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The relationship between surface fractal dimension and soil water content at permanent wilting point

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ABSTRACT

Permanent wilting point (PWP) is an important soil water parameter available from the soil water retention curve. Soil water content held at 1500 kPa determines plant survival or death. Recently, the application of fractal geometry concepts has been widely used for modeling soil and its hydraulic properties (e.g. soil water retention curve and unsaturated hydraulic conductivity). The objective of this study was to investigate the relationship between surface fractal dimension (D_s) and soil water content held at permanent wilting point, θ_{PWP} For this purpose, we used five datasets corresponding to Puckett et al. [Puckett, W.E., Dane, J.H., Hajek, B.F., 1985. Physical and mineralogical data to determine soil hydraulic properties. Soil Sci. Soc. Am. J. 49, 831–836], UNSODA [Leij, F.J., Alves, W.J., van Genuchten, M.T.h., Williams, J.R., 1996. Unsaturated Soil Hydraulic Database, UNSODA 1.0 user's manual. Rep. EPA/600/R96/095. USEPA, Ada, OK], GRIZZLY [Haverkamp, R., Zammit, C., Boubkraoui, F., Rajkai, K., Arrúe, J. L., Keckmann, N., 1997. GRIZZLY, Grenoble soil catalogue: Soil survey of field data and description of particle-size, soil water retention and hydraulic conductivity functions. Laboratoire d'Etude des Transferts en Hydrologie et en Environnement. Grenoble, France], Huang et al. [Huang, G., Zhang, R., Huang, Q., 2006. Modeling soil water retention curve with a fractal method. Pedosphere 16, 137–146], and Fooladmand [Fooladmand, H.R., 2007. Measurement of soil specific surface area and its relation to some soil physico-chemical properties. Ph.D. Thesis. Department of Irrigation. Science and Research Unit of Islamis Azad University, Tehran]. This yielded a total of 172 soil samples. The results showed that D_s was positively related to both θ_{PWP} and clay content. The D_s versus θ_{PWP} and D_s versus clay content relationships were well fitted by logarithmic functions (goodness of fit $R^2 = 0.97$ and $R^2 = 0.88$, respectively). Soil quality index (S-index) and D_s were also significantly correlated ($R = 0.911$). The water film retained at 1500 kPa (PWP) delineates the complex geometrical structure of the pore–solid interface which could be determined by the relative amount and orientation of clay particles.

1. Introduction

Soil water retention is a relevant soil hydraulic property. It has been widely used for characterizing, describing and/or simulating water and solute transport within soil matrix in close connection with analytical (Mualem, 1976; Wang et al., 2002) or numerical solutions of physical models (Šimůnek et al., 2006). Many empirical and physicoempirical models have been developed for representing the soil water retention curve based on its power, sigmoidal shape or lognormal distribution (Brooks and Corey, 1964; Campbell, 1974; van Genuchten, 1980; Hutson and Cass, 1987; Arya and Paris, 1981; Kosugi, 1996). A main drawback in predicting soil water retention curve using the above models refers to the estimation of their empirical parameters which usually have unclear physical meanings. Since their direct measurements are time consuming, indirect methods (i.e. pedotransfer functions) (Vereecken et al., 1989; Wösten et al., 1995; Wösten, 1997) and artificial neural networks (Schaap et al., 2001; Minasny and McBratney, 2007) have been developed to estimate these parameters from readily available characteristics (i.e. clay, silt, sand content and bulk density).

Recently, application of fractal geometry has been used widely to simulate porous media structure (i.e. soil and its hydraulic properties) (de Gennes, 1985; Tyler and Wheatcraft, 1990; Rieu and Sposito, 1991; Kravchenco and Zhang, 1997; Hunt, 2004; Perfect, 2005; Cihan et al., 2007). However, the interpretation and usefulness of fractal scaling parameters are not fully understood. In general, biological, chemical and physical soil quality indicators are all connected to the complex geometry of soil system.

Three types of models have been presented in simulation of soil water retention curve. The first one is based on the mass fractal (Sierpinski carpet or Menger sponge). In this model, the fractal dimension of mass, pore surface and pore volume are the exponents of Pareto-type functions (Rieu and Sposito, 1991; Perfect, 1999). The second type is based on the fractal surface in which the scaling of mass

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has not been considered (de Gennes, 1985; Toledo et al., 1990). The third one is based on the fractal pore size distribution without considering the geometry of mass (Perrier et al., 1996).

Although the exponent of soil water retention curve, D, is physically meaningful, its direct measurement is difficult as both, laboratory and field soil-water retention experiments are time consuming. A useful way might be to estimate D from pore-size distributions using image analyses of binary structures (Dathe et al., 2001; Bartoli et al., 2005). Aggregation and fragmentation are opposed processes occurring simultaneously in agricultural soils. That is, soil aggregation involves the formation of secondary soil units (e.g. aggregates) from the bond of elementary soil particles (clay, silt and sand) and organic products (e.g. root exudates, fungal hyphae, microbial activity) (SSSA, 1997) while fragmentation refers to the process of breaking-down soil apart across natural failure planes (e.g. slaking, freezing/thawing, tillage operations, swelling/shrinkage) (Arshad et al., 1996). Many authors have taken advantage of these processes for investigating the fractal structure of their corresponding distributions. Filgueira et al. (1999) used aggregate mass-size distributions for estimating mass fractal dimensions. The estimated values in that study were compared with those values computed from the soil-water retention fractal model derived by Rieu and Sposito (1991). Bird et al. (2000) tested the pore–solid fractal (PSF) model with particle-size distributions, Tyler and Wheatcraft (1989) also investigated soil-water retention scaling using fractal dimensions computed from particle-size distributions, while Ghanbarian-Alavijeh (2007) considered fragment mass-size distributions for estimating fractal dimensions. All the aforementioned studies have rendered promising results on the applicability of fractal concepts for describing soil-water retention scaling. Perfect and Kay (1991), Tyler and Wheatcraft (1992), Giménez et al. (2002), Millán et al. (2007) and many others have conducted analyses on the mass-size scaling from different soil unit distributions (fragment, aggregate, particle and microaggregate-size distributions). Another less explored issue could be the potential link among surface fractal dimension and some soil-water retention points (e.g. permanent wilting point) which are of agricultural interest. The objective of this study was to investigate the relationship between surface fractal dimension (D_s) and soil water content held at permanent wilting point, θ_{PWP}.

2. Materials and methods

In this study, five databases corresponding to Puckett et al. (1985), UNSODA (Leij et al., 1996), GRIZZLY (Haverkamp et al., 1997), Huang et al. (2006) and Fooladmand (2007) were used which rendered a total of 172 data sets to be analyzed. Soil sample properties are shown in Table 1. Soil texture was classified according to the U.S. Department of Agriculture (USDA) textural classification standard (Hillel, 1998). The number of (θ,h) pairs used for fitting the de Gennes fractal model ranged from 6 (UNSODA database) to 10 (Huang et al., 2006) data sets.

Table 1
Soil sample properties and parameter estimates for different datasets.

Reference	Texture	No. of samples	Clay		Θ_{pwp}		D_s		R^2	
			Min	Max	Min	Max	Min	Max	Min	Max
Huang et al. (2006)	Silt loam	1	–	17.6	–	0.114	–	2.803	–	0.963
	Loamy sand	2	3	9.2	0.023	0.032	2.497	2.563	0.942	0.954
	Loam	5	12.2	16.4	0.076	0.104	2.745	2.771	0.99	0.993
	Clay loam	1	–	33.5	–	0.152	–	2.789	–	0.99
	Clay	1	–	45.2	–	0.212	–	2.856	–	0.981
Fooladmand (2007)	Silty clay loam	8	28	39	0.116	0.224	2.835	2.891	0.98	0.999
	Silty clay	2	42	46	0.227	0.23	2.907	2.917	0.982	0.997
	Silt loam	4	12	27	0.147	0.244	2.818	2.876	0.991	0.998
	Sandy loam	2	7	9	0.11	0.146	2.776	2.831	0.996	0.998
	Loamy sand	3	4	6	0.89	0.1	2.761	2.807	0.993	0.996
	Loam	1	–	26	–	0.142	–	2.847	–	0.995
UNSODA	Silty clay loam	4	32	35.1	0.19	0.287	2.837	2.947	0.905	0.997
	Silty clay	4	40.3	43.5	0.154	0.278	2.832	2.96	0.856	0.993
	Silt loam	7	13.6	24.7	0.078	0.201	2.744	2.907	0.957	0.999
	Silt	1	–	9.2	–	0.08	–	2.802	–	0.926
	Sandy clay loam	2	26.8	28	0.178	0.206	2.909	2.946	0.964	0.977
	Sandy clay	2	40.5	41	0.271	0.273	2.922	2.965	–	0.937
	Sand	1	–	0.7	–	0.02	–	2.619	–	0.963
	Loamy sand	3	7	10.5	0.037	0.051	2.596	2.76	0.985	0.999
	Loam	7	17	26.2	0.148	0.294	2.861	2.92	0.948	0.997
	Clay loam	4	29.7	38.4	0.163	0.215	2.851	2.912	0.986	0.998
	Clay	6	45	63	0.285	0.414	2.941	2.969	0.846	0.995
Puckett et al. (1985)	Sandy loam	9	7.8	17.8	0.095	0.219	2.746	2.91	0.933	0.988
	Sandy clay loam	18	20.8	42.1	0.154	0.329	2.799	2.962	0.966	0.994
	Sandy clay	2	35.2	38	0.27	0.283	2.957	2.966	0.984	0.996
	Sand	2	1.4	1.8	0.054	0.058	2.569	2.594	0.936	0.964
	Loamy sand	5	2.3	10.8	0.062	0.136	2.607	2.837	0.897	0.984
	Loam	1	–	13.1	–	0.167	–	2.817	–	0.968
	Clay loam	5	30.4	34.8	0.278	0.332	2.936	2.967	0.936	0.989
GRIZZLY	Clay	12	43.7	77.5	0.250	0.358	2.819	2.925	na*	na
	Clay loam	2	27.0	33.9	0.114	0.150	2.793	2.844	na	na
	Loam	3	12.2	20.6	0.092	0.144	2.785	2.819	na	na
	Loamy sand	5	0.0	1.7	0.008	0.118	2.477	2.808	na	na
	Sand	15	0.0	0.0	0.000	0.064	0.409	2.747	na	na
	Sandy loam	9	0.4	12.9	0.003	0.148	2.408	2.816	na	na
	Silt loam	3	0.6	23.8	0.077	0.109	2.700	2.792	na	na
	Silty clay	8	44.2	57.4	0.206	0.390	2.810	2.919	na	na
	Silty clay loam	2	34.4	37.9	0.179	0.364	2.846	2.920	na	na

*na indicates that R^2 values are not available.