Fractal geometry of aggregates in natural grassland soils with different restoration stages

ZHOU PING[1], WEN ANBANG[1], ZHUANG WENHUA[2,3] & LIU GUOBIN[3]

1 Institute of Mountain Hazards and Environment, Chinese Academy of Sciences, The key Laboratory of Mountain Surface Processes and Ecological Regulation, Chengdu, Sichuan 610041, China
zhouping04@gucas.ac.cn

2 College of Water Conservancy and Hydropower, Sichuan University, Chengdu 610065, China

3 State Key Laboratory of Soil Erosion and Dryland Farming on Loess Plateau, Institute of Soil and Water Conservation, Chinese Academy of Sciences and Ministry of Water Resources, Yangling, Shaanxi 712100, China

Abstract Severe soil erosion occurs over 70% of the Loess Plateau in China. In this study, the fractal geometry of micro-aggregates were determined to compare fractal dimensions of the soils and physical and chemical characteristics of the soils in different restoration stages on the Loess Plateau. The results show that the fractal dimension of upper layer soil micro-aggregates decrease with increased restoration time. The fractal dimension (D) of soils at 0–20 cm changed from 2.360 ± 0.008 to 2.494 ± 0.015 with different restoration stage, while D changed from 2.441 ± 0.009 to 2.488 ± 0.016 at 20–40 cm and from 2.478 ± 0.028 to 2.492 ± 0.027 at 40–60 cm. D was significantly different ($p < 0.01$) for particles <0.001 at 0–20 cm. D increased with increasing sand content but decreased with increasing clay content. D was positively correlated with bulk density, non-capillary porosity, porosity ratio, total phosphorus, available potassium and ammonia nitrogen, but negatively correlated with capillary porosity, soil organic matter and total nitrogen.

Keywords erosion environment; soil micro-aggregates; fractal dimension; different restoration stage

INTRODUCTION

B. B. Mandelbrot first proposed the concept of fractals in 1967 and fractal geometry was founded in 1975 (Mandelbrot, 1977). Soils are porous materials with irregular but self-similar shapes that can be quantified using fractals (Decheng, 2000). Accordingly, fractal analysis is an effective tool to quantitatively study soils (Arya 1981). Yang (1993) proposed using the mass distribution instead of the particle diameter when calculating the fractal dimension. In recent years, fractal theory has been used to explain complex phenomena and processes in soil science (Perfect, 1992; Su, 2004). The fractal dimension of soil micro-aggregates and porosity were related to soil texture, construction, evenness, water content character and the erosion degree of the soil particle (Turcotte, 1986; Tyler, 1992; Xu, 1996; Lovejoy, 1998).

The Loess Plateau is comprised of Quaternary loess deposits ranging from 50 to 300 m thick. It is one of the most critical areas for soil erosion in China. Vegetation restoration is an effective best management strategy to reduce soil erosion and water loss on the Loess Plateau. During restoration of eroded sites with vegetation, the physical and chemical characteristics of soils can change. However, there is currently a lack of research on the nature of soil micro-aggregates of natural grasslands at different restoration stages in the Loess Plateau. This study quantifies the fractal dimension (D) of soil micro-aggregrates in natural grasslands at different restoration stages and relates this information to the physical-chemical characteristics of soils. Such information is necessary to evaluate soil quality and fertility during the restoration process on the Loess Plateau.

MATERIALS AND METHODS

Study area

Zhifanggou watershed drains an area of 8.73 km^2 and is located in Yan'an prefecture of Shaanxi province. The region is a typical of many loess hilly-gullied regions of the Loess Plateau in northwest China (109°13′46″～109°16′03E, 36°42′42″～36°46′28″N). The watershed represents a transition region of vegetation in the temperate forest-steppe. The climate is characterized by cold dry winters and warm moist summers with an average annual temperature of 8.8°C, aridity index of 1.5, and 157–194 frost-free days. The mean annual precipitation is 510 mm and most of this occurs from July to September. Calcic cambisols loess is the main soil type in the study area. The original vegetation was removed by land reclaimed. Herbs such as *Bothriochloa ischaemum, S. bungeana, L. davurica, Cleistogenes chinensis*, and *Trtemisia gmelinii*, are found at field edges and gully slopes. The main tree species are *Robinia pseudoacacia, Populus simonii, Cragana microphylla* and *Hippohae rhamnoides*. Since the 1970s, integrated strategies and works for soil and water conservation, soil erosion control and vegetation restoration have been carried out in this watershed (Wang *et al*., 2002).

Four natural grasslands with different restoration stages were selected for this study. All the geological information, soil properties and main species of each research site are presented in Table 1. Three 1 m × 1 m plots were selected at each site and the undisturbed soil was sampled at three depths (0–20, 20–40 and 40–60 cm) using a stainless steel cylinder.

Table 1 Physical and biological characteristics of the study sites.

Plot	Main species	Restorat-ion year	Altitude (m)	Slope aspect	Relief	Slope situation	Grad-ient	Soil type
1	*Dracocephalum moldavica, Heteropappus altaicus, Artemisia scoparia*	4	1168	SW28°	Gully	Middle	29°	Cultivated loessial soils
2	*Artemi siasacrorum, Poasphondy lodes, Ampelopsis revipedunculata*	12	1157	SW20°	Gully	Upper	24°	Cultivated loessial soils
3	*Artemi siasacrorum, Lespedeza formosa, Vicia sativa, Astragalus melilotoides*	20	1125	SW42°	Gully	Middle	26°	Cultivated loessial soils
4	*Stipa bungeana, Artemi siasacrorum, Artemisia giraldii, Sophora davidii, Periploca*	40	1090	SW20°	Gully	Middle	25°	Cultivated loessial soils

Physical and chemical analysis methods

Soil bulk density (BD) was determined using a soil core. Soil organic carbon (SC) was determined by wet digestion with mixture of potassium dichromate and concentrated sulfuric acid (ISSCAS, 1981). Total soil nitrogen (TN) was measured using the semi-micro Kjeldahl method (ISSCAS, 1981) and total soil phosphorus (TP) was determined by colorimeter after wet digestion with H_2SO_4-$HClO_4$ (ISSCAS, 1981). Available soil nitrogen (AN) was determined with a micro-diffusion technique after alkaline hydrolysis. Available soil phosphorus (AP) was determined by the Olsen method (ISSCAS, 1981). The soil micro-aggregrates were measure by a Long Bench Mastersizer 2000 (Malvern Instruments, Malvern, England).

Calculation of soil fractal dimension (D)

The pore-solid fractal model (PSF) relates symmetry between the distribution of pores and solids (Perrier *et al*., 1999). The cumulative solid mass distribution of the PSF model to particle size distributions is determined as:

$$M_s(d \le d_i) = c d_i^{3-D} \quad (1)$$

where $M_s(d \le d_i)$ is the cumulative mass of elements, which can be either solids or pores, below an upper limit d_i; D is the fractal dimension of the solid or pore-size distribution; and c is a composite scaling constant.

Statistical analysis

All results are reported as means ± standard deviations. Analysis of variance (ANOVA) was performed with SPSS 11.5 and Microsoft Excel software. If significant difference existed, then they were compared with the LSD test. The significance level was set as $p < 0.05$.

RESULTS AND ANALYSIS

Soil micro-aggregates composition and the fractal features

The mass and particle diameter distributions of soil micro-aggregrates could be used to evaluate the soil construction and anti-dispersion ability. In this research, the order of soil micro-aggregrate (0–20 cm soil depth) of 1–0.05 mm particle size were #4 > #3 > #1 > #2. The deeper soil layers had the similar changes. The results of analysis for significant difference among different restoration stages are listed in Table 2. The content of soil micro-aggregates with 0.05–0.001 mm particle size increased as the soil depth increased, and the content of soil micro-aggregrate less than 0.001 mm particle size also increased with depth increase. The proportion of soil micro-aggregrates with a diameter of <0.001 mm decreased as the restoration years increased, while the proportions of soil micro-aggregrate with a diameter of 0.05–0.001 mm increased first, then decreased. In the early restoration stages, the content of clay was high, the soil was compacted and soil porosity was low. As the restoration age increased, the organic litter increased and the soil organic matter content increased. The quality of soil colloid was enhanced, while the mass of the clay decreased.

For natural grassland soils at a depth of 0–60cm, the value of D for different restoration stages ranged from 2.360 to 2.494. The correlation coefficient for each of the regression analyses were all more than 0.900($p<0.05$). The sequence of D for 0–20 and 20–40 cm depth is #1 > #2 > #3 > #4.

Table 2 Size distribution and D values for soils of varying restoration age class.

Soil depth (cm)	Soil size (mm)	% in size class #1	#2	#3	#4
0–20	1–0.25	0.81± 0.09 Ca	4.42± 0.44Ba	1.84± 0.72Ca	11.91±0.77Aa
	0.25–0.05	31.64±10.26Aa	27.06±9.24Aa	29.50±7.26Aa	44.08±16.11Aa
	0.05–0.01	49.23±9.32Aa	48.01±10.16Aa	50.58±15.23Aa	33.24±10.25Ba
	0.01–0.005	6.79± 1.02Aa	7.84± 0.99Aa	6.91± 1.22Aa	4.46± 1.09Ba
	0.005–0.001	8.23± 0.78Aa	9.86± 1.08Aa	8.49± 1.98Aa	5.07± 0.78Ba
	<0.001	3.30±0.41Aa	2.82±0.69ABa	2.68±0.99BCa	1.23±0.24Da
	D	2.494±0.015Aa	2.488±0.013Aa	2.471±0.010ABa	2.360±0.008Ca
		0.915±0.005	0.902±0.004	0.907±0.001	0.942±0.004
20–40	1–0.25	0.82± 0.02Ba	0±0.02Cb	0.54± 0.04BCb	5.51± 1.07Ab
	0.25–0.05	29.16± 9.14Aa	26.66±10.19Aa	28.26±7.65Aa	40.24±13.18Aa
	0.05–0.01	52.36±10.98Aa	53.50±13.87Aa	52.83±12.96Aa	40.42±11.04Aa
	0.01–0.005	6.69± 2.13ABa	7.61± 0.96Aa	6.92± 2.31ABa	5.27± 0.28ABa
	0.005–0.001	7.73± 3.14ABa	9.27± 1.13Aa	8.60± 1.07Aa	6.24± 0.56Ba
	<0.001	3.24± 1.08Aa	2.97± 0.48ABa	2.85± 0.77ABCa	2.33± 0.23Cb
	D	2.488±0.016Aa	2.486±0.014ABa	2.477±0.011ABa	2.441±0.009Ba
		0.912±0.003	0.899±0.005	0.905±0.003	0.936±0.002
40–60	1–0.25	0.07± 0.07Cb	0.65± 0.26Bc	0± 0.06Cc	1.87± 0.27Ac
	0.25–0.05	29.01±11.97Aa	24.84±9.11Aa	27.53±7.52Aa	35.19±14.25Aa
	0.05–0.01	52.00±15.03Aa	53.30±17.14Aa	54.35±13.45Aa	44.41±11.18Ab
	0.01–0.005	7.58± 1.23ABa	8.29± 0.88Aa	6.93± 1.05BCa	6.88± 1.26BCa
	0.005–0.001	8.20± 2.01ABa	9.90± 1.07Aa	8.27± 2.01ABa	8.85± 1.04Ab
	<0.001	3.13± 0.78Aa	3.01± 0.98Aa	2.92± 0.54Aa	2.80± 0.11Ac
	D	2.480±0.020Aa	2.492±0.027Aa	2.478±0.028Aa	2.479±0.019Bb
		0.915±0.004	0.894±0.006	0.904±0.005	0.917±0.003

Notes: The same capital letter in the same column denotes non-significant difference ($p > 0.05$) while different capital letters denotes a significant difference ($p < 0.05$). In the same row compare different index of each restoration year's data among three soil layers and the same small letter denotes non-significant difference ($p > 0.05$) while different capital letters denotes a significant difference ($p < 0.05$).

The roots of grassland were concentrated in the upper soil layer and this strongly influenced the soil structure. The value of D decreased with the increasing period of restoration because the dominant plant species changed from annuals to perennials. The D value of the deeper soil layer was not correlated with restoration age. The sequence of sand content of the 0–60 cm soil horizon was #4 > #3 > #2 > #1. The sand content increased with restoration age but D was inversely related to restoration age. When the soil texture changed from coarse to fine, the values of D decreased. The clay content sequence was #1 > #2 > #3 > #4.

The concentration of certain particle sizes influences D (Wu, 1999). The relationship between D and soil characteristics was examined and the results are presented in Table 5. There was a significant positive relationship between D and < 0.001 mm particle content ($p < 0.01$).

Soil physical and chemical characteristics

The soil porosity directly influenced the soil infiltration and root depth (Mualem, 1976). There existed positive correlation between the non-capillary porosity and the water content. The results of soil physical characters are shown in Table 3. Capillary porosity played an important part in absorbing and retaining soil water and sustaining the herbage growth ability (Yu, 1999). The ratio of non-capillary porosity was less in the early restoration stages than for the later restoration stages. Soil chemical characteristics are presented in Table 4. Soil organic matter, total nitrogen

Table 3 Soil bulk density and soil porosity characters of grasslands with different restoration stages.

Plot	Soil layer (cm)	Bulk density (g cm^{-3})	Porosity ratio	Non-capillary porosity (%)	Soil porosity (%)
1	0–20	1.22±0.10	1.18±0.08	5.47±3.69	54.11±7.07
	20–40	1.32±0.09	1.01±0.05	5.95±2.66	50.11±6.21
	40–60	1.33±0.09	0.99±0.07	5.99±1.18	49.77±7.26
2	0–20	1.08±0.09	1.45±0.05	4.88±1.05	59.06±9.06
	20–40	1.09±0.07	1.44±0.07	4.91±1.19	58.86±5.29
	40–60	0.98±0.09	1.87±0.08	4.42±1.02	62.93±5.06
3	0–20	1.14±0.05	1.33±0.04	5.12±1.64	57.06±9.73
	20–40	1.07±0.06	1.47±0.06	4.83±0.83	59.47±8.95
	40–60	1.18±0.07	1.26±0.08	5.28±1.75	55.66±9.06
4	0–20	0.96±0.08	1.76±0.04	4.33±1.41	63.70±8.92
	20–40	1.05±0.07	1.03±0.05	5.87±2.25	50.80±7.02
	40–60	1.07±0.05	1.47±0.06	4.83±0.95	59.47±8.49

Table 4 Soil nutrient characteristics of grassland soils with different restoration stages.

Plot	Soil layer (cm)	SOC (g kg^{-1})	TN (g kg^{-1})	TP (g kg^{-1})	AN (mg kg^{-1})	AK (mg kg^{-1})
1	0–20	4.50±0.23	0.31±0.02	0.41±0.02	20.95±2.25	83.49±10.78
	20–40	2.41±0.47	0.18±0.02	0.38±0.01	4.41±0.89	62.79±7.42
	40–60	2.16±0.12	0.18±0.01	0.39±0.03	8.82±0.97	63.69±9.47
2	0–20	16.15±0.86	0.97±1.01	0.67±0.04	63.94±10.43	150.62±19.54
	20–40	10.05±0.86	0.64±0.07	0.62±0.05	37.48±5.11	78.68±5.46
	40–60	7.49±0.71	0.50±0.04	0.64±0.03	28.67±3.14	80.79±4.56
3	0–20	10.62±0.98	0.67±0.06	0.51±0.03	44.10±8.12	117.10±11.23
	20–40	10.11±0.63	0.52±0.04	0.58±0.05	34.18±73.23	81.54±6.15
	40–60	4.94±0.14	0.36±0.02	0.58±0.07	22.05±3.46	71.98±7.15
4	0–20	20.06±0.73	1.10±0.09	0.38±0.02	65.41±5.63	105.15±11.24
	20–40	6.00±0.63	0.39±0.06	0.42±0.01	24.25±3.25	51.20±2.46
	40–60	15.70±1.14	0.89±0.09	0.54±0.01	55.13±5.24	74.02±3.29

SOC: soil organic matter; TN: total nitrogen; P: total phosphorus; AN: available nitrogen; AK: available potassium.

and available nitrogen increased with the restoration period (Cheng, 2007) but total phosphorus and available potassium decreased with restoration age.

The relationship between soil physical-chemical characteristics and D

The results of regression analysis between D and physical/chemical characteristics are presented in Table 5. The data show that bulk density and non-capillary porosity and D are positively correlated, while capillary porosity and the ratio of porosity are negatively correlated with D. The results suggest that D may represent a useful effective index to describe soil texture (He, 2002). Soil organic matter, total nitrogen and available nitrogen were negatively correlated with D. Total phosphorus, available potassium and available nitrogen were positively correlated with D.

Table 5 Correlation analysis between D and soil characteristics.

Indices	Regression function Correlation coefficient	Indices	Regression function Correlation coefficient
1–0.25 mm	$y = -0.0116x + 2.5019$ $R^2 = 0.8301$*	Non-capillary porosity	$y = 0.115x + 1.8835$ $R^2 = 0.7766$
0.25–0.05 mm	$y = -0.0078x + 2.7109$ $R^2 = 0.9001$*	Capillary porosity	$y= -0.0112x + 3.0272$ $R^2 = 0.8215$*
0.05–0.01 mm	$y = 0.0074x + 2.1136$ $R^2 = 0.8769$*	Porosity ratio	$y = -0.2317x + 2.7845$ $R^2 = 0.8231$*
0.01–0.005 mm	$y = 0.0342x + 2.2373$ $R^2= 0.7955$*	Soil porosity	$y= -0.0137x + 3.2555$ $R^2= 0.7766$
0.005–0.001 mm	$y = 0.0258x + 2.2542$ $R^2 = 0.817$*	Soil organic matter	$y= -0.0694x + 2.5197$ $R^2= 0.7961$*
<0.001 mm	$y = 0.0692x + 2.2794$ $R^2 = 0.9645$**	Total nitrogen	$y= -1.3388x + 2.5302$ $R^2 = 0.7585$
>0.05 mm	$y = -0.003x + 2.697$ $R^2 = 0.0135$	Total phosphorus	$y= 4.6185x + 2.2023$ $R^2= 0.8201$*
<0.05 mm	$y = 0.0164x + 2.1758$ $R^2 = 0.6835$	Available nitrogen	$y= -0.0019x + 2.5214$ $R^2 = 0.6583$
Bulk density	$y = 0.4727x + 1.908$ $R^2 = 0.8215$*	Available potassium	$y = 0.001x + 2.4071$ $R^2 = 0.7851$

CONCLUSION

The fractal dimension (D) of soil micro-aggregates and the relationship between D and soil physical-chemical characteristics with different restoration stages of grasslands in the Zhifanggou watershed on the loess plateau of China were examined. The results show that D may be considered an effective index to evaluate changes in soil particle size distribution as well as the chemical and physical characteristics during various stages of vegetation restoration.

The fractal dimension could not only reflect the soil particle size, but also reflect the evenness degree of the soils. The higher the fractal dimension was, the more compact the soil structure and the worse the soil infiltration, and *vice versa*. The content of 1–0.05 mm aggregates in the upper soil layers was higher than in deeper soil layers. Deeper soil layers had more 0.05–0.001 mm material than upper soil layers. This particle size first increased then decreased with vegetation restoration age while the <0.001 content decreased. The fractal dimension ranged from 2.360 to 2.494.

The fractal dimension (D) of soils in the Loess Plateau was well correlated with chemical and physical characteristics and may provide a useful index of soil structural change in revegetation areas.

Acknowledgement The authors wish to thank the Foundation of National Key Science and Technology program (2011BAD31B03) and the Foundation of State Key Laboratory of Soil Erosion and Dry Land Farming (10501-276) for supporting this research.

REFERENCES

Arya, L. & Paris, J. (1981) A physical empirical model to predict the soil moisture characteristic from particle size distribution and bulk density data. *Soil Sci. Soc, Am. J*. 45, 1023–1031.

Cheng, J. & Gao, Y. (2007) Variability of soil nutrient in enclosed grassland of Yunwu Mountain. *Acta Agrestil Sinica* 15(3), 273–277.

He, D., Hong, W. & Wu, C., *et al*. (2002) Fractal features of soil aggregate structure under mixed plantations of *Phyllostachys edulis* and *Cunninghamia lanceolata*. *J. Tropical and Subtropical Botany* 10(3), 215–221.

Institute of Soil Science of Chinese Academy of Science (1981) *Soil Chemical and Physical Analysis*. Shanghai Science and Technology Press, Shanghai.

Li, D. & Zhang T. (2000) Fractal Features of particle size distribution of soils in China. *Soil and Environmental Sciences* 9(4), 263–265.

Lovejoy, S., Schertzer, D. & Silas P. (1998) Diffusion in one dimensional multifractal porous media. *Water Resour. Res*. 34(12), 3283–3291.

Lu, Z., Liang, Y. & Liu, G. (1997) *Ecological Agriculture of the Loess Plateau*. Shaanxi Scientific and Technical Press, 15–18.

Mandelbrot, B. (1977) *From, Chance and Dimension*. Freeman, San Francisco, 1–34.

Mandelbrot, B. (1979) *The Fractal Geometry of Nature*. Freeman, San Francisco, 236–237.

Mualem, Y. (1976) A new model for predicting the hydraulic conductivity of unsaturated porous media. *Water Resour. Res*. 12, 593–622.

Pefect, E., McHaughlin, N., Kay, B. D., *et al.* (1996) An improved fractal equation for the soil water retention curve. *Water Resour. Res.* 32(2), 281–287.

Perfect, E., Rasiah, V. & Kay, B. (1992) Fractal dimensions of soil aggregate size distribution calculated by number and mass. *Soil Sci. Soc, Am. J.* 56, 1407–1409.

Perrier (1999) Generalizing the fractal model of soil structure: the pore–solid fractal approach. *Geoderma* 88, 137–164.

Su Y. (2004) Fractal features of soil particle size distribution in the desertification process of the farm land in Horqin Sandy Land. *Acta Ecological Sinica* 24(1), 71–74.

Turcotte, D. (1986) Fractals and fragmentation. *J. Geophys. Res*. 91(B2), 1921–1926.

Tyler, S. & Wheatcraft, S. (1992) Fractal scaling of soil particle size distribution: Analysis and limitations. *Soil Sci. Soc. Am. J.* 56, 362–369.

Wang, G., Liu, G. & Liu, F. (2002) The vegetative characteristics and ecotone effect of Zhifanggou watershed in Loess Hilly Region. *Acta Bot. Boreal–Occident. Sin*. 22(5), 1102–1108.

Wu, C. & Hong, W. (1999) Study on fractal features of soil aggregrate structure under different management patterns. *Acta Pedological Sinica* 36(2), 162–167.

Xu, Y. & Tian, M. (1996) The fractal dimension of soil micro-aggregrates. *Scientific Process of Hydrological and Hydro-Engineer* 16(1), 25–29.

Yang, P., Luo, Y. & Shi, Y. (1993) The characters of fractal dimension using the quality disperse of soil particles. *Chinese Science Bull.* 20(38), 1896–1899.

Yu, Z. & Yu, X. (1999) *Research on Benefits of Water Conservation in Forest*. Beijing: Chinese Forestry Press, 45–55.