. In addition, 16 disturbed 16 soil samples were collected from the same sampling points for basic soil analyses.

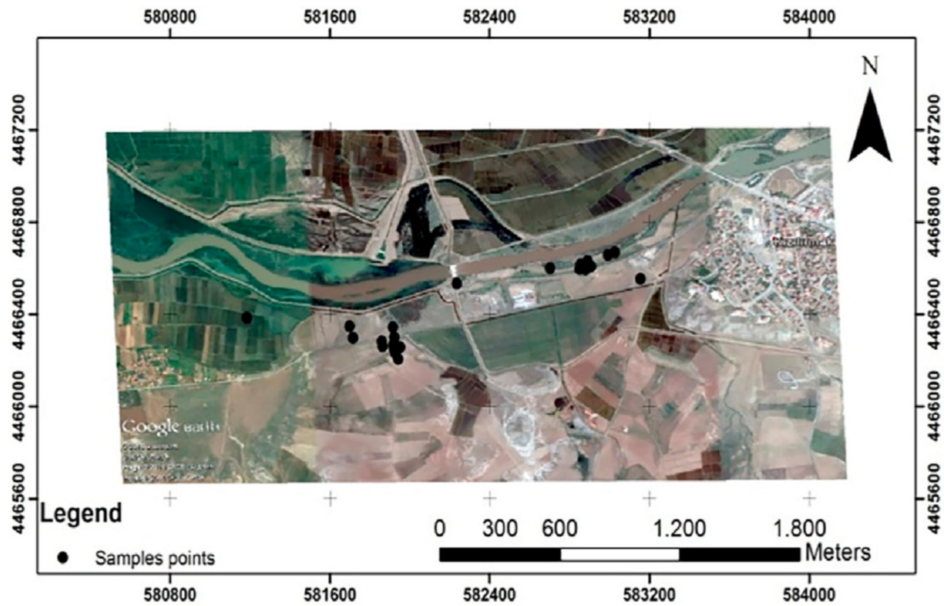
Infiltration rate was measured with a mini-disc infiltrometer (MDI) (Perroux and White 1988) on undisturbed soil samples. Sorptivity was calculated from early time infiltration rate (1–5 min) (Lewis et al. 2006; Robichaud et al. 2008; Hunter et al. 2011). The early stage of infiltration normally occurs between 1 and 400 s, which is equivalent to square root of 1–20 $s^{0.5}$ (Cook and Broeren 1994). It has been noted that the MDI proved to be a practical alternative to the classical tension infiltrometer to estimate hydrodynamic properties (Alagna et al. 2016). MDI does not disturb soil surface (White and Perroux 1987) and prevents the macropore flow due to the applied negative potential during the infiltration measurements (Minasny and George 1999).

Infiltration rate was measured at each soil water matric pressure at time steps of 5 s (0–60), 10 s (60–120), and 30 s (120–240) for approximately 4 min. Soil samples were saturated with water and equilibrated on pressure plate apparatus at different pressures (200, 330, 500, 600, 700, 800, 900, 1000, 1200, 1500, 2000, 3000, 4000, 5000, 10000, and 15000 kPA). Cumulative infiltration (I) was plotted as a function of square root of time according to equation of Philip (1957), and S value for each sample was calculated as the slope of the resultant regression equation (Cook and Broeren 1994; Baranian Kabir et al. 2020).

Correct measurements of the water infiltration with the tension infiltrometer require the disc base to be completely in contact with the soil surface (Reynolds and Zebchuk 1996; Latorre et al. 2015). In this study, a moist fine sand layer with a possible minimum thickness (≈0.25 mm) was used to avoid the effect of sand on the S (Kelishadi et al. 2014).

Soil parametric characteristics such as saturated hydraulic conductivity (Klute and Dirksen 1986), soil texture components (Gee and Bauder 1986), bulk density (Black and Hartge 1986), field capacity, permanent wilting point (Klute and Dirksen 1986), pH (McLean 1982), specific surface area (SSA) (Carter and Mortland 1986), soil organic matter (SOM) content (Nelson and Sommers 1982), cation exchange capacity (Rhoades 1982), and $CaCO_3$ content (Nelson 1982) were measured. Soil structure and consistency properties and structural and mechanical properties such as stickiness, plasticity (Schoeneberger et al. 2012), and coefficient of linear

Fig. 1. Location of study area and sampling points (based on UTM datum WGS 84 North 36 zone). The map was downloaded from Google Earth, transferred to ArcGIS, and the sampling points, scale, and the map coordinates were edited (Karahan and Erşahin 2017). [Colour online.]



extensibility (COLE) (Schafer and Singer 1976) were described using soil description charts. Then soil structural and mechanical properties were converted to numerical values to enable their quantitative use (Table 1) (Karahan and Erşahin 2017).

Relationship between S and h_i was modelled using a linear or logarithmic regression equation. The type of equation was decided according to the result of Williams and Kloot test (Williams and Kloot 1953; Cho et al. 2016). When the slope between residuals of linear and logarithmic models was significantly different from 0 at the significance level of 0.05, logarithmic equation was regarded instead of linear one. The slope of linear or logarithmic equation was designated as η. Finally, relationships between η and soil properties were evaluated by the Spearman's correlation analysis.

Results

Exploratory statistics of soil parametric and morphologic properties are given in Table 2. K_s has the highest (116.5%) and bulk density has the lowest (4.23%) coefficient of variation among the parametric soil properties. Similarly, COLE has the highest (30.0%) and consistency has the lowest (3.29%) variation among the morphological soil properties.

Relationships between S and initial soil matric pressure (h_i) of the soil samples are given in Fig. 2. The slopes of the graphs (η) indicate that the strongest relationship between S and h_i occurred for sample 4, while the weakest occurred for sample 13. A logarithmic relationship occurred between S and h_i for majority of the soil samples (Fig. 2). The behaviour of S within the range of h_i (between −200 and −1500 kPa) showed differences among the soil samples. Some of S–h_i graphs increase more steeply up to h_i then flatten out at more negative values of h_i as shown in Fig. 2 (e.g., 3, 4, 6, and 8), and some others exhibited three distinct segments (e.g., 2, 5, 8, 14, 15, 16). Similar relationships between S and h_i have been reported by Kumke and Mullins (1997), who noted that measured S values were strongly related to the values of h_i at their two test sites. Kumke and Mullins (1997) further noted that overall S–h_i relationship was exponential between −3 and −18 kPa of soil water pressure.

Table 3 presents the correlation coefficients between η and some properties of studied soils. Spearman's correlation test was conducted to lessen effect of skewed distribution of many of the soil properties (Table 2). A significant positive correlation was found between η and structure type, plasticity, and stickiness (Table 3). Also, factors with eigenvalues >1 that obtained using correlation matrix (SAS Institute 1989) were showed in Table 4. While relatively uncorrelated variables are loaded in different factors, highly related variables are loaded in the same factor (Kalaycı 2010). The coefficient η and structure type, plasticity, and stickiness were loaded in the same component (Factor 2), suggesting presence of increasing or decreasing relationships among those variables. The factors are ordered according to their eigenvalues and identification percentage of the total variation in the dataset. For example, Factor 1 explained 27.35% and Factor 2 explained 19.74% of the total variation in the dataset. Clay

Table 1. Criteria applied to coding soil properties (Schoeneberger et al. 2012).

Structure size	Score	Structure type	Score	Structure grade	Score
Very thin	<1	Massive	1	Structureless	1
Thin	1–2	Platy	2	Weak	2
Medium	3–5	Prismatic	3	Moderate	3
Coarse	6–10	Blocky/angular	4	Strong	4
Very coarse	>10	Blocky/subangular	5	Very strong	5
		Granular	6		
		Single grain	7		
Stickiness		Definition			
Not sticky	4	Soil does not stick when squeezed between the fingers			
Slightly sticky	3	Soil sticks to one finger			
Moderately sticky	2	Sticks to two fingers, mud elongate slightly when fingers opened			
Very sticky	1	Soil sticks firmly to two fingers and mud extend in certain ways when fingers opened			
Plasticity		Definition			
Not plastic	4	Will not form a roll 6 mm in diameter, or if a roll is formed; it can't support itself if held on end.			
Slightly plastic	3	6 mm diameter roll supports itself; 4 mm diameter roll does not.			
Plastic	2	4 mm diameter roll supports itself; 2 mm diameter roll does not.			
Very plastic	1	2 mm diameter roll supports its weight.			

Table 2. Exploratory statistics of some soil physical, chemical, and morphological properties.

Variable	Max.	Min.	Mean	SD±	CV±	Skewness	Kurtosis
K_s, cm·h^{-1}	1.07	0.0036	0.26	0.31	116.50	2.02	3.38
Sand, %	28.40	2.91	12.60	7.16	56.70	0.53	0.35
Silt, %	32.30	4.89	23.20	8.15	35.20	0.88	0.16
Clay, %	74.90	50.40	64.20	5.87	8.85	0.48	1.38
D_b, g·m^{-3}	1.29	1.18	1.18	0.05	4.23	1.11	0.30
SOM, %	7.09	0.40	4.15	1.36	32.70	0.52	3.80
FC, %	43.00	33.00	40.20	2.86	7.11	1.35	1.24
COLE, %	9.80	8.60	9.46	0.31	30.00	1.80	3.35
Structure strength	2.00	1.00	1.12	0.34	3.29	2.50	4.89
Structure type	4.00	2.00	3.81	0.54	7.00	3.02	9.09
Structure size	3.00	1.00	1.93	0.57	3.37	0.02	0.76
Consistency	2.00	1.00	1.12	0.34	3.29	2.50	4.89
Plasticity	7.00	5.00	5.93	0.57	10.34	0.02	0.76
Stickiness	7.00	5.00	5.93	0.57	10.34	0.02	0.76

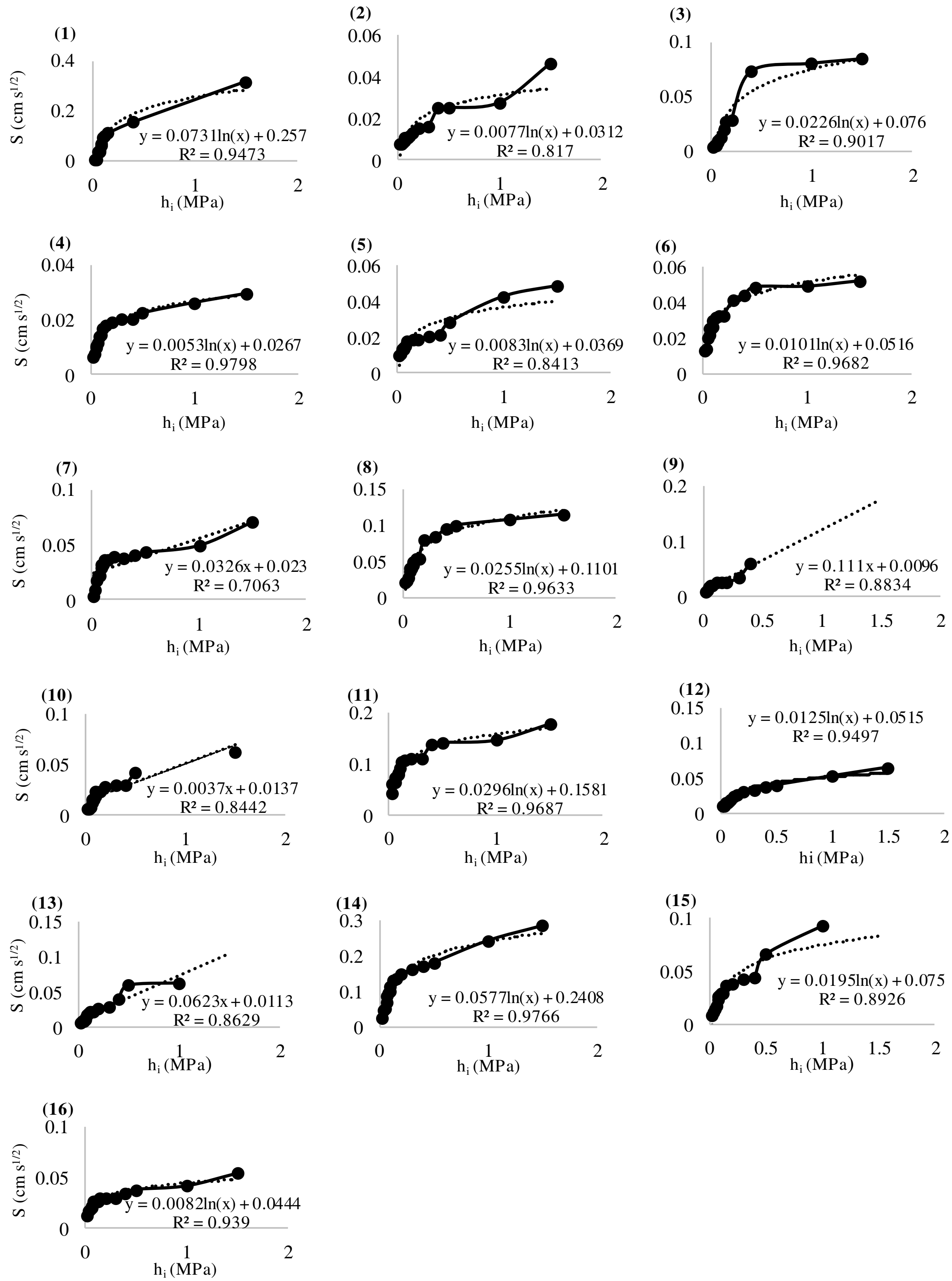
Note: COLE, coefficient of linear extensibility; CV, coefficient of variation; D_b, bulk density; FC, soil water content at field capacity; K_s, saturated hydraulic conductivity; SD, standard deviation; SOM, soil organic matter.

content, SSA, structure size, and SOM content were correlated moderately but not significantly with η, suggesting a relatively weak relationship between those soil attributes and S–h_i relations. However, the inherent relationship between SOM and soil stickiness and plasticity suggests a significant effect of SOM content on η.

Discussion

The variable S fundamentally depends on the soil water matric pressure (Vogelmann et al. 2017); a greater h (in absolute value) results in a greater S. Logarithmic behaviour of graphs in Fig. 2 may be attributed to hydrophobicity to a large extent. Hydrophobicity has been recognized as an important factor, which negatively

Fig. 2. Regression analysis between sorptivity (*S*) and soil water matric pressure (h_i) values of study soils. The number in parentheses refers to soil sample ID.



affects *S*, especially in the dry soils (Carrick et al. 2011); it becomes an important factor below a critical soil water content (Dekker et al. 2001). Hydrophobicity may influence soil matric pressure via the contact angle (Vogelmann et al. 2017). The graphs show that the critical h_i at which the curves start flattening differs among the soil samples, which was attributed to differences in soil variables such as soil structure, SOM content, soil

Table 3. Correlation analysis results regarding slope and soil properties (N = 16).

	Slope	ST	Plasticity	Stickiness	SSA	OM	Clay	SS	FC	COLE	Consis.	K_s
Slope	1.00											
ST	0.69*	1.00										
Plasticity	0.57*	−0.94**	1.00									
Stickiness	0.57*	−0.94**	1.00**	1.00								
SSA, $m^2 \cdot g^{-1}$	−0.50	0.55*	−0.46	−0.46	1.00							
SOM, %	−0.45	0.03	−0.05	−0.05	0.10	1.00						
Clay, %	0.42	−0.63**	0.65**	0.65**	−0.25	−0.23	1.00					
SS	−0.36	0.60	−0.64**	−0.64**	0.11	0.27	−0.88**	1.00				
FC, %	−0.31	0.11	−0.17	−0.17	0.02	0.21	−0.20	−0.03	1.00			
COLE	0.29	−0.39	0.41	0.41	−0.05	−0.24	0.87**	−0.86**	−0.04	1.00		
Consis.	0.24	−0.17	0.18	0.18	0.02	−0.37	0.74**	−0.63**	−0.13	0.79**	1.00	
K_s, $cm \cdot h^{-1}$	−0.22	0.30	−0.32	−0.32	0.07	0.35	−0.84**	0.85**	−0.01	−0.93**	−0.75**	1.00

Note: COLE, coefficient of linear extensibility; Consis., consistency; FC, soil water content at field capacity; K_s, soil saturated hydraulic conductivity; SOM, soil organic matter; SS, soil structure size; SSA, specific surface area; ST, soil structure type. An asterisk (*) indicates that the correlation is significant at the 0.05 level. Two asterisks (**) indicate that the correlation is significant at the 0.01 level.

Table 4. The factor analysis for some soil properties (N = 16).

Variables	Factor 1	Factor 2	Factor 3	Factor 4	Factor 5
Soil structure grade	0.98				
K_s, $cm \cdot h^{-1}$	0.93				
COLE	−0.91				
Consistency	−0.82				
Clay, %	−0.75				
Soil structure size	0.73				
Soil structure type		−0.96			
Plasticity		0.96			
Stickiness		0.96			
Slope		0.65			
CEC, $cmol_c \cdot kg^{-1}$			0.84		
SSA, $m^2 \cdot g^{-1}$			0.75		
PR (kPa)			0.66		
Sand, %				−0.94	
Silt, %				0.82	
pH					0.91
D_b, $g \cdot cm^{-3}$					0.74
FC					−0.65
Variance, %	27.35	19.74	9.41	9.40	7.76

Note: CEC, cation exchange capacity; COLE, coefficient of linear extensibility; D_b, soil bulk density; FC, soil water content at field capacity; K_s, soil saturated hydraulic conductivity; pH, soil acidity; PR, penetration resistance; SSA, specific surface area.

texture, and so on between the samples as those factors were significantly correlated with parameter η.

Soil structure type (SST) was significantly positively correlated with η (Table 3). In this study, soil structure features (structure type, structure size, and structure grade) were quantified (Table 1), and then the quantified values were correlated with η. Structure type was significantly correlated with η. Greatest scores were given to granular structure and lowest to massive ones in scoring SST. Also, the structure size was correlated negatively but not significantly with η. Therefore, those results indicated that small-sized granular aggregates had high capacity to imbibe water, due probably to their high surface area and total porosity. Aggregation has been long recognized as a critical factor to maintain water infiltration of soils (Shaver et al. 2013). Shaver et al. (2013) found a strong positive influence of aggregation on S, noting that increased aggregation, stimulated by accumulation of crop residue, resulted in greater values of S.

SOM content was correlated negatively with η, which may be attributed to influence of hydrophobicity, promoted by SOM, on S. Hydrophobicity (water repellence) is mainly associated with SOM (Vogelmann et al. 2017). SOM content was moderately variable; it ranged from 0.40% to 7.09% with a mean of 4.15%. Relatively high mean and spatial variability of SOM content indicate that it has a potential to influence variability of S via its influence on severity of hydrophobicity. On the other hand, SOM may have an important impact over S via soil structure. Shaver et al. (2013) reported that SOM had a considerable positive indirect influence on S via its aggregation promotion effect. Multiple interactions among SOM and other soil attributes may have regulatory influence of SOM on η. For example, the soil water content below which hydrophobicity becomes a critical factor may differ depending on soil structure–SOM–clay (or texture) interactions. The multiple interactions between η and soil properties deserve further studying. Results from Vogelmann et al. (2017) showed that the effect of initial soil matric pressure on the S maxima was highly variable across Dystrudept, Hapludox, Paleudalf, Haplaquent, Albaqualf, and Hapludert due to differences in soil physical properties besides soil SOM content.

Conclusion

This study evaluated relationships between some soil properties and sorptivity measured at varying initial soil water matric pressure (h_i). A parameter (η) was introduced, representing the relationship between S and h_i between −200 and −1500 kPa. Correlation coefficients between η and soil properties were calculated. The results showed that the shapes of graphs for S–h_i relation were highly different due probably to differences in soil variables such as soil structure, SOM content, stickiness, and plasticity; those soil attributes were significantly correlated with parameter η. Soil structure had a significant influence on η; the finer granular structure appeared to increase S. Soil organic matter had a significant indirect positive influence on η through its influence on stickiness and plasticity. The results provided a fundamental understanding of S–h_i–soil properties interactions in a clay soil. The results have important implications on the other soil hydraulic properties, such as K (Ψ) and D (Ψ), having inherent relationship with S. Further studies need to conductacross different soil textures, soil matric pressure ranges, and infiltrometer disc sizes for an in-depth understanding of η-soil properties relations.

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