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Fractal features of soil profiles under different land use patterns on the Loess Plateau, China

Lie XIAO[1], Sha XUE[1,2], GuoBin LIU[1,2*], Chao ZHANG[1]

[1] State Key Laboratory of Soil Erosion and Dryland Farming on the Loess Plateau, Institute of Soil and Water Conservation, Northwest A&F University, Yangling 712100, China;
[2] Institute of Soil and Water Conservation, Chinese Academy of Sciences and Ministry of Water Resources, Yangling 712100, China

Abstract: Fractal theory is becoming an increasingly useful tool to describe soil structure dynamics for a better understanding of the performance of soil systems. Changes in land use patterns significantly affect soil physical, chemical and biological properties. However, limited information is available on the fractal characteristics of deep soil layers under different land use patterns. In this study, the fractal dimensions of particle size distribution (PSD) and micro-aggregates in the 0–500 cm soil profile and soil anti-erodibility in the 0–10 cm soil profile for 10 typical land use patterns were investigated in the Zhifanggou Watershed on the Loess Plateau, China. The 10 typical land use patterns were: slope cropland, two terraced croplands, check-dam cropland, woodland, two shrublands, orchard, artificial and natural grasslands. The results showed that the fractal dimensions of PSD and micro-aggregates were all significantly influenced by soil depths, land use patterns and their interaction. The plantations of shrubland, woodland and natural grassland increased the amount of larger micro-aggregates, and decreased the fractal dimensions of micro-aggregates in the 0–40 cm soil profile. And they also improved the aggregate state and aggregate degree and decreased dispersion rate in the 0–10 cm soil profile. The results indicated that fractal theory can be used to characterize soil structure under different land use patterns and fractal dimensions of micro-aggregates were more effective in this regard. The natural grassland may be the best choice for improving soil structure in the study area.

Keywords: fractal dimension; anti-erodibility; soil profile; land use pattern; Loess Plateau

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Fractal theory is a powerful tool used to characterize phenomena that display large, scale-invariant and self-similar characteristics (Turcotte, 1986). Soil exhibits different particle compositions with irregular shapes and self-similar structures (Tyler and Wheatcraft, 1989, 1992; Kravchenko and Zhang, 1998), thus revealing fractal characteristics. Land use could influence soil particle size distribution (PSD) by hindering or facilitating water erosion (Erskine et al., 2002; Basic et al., 2004), thus affecting soil structure as well as physical, chemical and biological activity (Lobe et al., 2001; Caravaca et al., 2002; Zalibekov, 2002; Su et al., 2004). Characterizing PSD under different vegetation types using fractal theory is necessary for evaluating the impact of land use patterns on soil structure and quantifying the relationship between land use patterns and other important soil properties.

Numerous researchers have recently used fractal theory to characterize PSD, pore size distribution and aggregate size distribution to evaluate the impact of land use pattern changes on soil structure (Anderson et al., 1997; Millan and Orellana, 2001), soil erodibility (Martinez-Mena et al., 1999; Ahmadi et al., 2011), and soil permeability (Xu and Sun, 2002). Wang et al. (2006) conducted a study to determine the effect of land use types on the fractal dimensions of PSD in the arid and semi-arid regions of the Tibetan Plateau, China. They found that land use had a significant

*Corresponding author: GuoBin LIU (E-mail: gbliu@ms.iswc.ac.cn)
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effect on the fractal dimensions of PSD and other soil properties. The fractal dimensions of PSD can be a useful parameter to monitor soil degradation induced by land use patterns and changes. By using the fractal method to estimate soil structure changes under different vegetations, Zhao et al. (2006) found that the aggregate fractal dimension is more effective than the particle fractal dimension in describing soil structure and function. After studying the soil aggregate stability of different land use patterns in the Sichuan Basin, China, Zhang et al. (2008) reported that the intensity of human disturbance and cultivation facilitates the breakdown of unstable aggregates and induces soil degradation

In the Yimeng mountainous region of mid-eastern China, Liu et al. (2009) determined the fractal dimensions of PSD and soil porosity under different land use patterns. The results of their study demonstrate that fractal dimension analysis can better quantify the differences in PSD and soil porosity associated with soil degradation caused by the anthropogenic disturbance of plant community environments. Studies conducted at the southern margin of the Tarim Basin found that years of farmlands utilization significantly influence PSD and that long-term and effective tillage management of farmlands would be beneficial for maintaining and improving the states of soil PSD and other soil properties (Gui et al., 2010). Zheng et al. (2011) studied the fractal dimensions of soil structure and soil anti-erodibility under different land use patterns in western Sichuan province, concluding that the land use patterns of the Chinese fir and eucalyptus plantations were reasonable for increasing soil anti-erodibility and improving soil structure. A number of studies applied a multifractal analysis of PSD in soils (Grout et al., 1998; Posadas et al., 2001; Montero, 2005; Zhao et al., 2011). Wang et al. (2008) applied multifractal dimensions to characterize PSD in soils with the same taxonomy but with different land use types and found that the entropy dimension and entropy dimension/capacity dimension ratio were significantly influenced by land use and positively correlated with finer particle content and soil organic carbon (SOC). Paz-Ferreiro et al. (2010) accessed soil PSD under different management systems using multifractal parameters and concluded that multifractal analysis was useful for testing the similarity or variation of PSDs, thus being a promising tool for further insights into the verification of the patterns of soil texture variations. Overall, fractal theory is an effectively descriptive tool for evaluating the effects of land use pattern changes on soil structure.

The Loess Plateau is classified under arid and semi-arid regions that are subjected to the irrational use of land resources, which results in severe soil erosion because of the increases of population (Wei et al. 2006). The Chinese government acknowledged the severity of this problem and implemented the Conservation of Cropland to Forest and Grassland Project in 1999, through which numerous croplands were converted to forestland or grassland or abandoned for natural recovery (Zhang et al., 2011). A number of researchers studied the impact of land use pattern changes on the physical, chemical and enzymatic activities in surface soils (Wang et al., 2009a; Wang et al., 2012), whereas several researchers evaluated the variations in soil moisture (Wang et al., 2009b; Gao and Shao, 2012), SOC and total nitrogen (TN) (Zhang et al., 2013) in soil profiles, and found that land use patterns significantly affect the physical and chemical properties in the soils. Although a large number of studies have focused on the fractal behavior of surface soils under different land use patterns, few have applied the fractal theory to determine the influence of different plant communities on the fractal dimensions of deep soil profiles (Dang et al., 2009). Few studies that investigate the soil fractal features associated with soil profiles under different land use patterns on the Loess Plateau, China have been published.

In this study, the fractal dimensions of PSD and the micro-aggregates in the 0–500 cm soil profile and soil anti-erodibility characteristics in the 0–10 cm soil profile under 10 types of typical land use patterns were analyzed to identify their relationship with selected soil properties such as organic carbon and total nitrogen content. The objectives of this study are: 1) to determine the effect of different land use patterns on soil profile fractal dimensions, 2) to investigate the relationship between soil fractal dimensions and soil properties, and 3) to explore the possibility of using fractal theory, an integrating index for quantifying soil profile degradation attributed to land use pattern changes.

1 Materials and methods

1.1 Study area

The study was conducted in the Zhifanggou Watershed of Ansai county, which located in Shaanxi province, China. The geographical coordinates are 36°46′N and 109°16′E. The area has a semiarid climate, with an annual mean temperature of 8.8°C. The average annual precipitation is 510 mm, which mostly occurs from July to September. Annual evaporation ranges from 1,500 to 1,800 mm, and the average frost-free period is approximately 203 days. The soil is mainly Huangmian soil (Calcaric cambisols, Food and Agriculture Organization), developed on wind-deposited loessial parent material and characterized by yellow color, absence of bedding, silty texture, looseness, macroporousness and wetness-induced collapsibility (Zhang et al., 2011). The minimum soil depth exceeds 10 m (Wang et al., 2009c). In the middle of the 20th century, the natural ecological environment was severely destroyed by irrational human activities. Various efforts have attempted to prevent the continuance of severe soil erosion over the past decade. The development of woodland (*Robinia pseudoacacia*), shrubland (*Caragana korshinskii*, *Hippophae rhamnoides*), artificial grassland (*Medicago sativa*) and orchard (*Medicago sativa*) dramatically improved the ecological environment in this area (Zhang et al., 2011).

1.2 Experimental design and soil sampling

In August 2011, 10 typical land use patterns were selected for the study of soil PSD and micro-aggregates. The 10 land use patterns include: slope cropland, two terraced croplands, check-dam cropland, woodland, two shrublands, orchard, artificial grassland and natural grassland. All these sites have similar elevations and have been subjected to similar farming practices before conversion. The detailed descriptions are shown in Table 1.

Three 20 m×20 m plots were established for each land use pattern and considered to be true replicates because the distance among them exceeded the spatial dependence (<13.5 m) of most soil chemical and microbial variables (Mariotte et al., 1997; Wang et al., 2011). At each sampling plot, four random sampling sites were selected to eliminate the sampling error. In each sampling site, 14 soil layers (0–10, 10–20, 20–40, 40–60, 60–80, 80–100, 100–150, 150–200, 200–250, 250–300, 300–350, 350–400, 400–450 and 450–500 cm) were collected. All the samples were taken to the laboratory, air-dried and crushed; one part passed through a 1-mm sieve for PSD and micro-aggregate analysis, and the other part passed through a 0.25-mm sieve for total organic carbon (TOC) and TN measurement (Zhang et al. 2013).

1.3 Laboratory analysis

Soil PSD and micro-aggregates were analyzed by a laser diffraction technique using a Longbench Mastersizer 2000 (Malvern Instruments, Malvern, England). For soil PSD determination, samples were pretreated with 6% H_2O_2 to remove organic matter and added 10% HCL for removing carbonates and oxides, and then were soaked in distilled water for 24 h. After

Table 1 Detailed information on the 10 land use patterns (Zhang et al., 2013)

Land use pattern	Latitude, Longitude	Altitude (m)	Restoration year (a)	Main vegetation or crop species
Slope cropland	36°44′38″N, 109°15′05″E	1,286	30	*Setaria italica*
Terraced cropland I	36°43′45″N, 109°14′25″E	1,296	30	*Setaria italica*
Terraced cropland II	36°44′56″N, 109°15′23″E	1,205	30	*Zea mays*
Check-dam cropland	36°43′21″N, 109°14′14″E	1,179	30	*Zea mays*
Woodland	36°44′22″N, 109°15′34″E	1,242	30	*Robinia pseudoacacia* L.
Shrubland I	36°44′34″N, 109°15′40″E	1,281	30	*Caragana microphylla* Kom.
Shrubland II	36°44′05″N, 109°15′29″E	1,184	30	*Hippophea rhamnoides* Linn.
Orchard	36°44′27″N, 109°15′04″E	1,205	30	*Malus domestica*
Artificial grassland	36°43′45″N, 109°15′22″E	1,264	15	*Medicago sativa* L.
Natural grassland	36°44′15″N, 109°15′10″E	1,203	30	*Artemisia sacrorum* Ledeb, *Stipa bungeana* Trin.

removing the distilled water, the samples were chemically dispersed with 0.4% Calgon and mechanically dispersed in an ultrasonic bath for 5 min. For micro-aggregate determination, the samples were only soaked in distilled water for 24 h, and mechanically dispersed in an ultrasonic bath for 5 min. Soil PSD was described in terms of the percentage of clay (<0.002 mm), fine silt (0.002–0.02 mm), coarse silt (0.02–0.05 mm), very fine sand (0.05–0.1 mm), fine sand (0.1–0.25 mm), medium sand (0.25–0.5 mm) and coarse sand (0.5–1 mm). The size grades of the micro-aggregates were classified to be the same as that of the PSD. Soil TOC and TN were measured using the Walkley–Black method (Nelson and Sommers, 1982) and the Kjeldahl method (Bremner and Mulvaney, 1982), respectively.

1.4 Soil fractal model theory

Tyler and Wheatcraft (1992) developed an equation to determine the mass fractal dimension value (D_m) of soil PSD, which has become widely used in agrology. The calculation of D_m assumes that the densities of different soil particles are the same, but this assumption is not ideal given the actual conditions of soil (Clifton et al., 1999). Laser diffraction (LD) technology can be used to obtain the volume information regarding soil PSD in particle fractions and is independent of the soil particle mass, thus making this method ideal for the use of the volume fractal dimension value (D_v) to evaluate soil PSD. The equation used to calculate D_v (i.e. D) is expressed as:

$$\frac{V(r<R_i)}{V_T}=(\frac{R_i}{R_{max}})^{3-D}. \quad (1)$$

Where r is the soil particle size, R_i is the particle size of grade i in the particle size grading, $V(r<R_i)$ is the volume of soil particles with a diameter less than R_i, V_T is the volume of all the soil particles, R_{max} is the maximum diameter of the soil particles, and D is the fractal dimension value. We took the logarithms in both sides of the equation, and obtained the D values of all the soil samples based on the slopes of the logarithmic curves that fit the data.

1.5 Soil anti-erodibility index

Baver (1932) proposed the concept of aggregate state and degree to evaluate soil structure *via* the following equations:

Aggregate state (%)=content of >0.05 mm micro-aggregates–content of >0.05 mm particles. (2)

Aggregate degree (%)=(aggregate state/content of >0.05 mm micro-aggregates)×100%. (3)

Ayres (1936) proposed the use of the dispersion rate to characterize the degree of soil resistance to soil erosion *via* the following equation:

Dispersion rate (%)=(content of <0.05 mm micro-aggregates/content of <0.05 mm particles)×100%. (4)

1.6 Statistical analysis

To calculate the D values, the measured particle sizes and micro-aggregate volumes of all soil samples were imported to Excel. Two-way analysis of variance (ANOVA) was employed to identify the effects of land use patterns, soil depth and their interaction on fractal dimensions of PSD and micro-aggregates. The differences in the D values between different land use patterns and soil depth were compared using one-way ANOVA. If a significant difference at $P<0.05$ was observed, a comparison among the means was performed using the Duncan multiple-range procedure. Regression analysis was used to analyze the relationship between D and the contents of particles of different sizes and micro-aggregate fractions, TOC and TN. All statistical analyses were conducted using the SPSS software (version 16.0). All figures were drawn using SigmaPlot 10.0.

2 Results

2.1 Fractal dimensions of PSD

The two-way ANOVA indicated that land use patterns, soil depths and their interaction exhibited a significant effect on fractal dimensions of PSD ($P<0.001$ or $P<0.05$) (Table 2). The check-dam cropland and natural grassland had the highest fractal dimensions in the 0–500 cm soil profile, whereas shrubland I always had the lowest fractal dimensions with D values ranging from 2.600 to 2.676 (Table 3). Terraced cropland I, woodland and artificial grassland had a relatively higher fractal dimension than shrubland I, which was not significant. In the 0–150 cm soil profile, the D values of woodland varied between 2.602 and 2.635, lower than terraced cropland I and artificial grassland with D values between 2.628 and 2.669 and between 2.637 and 2.668, respectively. In the 150–500 cm soil profile, artificial grassland had the highest fractal dimensions, followed by the woodland and then terraced cropland I. Slope cropland, terraced cropland II, shrubland II and orchard had relatively higher fractal dimensions than terraced cropland I, woodland and artificial grassland in the 0–60 cm soil profile. Overall, shrubland I with *Caragana korshinskii* had the lowest fractal dimension in the 0–500 cm soil profile, followed by woodland, terraced cropland I and artificial grassland. Natural grassland had the highest fractal dimensions except in the 0–10 cm profile, followed by check-dam cropland. Slope cropland, terraced cropland II, shrubland II and orchard had relatively higher fractal dimensions in the top soil (0–60 cm depth).

2.2 Fractal dimensions of micro-aggregates

Land use pattern and soil depth, as well as their interaction significantly affected the fractal dimensions of micro-aggregates ($P<0.001$) (Table 2). The fractal dimensions of micro-aggregates significantly increased with soil depth under the 10 typical land use patterns (Table 4). In the entire 0–500 cm soil profile, shrubland I had the lowest fractal dimensions of micro-aggregates, varying between the D values of 2.499 and 2.658, followed by the woodland with D values ranging between 2.524 and 2.660; and artificial grassland with D values between 2.553 and 2.662. Natural grassland also had lower fractal dimensions in the 0–40 cm soil profile, but then fractal dimensions significantly increased compared with the other land use patterns. By contrast, slope cropland, terraced cropland I and check-dam cropland had higher fractal dimensions in the 0–40 cm soil profile, and fractal dimensions were lower than those of other land use patterns, in the order of terraced cropland I<slope cropland<check-dam cropland.

Table 2 Results of two-way ANOVA for the effect of land use pattern and soil depth on fractal dimensions of PSDs and micro-aggregates

	df	$D_{particle}$		D_{micro}	
		F	*P*	*F*	*P*
Land use pattern	9	77.589	<0.001	41.362	<0.001
Soil depth	13	13.267	<0.001	81.909	<0.001
Land use pattern×Soil depth	117	1.360	0.021	2.597	<0.001

Note: $D_{particle}$ means fractal dimensions of PSD; D_{micro} means fractal dimensions of micro-aggregates. n=420.

Table 3 Fractal dimensions of soil PSDs under different land use patterns

Soil depth (cm)	Slope cropland	Terraced cropland I	Terraced cropland II	Check-dam cropland	Woodland	Shrubland I	Shrubland II	Orchard	Artificial grassland	Natural grassland
0–10	2.663^{aBCD}	2.630^{aAB}	2.689^{abCD}	2.702^{abD}	2.624^{abcAB}	2.609^{aA}	2.686^{aCD}	2.667^{abBCD}	2.637^{aABC}	2.656^{aABCD}
10–20	2.690^{aCD}	2.628^{aAB}	2.680^{aBCD}	2.712^{abD}	2.609^{abA}	2.613^{abA}	2.704^{aD}	2.672^{abBCD}	2.637^{aABC}	2.694^{abD}
20–40	2.718^{aDE}	2.643^{aABC}	2.698^{abcCDE}	2.740^{abE}	2.602^{aA}	2.603^{aA}	2.677^{aBCD}	2.692^{abBCDE}	2.638^{aAB}	2.699^{abCDE}
40–60	2.703^{aC}	2.635^{aAB}	2.709^{abcC}	2.707^{abC}	2.613^{abA}	2.600^{aA}	2.682^{aBC}	2.682^{abBC}	2.642^{aAB}	2.719^{bcC}
60–80	2.710^{aBC}	2.669^{aABC}	2.716^{abcBC}	2.704^{abBC}	2.618^{abA}	2.611^{aA}	2.685^{aABC}	2.674^{abABC}	2.642^{aAB}	2.734^{bcC}
80–100	2.705^{aBC}	2.643^{aAB}	2.729^{bcC}	2.680^{aBC}	2.613^{abA}	2.612^{aA}	2.718^{aC}	2.654^{aAB}	2.651^{aAB}	2.702^{abcBC}
100–150	2.698^{aBC}	2.654^{aAB}	2.732^{bcC}	2.706^{abBC}	2.635^{abcdA}	2.629^{abcA}	2.698^{aBC}	2.709^{bBC}	2.668^{bAB}	2.746^{cdC}
150–200	2.694^{aBC}	2.645^{aAB}	2.729^{bcCD}	2.722^{abC}	2.644^{bcdAB}	2.633^{abcA}	2.681^{aABC}	2.704^{bC}	2.682^{cdABC}	2.779^{deD}
200–250	2.687^{aABC}	2.640^{aAB}	2.732^{bcC}	2.730^{abC}	2.658^{cdeAB}	2.629^{abcA}	2.700^{aBC}	2.684^{abABC}	2.691^{dBC}	2.821^{eD}
250–300	2.692^{aABC}	2.643^{aA}	2.743^{cCD}	2.750^{abDE}	2.662^{deAB}	2.655^{bcdAB}	2.700^{aBCD}	2.705^{bBCD}	2.691^{dABC}	2.794^{eE}
300–350	2.701^{aBC}	2.658^{aA}	2.729^{bcCD}	2.778^{bEF}	2.67^{deAB}	2.659^{cdA}	2.750^{aDE}	2.698^{bBC}	2.677^{bcAB}	2.799^{eF}
350–400	2.699^{aABC}	2.668^{aAB}	2.716^{abcBC}	2.745^{abC}	2.675^{eAB}	2.659^{cdA}	2.738^{aC}	2.700^{bABC}	2.69^{dABC}	2.797^{eD}
400–450	2.696^{aABC}	2.670^{aAB}	2.719^{abcBC}	2.774^{bD}	2.680^{eABC}	2.665^{cdA}	2.725^{aC}	2.691^{abABC}	2.688^{cdABC}	2.795^{eD}
450–500	2.714^{aBC}	2.675^{aA}	2.716^{abcBC}	2.694^{abAB}	2.674^{eA}	2.676^{dA}	2.733^{aC}	2.684^{abA}	2.694^{dAB}	2.798^{eD}

Note: Values followed by capital letters within rows and lowercase letters within columns are significantly different at $P<0.05$. Sloped cropland: *S. italica*; Terraced cropland I: *S. italica*; Terraced cropland II: *Z. mays*; Check-dam cropland: *Z. mays*; Woodland: *R. pseudoacacia* L.; Shrubland I: *C. microphylla*; Shrubland II: *H. rhamnoide*; Artificial grassland: *M. sativa* L.

Table 4 Fractal dimensions of soil micro-aggregates under different land use patterns

Soil depth (cm)	Slope cropland	Terraced cropland I	Terraced cropland II	Check-dam cropland	Woodland	Shrubland I	Shrubland II	Orchard	Artificial grassland	Natural grassland
0–10	2.604^{aCDE}	2.564^{aBCD}	2.62^{aDE}	2.635^{abcdE}	2.524^{aAB}	2.499^{aA}	2.566^{aBCD}	2.611^{abcCDE}	2.553^{aABC}	2.51^{aAB}
10–20	2.602^{aCD}	2.529^{aAB}	2.612^{aD}	2.612^{abcD}	2.538^{aABC}	2.528^{abAB}	2.587^{abBCD}	2.58^{aABCD}	2.592^{bBCD}	2.522^{abA}
20–40	2.611^{abC}	2.573^{aBC}	2.62^{aC}	2.603^{abC}	2.535^{aAB}	2.502^{aA}	2.596^{abBC}	2.599^{abC}	2.57^{abBC}	2.574^{bcBC}
40–60	2.594^{aABC}	2.573^{aABC}	2.633^{abCD}	2.578^{aABC}	2.551^{aAB}	2.54^{abA}	2.607^{bcBCD}	2.595^{abABC}	2.574^{abABC}	2.669^{deD}
60–80	2.597^{aABC}	2.579^{abABC}	2.638^{abcCD}	2.594^{abABC}	2.536^{aA}	2.567^{bAB}	2.623^{bcdBCD}	2.617^{bcdBCD}	2.589^{abABC}	2.677^{defD}
80–100	2.61^{abCDE}	2.572^{aABC}	2.622^{aCDE}	2.595^{abCDE}	2.537^{aA}	2.542^{abAB}	2.643^{cdeE}	2.611^{abcCDE}	2.588^{abBCD}	2.626^{cdDE}
100–150	2.631^{abcAB}	2.636^{cABC}	2.667^{bcdBCD}	2.659^{bcdABCD}	2.623^{bA}	2.63^{cAB}	2.667^{efgBCD}	2.676^{fCD}	2.656^{cABCD}	2.68^{defD}
150–200	2.651^{cdAB}	2.631^{cAB}	2.671^{cdB}	2.664^{bcdAB}	2.631^{bAB}	2.628^{cA}	2.657^{defAB}	2.673^{fB}	2.662^{cAB}	2.713^{efgC}
200–250	2.645^{bcdABC}	2.622^{bcA}	2.68^{dC}	2.657^{bcdABC}	2.639^{bAB}	2.639^{cAB}	2.671^{efgBC}	2.649^{defABC}	2.656^{cABC}	2.752^{gD}
250–300	2.659^{cdAB}	2.631^{cA}	2.696^{dC}	2.676^{cdBC}	2.644^{bA}	2.65^{cAB}	2.654^{defAB}	2.652^{efAB}	2.66c^{AB}	2.748^{gD}
300–350	2.673^{dABC}	2.635^{cA}	2.677^{dBC}	2.686^{dC}	2.657^{bABC}	2.647^{cABC}	2.675^{efgBC}	2.653^{efABC}	2.641^{cAB}	2.737^{fgD}
350–400	2.667^{cdAB}	2.641^{cA}	2.672^{cdAB}	2.675^{cdAB}	2.654^{bAB}	2.647^{cA}	2.701^{gBC}	2.656^{efAB}	2.661^{cAB}	2.728^{efgC}
400–450	2.654^{cdAB}	2.643^{cA}	2.684^{dBCD}	2.695^{dD}	2.660^{bABC}	2.651^{cA}	2.686^{fgCD}	2.647^{defA}	2.642^{cA}	2.731^{efgE}
450–500	2.669^{cdBCD}	2.645^{cAB}	2.68^{dCD}	2.654^{bcdAB}	2.642^{bA}	2.658^{cABC}	2.689^{fgD}	2.638^{cdeA}	2.643^{cA}	2.757^{gE}

Note: Values followed by capital letters within rows and lowercase letters within columns are significantly different at *P*<0.05. Sloped cropland: *S. italica*; Terraced cropland I: *S. italica*; Terraced cropland II: *Z. mays*; Check-dam cropland: *Z. mays*; Woodland: *R. pseudoacacia* L.; Shrubland I: *C. microphylla*; Shrubland II: *H. rhamnoide*; Artificial grassland: *M. sativa* L.

2.3 Soil anti-erodibility

Maintaining high soil anti-erodibility, especially that of the surface soil, is very important for the reinforcement of soil strength in withstanding water flow flush and for effective reduction of soil erosion. In the present study, natural grassland had the highest aggregate state and aggregate degree in the 0–10 cm soil profile, with the values being 16.46% and 41.45%, which were significantly higher than those of the other nine land use types (Figs. 1a and b). And the shrublands and woodland had moderate values of aggregate state and aggregate degree. However, the croplands had the lowest values of aggregate state and aggregate degree, being 2.45% to 6.78% and 9.90% to 12.76%, respectively. While the dispersion degree showed an opposite trend (Fig. 1c). The natural grassland had the lowest dispersion degree, with the value being 78.25%. The slope cropland had the highest dispersion degree, with the value being 96.55%.

2.4 Relationship between fractal dimensions and soil properties

Correlation analysis showed that the fractal dimensions of PSD had a significantly positive correlation with the fractal dimensions of micro-aggregates (*P*<0.001) (Fig. 2). Fractal dimensions of PSD had a significantly positive correlation with clay content and silt content (*P*<0.001 or *P*<0.01) but a significantly negative correlation with sand content (*P*<0.001) (Fig. 3).

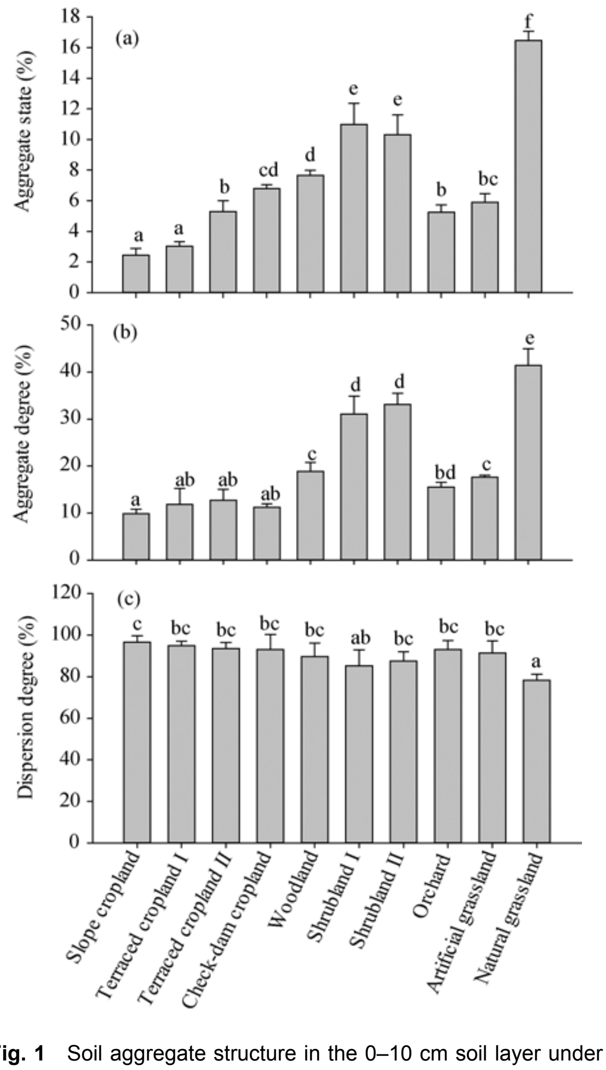

Fig. 1 Soil aggregate structure in the 0–10 cm soil layer under different land use patterns

Meanwhile, fractal dimensions of PSD had a significantly positive correlation with TN (P<0.05), whereas fractal dimensions of micro-aggregates had significantly negative correlation with TOC (P<0.001) (Fig. 4). Also, fractal dimensions of micro-aggregates was significantly positive correlated to the content of <0.002 mm micro-aggregates, while negatively correlated to the content of 0.002–0.05 and >0.05 mm micro-aggregates (P<0.001 or P<0.01).

3 Discussion

3.1 Fractal dimensions of PSD at different soil depths among various land use patterns

Our results showed that the effects of land use patterns and soil depths on fractal dimensions of PSDs were highly significant (Table 2), indicating that land use patterns and soil depths were all main factors influencing PSD. The Loess Plateau is known for its thick soil layers, with the minimum soil thickness being more than 10 m (Wang et al., 2009c). At different soil depths, the diversity in PSD caused differentiated fractal dimensions of PSD. Land use patterns significantly affected the extent of wind erosion and water erosion, thereby resulting in differences in PSD, C concentrations, N concentrations and other soil properties (Er-

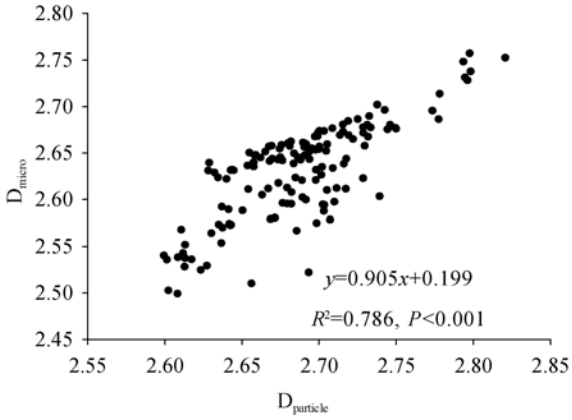

Fig. 2 Correlation between fractal dimensions of PSDs and fractal dimensions of micro-aggregates

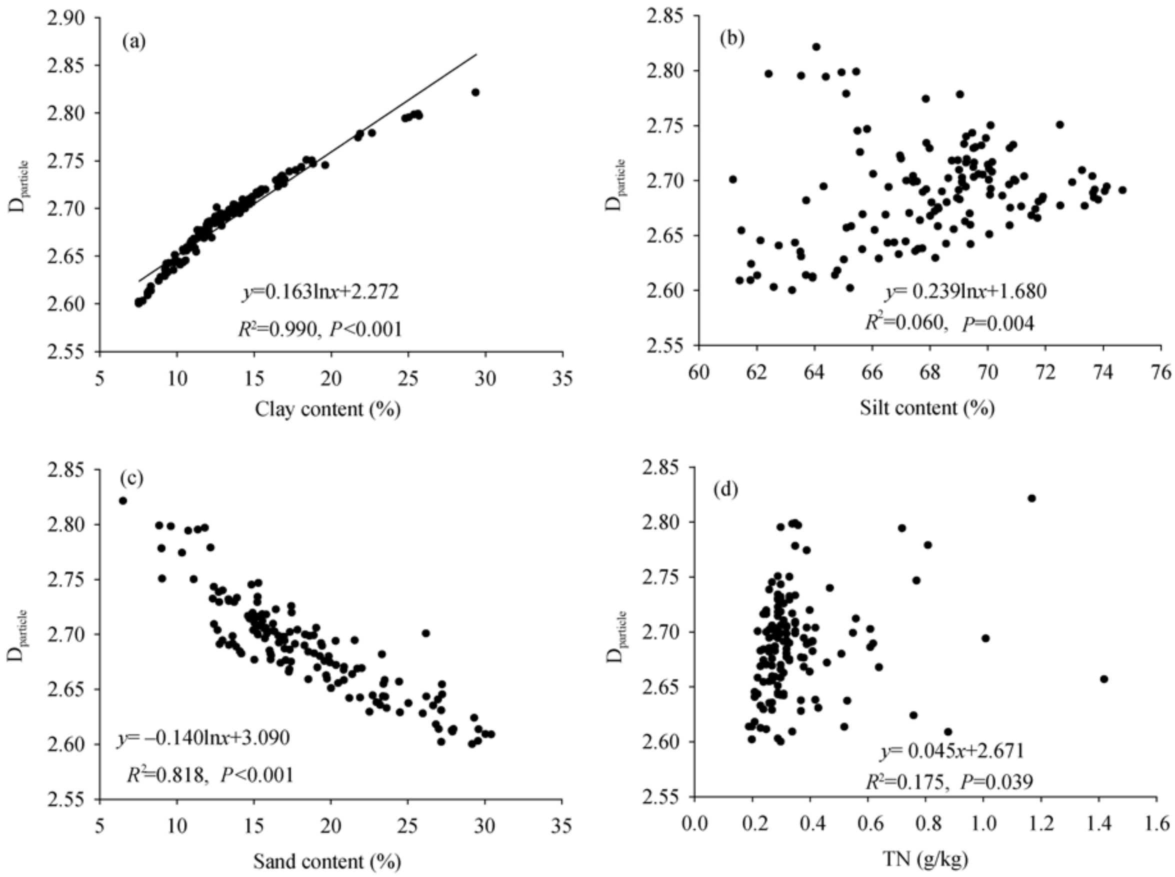

Fig. 3 Correlations between fractal dimensions of PSD and clay content (a), silt content (b), sand content (c) and TN (d)

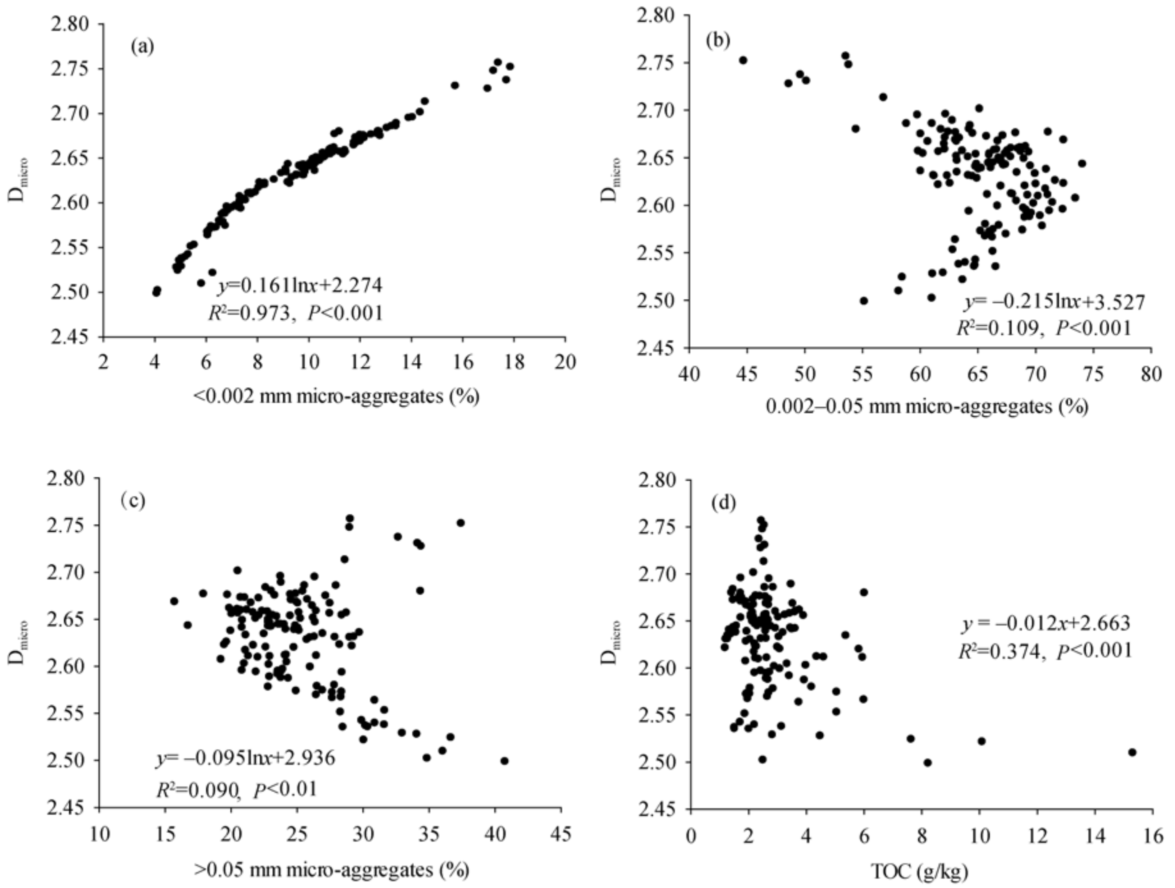

Fig. 4 Correlations between fractal dimensions of micro-aggregates and <0.002 mm micro-aggregates (a), 0.002–0.05 mm micro-aggregates (b), >0.05 mm micro-aggregates (c) and TOC (d)

skine et al., 2002; Basic et al., 2004). Thus, significant differences were found in the fractal dimensions of PSD among different land use patterns. However, soil erosion occurred mainly in the topsoil, which indicated that the diversity of fractal dimensions of PSD in the deep soil layers was mainly caused by slight changes in parent material or even the natural spatial variability of soil properties.

Land use patterns had significant effects on the fractal dimensions of PSD in the surface soil profile (Su et al., 2004; Liu et al., 2009). Previous studies indicated that natural grassland, woodland and shrubland usually had higher fractal dimensions than cropland. The high D values of these land types can be attributed to the well-covered vegetation (Wang et al., 2006, Liu et al., 2009) and reduced human activities (Zou et al., 2002), which obvious decreased the soil erosion, and increased the soil clay content. Our results confirmed that fractal dimensions of PSD were significantly positive correlated with the clay content (Fig. 3a). In the present study, the check-dam cropland had the highest fractal dimensions in the surface 0–40 cm soil profile, which was mainly attributed to the deposit of finer soil particles from other land surfaces. However, the slope cropland had higher fractal dimensions than the woodland, shrubland and natural grassland. This result indicated that the fractal dimensions of PSD were more affected by soil parent material in this area.

Numerous studies demonstrated that the fractal dimension of PSD increases as the soil becomes finer in texture (i.e. from sand to loam and to clay) (Su et al., 2004; Liu et al., 2009), and the fractal dimension of soils with finer texture typically ranges from 2.60 to 2.80 (Tyler and Wheatcraft, 1992; Yang et al., 1993; Li and Zhang, 2000; Millan et al., 2003; Filgueira et al., 2006). In this study, the fractal dimension of PSD had a significantly positive correlation with clay content and silt content but a significantly negative correlation with the sand content. Moreover, the D values varied between 2.609 and 2.798. These findings demonstrate that the implementation of the Grain for Green Project on the Loess Plateau dramatically improved soil properties and had a positive effect on the local ecological environment.

3.2 Fractal dimensions of micro-aggregates at different soil depths among different land use patterns

The present study indicated that land use types, soil depths and their interaction significantly affected the fractal dimensions of micro-aggregates. Although the fractal dimensions of micro-aggregates had a significantly positive correlation with those of PSD (Fig. 2), they were more effective in describing the soil structure in the soil profile. Our results are in accordance with the findings of Zhao et al. (2006), who discovered that the aggregate fractal dimensions could describe the changes in soil structure associated with vegetative succession, whereas particle fractal dimension could not distinguish this diversity. This situation may be attributed to the difference in soil humus, root biomass and root exudates under different land use patterns. Moreover, soil depth showed a greater effect on soil micro-aggregates than particle sizes (Zheng et al., 2009). Thus, among the 10 typical land use patterns, fractal dimensions of micro-aggregates showed a significant difference between different soil depths. The fractal dimensions of micro-aggregates had a significantly positive correlation with the content of <0.002 mm micro-aggregates but a negative correlation with the contents of 0.002–0.05 and >0.05 mm micro-aggregates. In the 0–40 cm soil profile, the fractal dimensions of micro-aggregates in natural grassland, shrubland, and woodland were significantly lower than those of cropland and orchard. These findings demonstrate that human activities resulted in the breakdown of soil micro-aggregates, increased the amount of <0.02 mm micro-aggregates, and inhibited the formation of larger aggregates. On the contrary, high vegetation cover and litter in the grassland, woodland and shrubland supplied much natural organic matter, which obviously improved the soil physical properties and increased the amount of larger aggregates. The results are in accordance with the study of Zheng et al. (2011), who found that the fractal dimensions of soil micro-aggregates in Chinese fir forest were significantly lower than that in the farmland and that agricultural activities significantly reduced soil structure and stability.

3.3 Soil anti-erodibility under different land use patterns

The characteristics of soil micro-aggregates under different land use patterns varied because of inter-aggregate agglomeration and cohesive action (Zhang et al., 2008). In this study, natural grassland had the highest aggregate state and aggregate degree in the 0–10 cm soil layer, followed by shrubland and woodland. By contrast, cropland had a lower aggregate state and aggregate degree. However, the dispersion rates of these land use types show an opposite trend compared to the aggregate state and aggregate degree. The reason might be that the natural grassland, shrubland and woodland had relatively larger amounts of litter than the artificial grassland, orchard and cropland. The decomposition of litter, as a source of organic matter, caused the difference in the amount and composition of surface oxide, resulting in the variabilities in cohesive action among soil particles. The results of this study are supported by Putteman et al. (2005), who found significantly more micro-aggregates under permanent pastures than under conventional arable fields.

4 Conclusions

The results of our study showed that the fractal dimensions of PSD and micro-aggregates were all significantly influenced by soil depths, land use patterns and their interaction, and the fractal dimensions of micro-aggregates could better describe the changes in soil structure with soil depths among different land use patterns. The vegetation types of shrubland, woodland and natural grassland increased the amount of larger micro-aggregates, and decreased the fractal dimensions of micro-aggregates in the 0–40 cm soil profile. And they also had higher values of aggregate state and aggregate degree but lower dispersion rates than the croplands in the 0–10 cm soil layer. The results of this study indicated that fractal theory can be used to characterize soil structure in the soil profile under different land use patterns and that natural grassland may be the best land use type for improving soil structure in the Loess Plateau, China.

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