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Analysis of spatial variability of the fractal dimension of soil particle size in *Ammopiptanthus mongolicus'* desert habitat

X. H. Jia · X. R. Li · J. G. Zhang · Z. S. Zhang

Abstract Quantitative analyses of soil texture with the help of the fractal dimensions of soil particle sizes show that fractal dimensions exhibit a significant linear negative correlation with the sand content (>0.1 mm) and a significant power-law positive correlation with the content of clay and silt (<0.05 mm) ($P < 0.0001$). However, results revealed that the range of spatial heterogeneity was not restricted to the range of the shrub canopies of the dominant *Ammopiptanthus mongolicus* communities in the desert region. These results did not support the theory of the "fertile island effect" arising from the interception of fine-grained materials including dust by the shrubs in a desert ecosystem. We hypothesize that the high spatial heterogeneity existing beyond the scope of the shrub canopies and the lack of proper soil substrate conditions required for the invasion of other species, lead to the steady dominance of *A. mongolicus* communities in these arid desert regions.

Keywords *Ammopiptanhus mongolicus* ·
Psammophytic vegetation · Fractal dimension of soil particle size · Spatial variation

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Introduction

Schlesinger et al. (1990) have postulated that various processes, especially overgrazing, that create spatial heterogeneity in the soils of arid and semiarid grasslands, may lead to the invasion of these communities by desert shrubs. This is because the invasion of shrubs in grasslands increases the heterogeneity of the spatial distribution of primary vegetation and soil resources. The fine-scale pattern of soil resources in grassland suggest that the soil changes that accompany the transition from grassland to shrub-land may be associated with a change in the scale of soil heterogeneity (Schlesinger et al. 1996; Hook et al. 1991).

Some researchers have analyzed and explained the underlying ecological processes using the mechanism for formation of a 'fertile island' of shrubs (Schlesinger et al. 1996; Noy-Meir 1985; Charley and West 1975; Garner and Steinberger 1989; Hook et al. 1991; Tongway and Ludwig 1994). Reynolds et al. (1996) suggested that the accumulation of soil resources under desert shrubs is an autocorrelation process that may promote the persistence of shrubs in the community. Thus, the desertification of grasslands based on the distribution of soil resources due to the invasion by shrubs, was relatively uniform. Li (2005) proposed that the decrease of spatial heterogeneity in the soil resources of a shrub-land was a result of the restoration of vegetation or desertification reversal in arid zones, because of the change in plant species from shrubs to grasses.

Other researchers working in the area of restoration ecology considered the distribution of shrub vegetation in patches and concluded that shrubs are the 'trigger spots' for the restoration of vegetation in arid and semiarid zones (Lal 2000). In fact, the most distinct aspect of heterogeneity is the spatial one, and this was suggested to reflect the

intrinsic characteristics of ecological processes and patterns (Bellehumeur and Legendre 1998). However, spatial heterogeneity is closely related to scale. Shifts of scale may even lead to alternation between heterogeneity and homogeneity, making the study of scale-dependent spatial heterogeneity important (Dutilleul and Legendre 1993). Hence, spatial and scale variations of soil resources are the determining factors in changes in plant species in arid regions (Ettema and Wardle 2002). This point is well illustrated in the changes in spatial heterogeneity and the scale of soil resources due to invasion of the grasslands by shrubs and of shrub-land habitats by grass (Li 2005; Schlesinger et al. 1996; Hook et al. 1991; Tongway and Ludwig 1994).

Although both physical and biological factors play important roles in the degradation of grasslands and the reversal of desertification in arid and semiarid regions, little is known about the physical factors. Soil texture can affect the migration, distribution and efficiency of use of water and nutrients and has an important effect on the composition and structure of vegetation (Stark 1994). To quantitatively characterize soil texture, it is necessary to have a single parameter that can replace soil particle size composition in describing soil texture. To this end, soil fractal dimension can help to not only characterize the soil particle size composition but also to reflect the uniform degree of soil texture (Yang et al. 1993). Many studies show that the finer the soil texture, the higher the fractal dimension of soil particle size (Li and Zhang 2000; Bittelli et al. 1999).

Previous studies have mostly focused on characterizing soil texture differences using the fractal dimension parameter of soil particle size (Yang et al. 1993; Li and Zhang 2000; Su and Zhao 2004; Zhao et al. 2002). However, no information is available in the literature as to the use of the fractal dimension of soil particle size to study differences in spatial distribution of soil texture. Reports of particle size analyses of soil suggest that fine-grained soils in many shrub islands may be the result of the deposition of windblown materials that are captured by the shrub canopy (Elkins et al. 1986; Coppinger et al. 1991). Thus, spatial distribution and heterogeneity of soil texture help in understanding changes in properties such as water content, biological activity, and nutrient availability in soil, as well as spatial soil distribution patterns in arid desert zones.

In addition, they may also provide a theoretical basis for the restoration of vegetation and the rehabilitation of the eco-environment in arid desert zones. This is especially the case for our study of the stability of the endemic plant species—*Ammopiptanthus mongolicus* in the Alashan desert of China. In this paper, we will use a geostatistical method to describe the spatial variation in soil particle size distribution (PSD) using the quantitative fractal dimension parameter calculated with the help of a semi-variogram.

Our hypothesis was that the distribution of soil particle size in shrub-lands would show spatial autocorrelation up to the average size of the dominant individuals. The objectives of this study conducted in a psammophytic region in a desert zone are to: (1) to study the spatial variability and scale of soil particle size, and (2) to investigate whether the physical presence of the shrub, *A. mongolicus*, can change the soil texture under and outside the shrub-canopy area.

Materials and methods

Description of study area

The study area is a sand-covered, low mountainous region at the southeastern edge of the Tengger Desert in China. It is uniformly covered by sand of approximately 30 cm thickness and the underlying soil has a clayey texture (Table 1) (Jia 2006), typical of a psammophytic region in a desert zone. The study was conducted in a sample plot located in the Yandilatu area of Alashan Zuoqi (37°52.65′N, 105°5.26′E) at an elevation of 1450 m with an annual air temperature of approximately 10°C, extreme minimum and maximum temperatures of −25.1 and 38.1°C, respectively; annual sunshine duration of 2,778–2,980 h, annual precipitation of 150–180.2 mm, annual potential evaporation of 2,800–3,000 mm, mean annual wind velocity of 2.9 m/s, and an annual dust storm frequency of 55–64 days.

Prevailing winds in the region are northwesterly, which is the strongest, followed by northeasterly and easterly winds. Psammophytic species in the region include *A. mongolicus*, *Zygophyllum xanthoxylon* and *Artemisia ordosica*. Other species found scattered in the region are *Cynanchum komarovii*, *Allium mongolicum* and *Scorzonera divaricata* constituting a total cover of about 20%. The groundwater table in the region is about 4 m deep (Compositive review 1985). Due to the soil characteristics in this region (Tables 1, 2), the root systems of *A. mongolicus* develop horizontally rather than vertically, and are mainly concentrated in the top 0–30 cm of the soil layer (Liu et al. 1995).

Soil sampling and analysis

The study area was chosen based on the criteria of having a sand-covered site with excellent biomass, coverage, height and abundance of *A. mongolicus* (Jia 2006). Vegetation in the study site mainly consists of xerophytic shrubs and herbaceous species. Most of the shrubby and herbaceous roots are concentrated at a depth of 50–70 cm in the soil layer. However, surface characteristics such as the texture of the top 0–5 cm of the soil play a vital role in the infiltration of the soil by the roots of the herbaceous cover (Li 2005). Therefore, two layers have been chosen for soil

Table 1 Physical characteristics of soil at this site

Depth (cm)	Particle size (mm)					Soil type	Bulk density	pH	Mean soil moisture (%)
	Particle size distribution (%)								
	1>	1–0.25	0.25–0.05	0.05–0.01	>0.05				
0–10	0	23.43	76.57	0.00	100	Aeolian sand soil	1.58	8.62	1.0
10–20	0.43	27.05	72.52	0.00	100	Aeolian sand soil	1.54	8.63	1.2
20–40	1.17	32.47	66.37	0.00	100	Aeolian sand soil	1.52	8.58	2.0
40–60	1.91	18.54	64.28	15.27	84.73	Light sierozem	1.27	8.51	2.7
60–100	1.24	18.04	64.95	15.77	84.23	Light sierozem	1.30	8.54	4.0

Table 2 Nutrient characteristics of soil at this site

Depth (cm)	CEC (cmol/kg)	EC (uS/cm)	SOM (g/kg)	Total N	Available N (mg/kg)	Available P	Available K
0–10	3.70	103.58	0.94	0.16	6.30	1.58	66.40
10–20	3.78	87.88	1.35	0.05	5.20	1.53	66.40
20–40	3.77	104.78	4.68	0.09	5.90	1.38	58.10
40–60	3.88	129.68	1.83	0.17	9.00	1.28	49.80
60–100	3.85	132.60	2.01	0.21	8.89	1.29	49.21

CEC cation exchange capacity, *EC* electrical conductivity, *SOM* soil organic matter, *N* nitrogen, *P* phosphorus, *K* potassium

sampling: a 0–5 cm and a 50–70 cm layer. A level and apparently topographically uniform field site was selected to avoid anisotropic effects in the geostatistical analysis.

Soil samples for the study of the heterogeneity of soil particle size composition were collected from a randomly selected 10 m × 10 m sample plot located in flat land with psammophytic *A. mongolicus* shrubs. One hundred sampling points were selected according to the contiguous grid method, with transverse and longitudinal spacings of 1 m (Fig. 1) to take soil samples from 0–5 and 50–70 cm soil layers. Three soil cores were randomly collected from each of the quadrants and merged to reduce soil sample heterogeneity for each quadrant. Careful note was made for each sample as to whether it was taken from beneath a shrub or from the bare soil between plants.

Soil particle size compositions were analyzed by vibrating screen and pipette methods (Institute of Soil Sciences, Chinese Academy of Sciences 1978). Samples were sequentially wet-sieved through sieves of mesh sizes >4, 3.15, 2.5, 2, 1.6, 1.25, 1, 0.8, 0.63, 0.5, 0.4, 0.315, 0.25, 0.2, 0.16, 0.125, 0.1, 0.08, and 0.063 mm. Material that was smaller than the 0.063 mm mesh was analyzed by the pipette method. Sedimentation techniques were used to obtain the following diameters: 0.05, 0.02, 0.01, 0.005, 0.002, 0.001, and <0.001 mm. Each sample was tested for the presence of carbonates by treatment with 0.2 M HCl The treated samples were then washed with deionized water and titrated with 0.5 N NaOH. Soil organic matter (SOM) content was determined by using the Walkley-Black
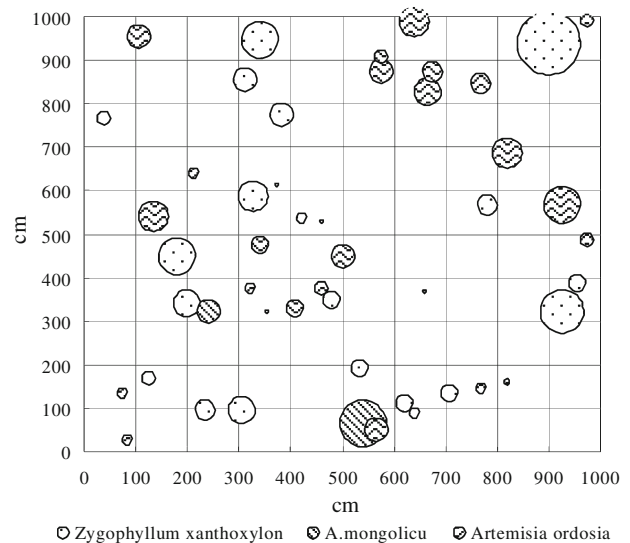

Fig. 1 Image of the sample plot and vegetation

dichromate oxidation technique (Institute of Soil Sciences, Chinese Academy of Sciences 1978).

Theoretical sections

Fractal dimension model of particle size

Fractal features can be described in terms of the fractal dimension (also known as fractal dimensionality) of

particle size. The volume V ($\delta > di$) constituted by soil particles in porous media with self-similar structures, that are larger than a given diameter di ($di > di + 1$, $i = 1, 2, \ldots$) can be expressed by the formula (Yang et al. 1993; Turcotte 1986; Tyler and Wheatcraft 1992):

$$V(\delta > di) = A\left[1 - \left(di/k\right)^{3-D}\right] \quad (1)$$

where δ is size, A and K are constants used to describe shape, and D is the fractal dimension of the PSD in a number-based form.

Turcotte (1986) as well as Tyler and Wheatcraft (1992) pointed out that it is generally more convenient to express the number-based power law (Eq. 1) as a mass-based form for soil particles. The mass-based approach is compatible with data obtained from experimentation, where mass fractions rather than number fractions, are usually measured. The mass-based form of Eq. 1 is expressed as Eq. 2 (Turcotte 1986; Bittelli et al. 1999; Tyler and Wheatcraft 1992):

$$W\left(\delta > \overline{di}\right) = V\left(\delta > \overline{di}\right)\rho = \rho A\left[1 - \left(\overline{di}/k\right)^{3-D}\right] \quad (2)$$

Generally, data for particles is expressed by the mass distribution of certain particle sizes. With $\overline{di}$ expressing the mean particle size value of two sieved particle sizes—di and $di + 1$, and assuming a constant density for the soil particles, namely $\rho_i = \rho$ ($i = 1, 2, \ldots$), a particle's radius di is proportional to its mass m. Then, from Eq. 2, $W\left(\delta > \overline{di}\right)$ is the accumulated mass of soil particles larger than di. With W_0 as the mass sum of soils containing all particle sizes, by definition, $\lim\limits_{i\to\infty} \overline{di} = 0$ (from the Eq. 2).

$$W_0 = \lim\limits_{i\to\infty} W\left(\delta > \overline{di}\right) = \rho A \quad (3)$$

From Eqs. (2) and (3),

$$W\left(\delta > \overline{di}\right)/W_0 = 1 - \left(\overline{di}/k\right)^{3-D} \quad (4)$$

Let $\bar{d}_{\max}$ be the mean diameter of soil particles of the largest particle size; then, substituting $W(\delta > \bar{d}_{\max}) = 0$ in Eq. 4, we get $k = \bar{d}_{\max}$. The mass distribution of soil particles and its fractal relation with mean particle size can now be obtained:

$$W\left(\delta > \overline{di}\right)/W_0 = 1 - \left(\overline{di}/\bar{d}_{\max}\right)^{3-D} \quad (5)$$

or

$$\left(\overline{di}/\bar{d}_{\max}\right)^{3-D} = W_i\left(\delta > \overline{di}\right)/W_0 \quad (6)$$

W_i ($\delta < di$) in Eq. 6 is the accumulated mass of soil particles smaller than di. The fractal dimension of soil particle size can be obtained through the logarithmic transformation of Eq. 5 or 6 and a regression operation. In other words, the 3-D value can be obtained as the slope from

linear regression with $\log\left(Wi/W_0\right)$, $\log\left(\overline{di}/\bar{d}_{\max}\right)$ for y- and x-axes variables, respectively, through the logarithmic transformation of Eq. 5 or 6. Furthermore, the fractal dimension can be calculated for each sample. Soil samples that fall into a certain textural class may have considerably different clay, silt and sand contents. The size definitions of the three main particle fractions (clay, sand, and silt) are rather arbitrary, and they do not provide complete information on the soil PSD (Bittelli et al. 1999). Hence, the slope of the linear regression described above can be obtained by testing the range of PSD percentages of samples.

Analysis of spatial variations of the fractal dimension of soil particle size

A variogram can be used as a basic geostatistical tool to estimate the variation function.

$$\gamma(h) = \frac{1}{2N(h)}\sum_{i=1}^{N(h)}\left[Z(xi) - Z(xi + h)\right]^2 \quad (7)$$

where $N(h)$ is the number of pairs of sample points separated by the distance h when the distance is h, $Z(xi)$ is the value at xi position, and $Z(xi + h)$ is the value at a distance of $xi + h$.

Two aspects need to be considered for the construction of variogram curves. First, variogram curves can be established through theoretical derivation or previous experience; second, a scatter diagram can aid in the preliminary definition of the type of the curve. The R^2 coefficient of an experimental variogram can help to determine the degree of curve fitting. The degree of fit is reflected in the coefficient R^2 determined with the help of an experimental variogram. Regression precision can be verified by Rss (Residual).

Semi-variograms may take many shapes. A spherical model is often used to fit the form of a semi-variogram (Webster 1985; Issaks and Srivastava 1989). For data with spatial autocorrelation or dependence in a certain spatial domain, the semi-variogram will rise with h within the domain, and then to a more or less constant value (sill variance, $C_0 + C$) at a distance a (range), beyond which samples are spatially independent. A spherical model (Eq. 8) can be used to calculate the contents of various particle size fractions and the variogram value of particle fractal dimension. The range of the spherical model is equal to the related distance a.

$$\begin{aligned} \gamma(h) &= C_0 + C\left(\frac{3}{2}\frac{h}{a} - \frac{1}{2}\frac{h^3}{a^3}\right) \quad 0 < h \leq a \\ \gamma(h) &= C_0 + C \quad h > a \\ \gamma(h) &= 0 \quad h = 0 \end{aligned} \quad (8)$$

where C_0 also termed as 'nugget variance,' is the value of $\gamma(h)$ when h is zero, and represents random variation and fine scale variations (Burrough 1983; Bellehumeur and Legendre 1998). C is the structural variance at distance a. A high nugget variance indicates that most variance occurs over a short distance, and a high ratio of nugget variance (C_0) to sill variance ($C_0 + C$) is an indication of a random pattern in the data (Schlesinger et al. 1996; Trangmar et al. 1985).

Data processing

The correlations between the fractal dimension and the contents of various soil particle size fractions were analyzed using the Origin 6.0 software package obtained from Microcal Software Inc. (Northampton, MA, USA). The fractal dimension D of soil particle size was obtained by the logarithmic transformation of Eq. 5 or 6. The regression operation, the fractal dimension of soil particle size and the spatial variations of the contents of various particle sizes and various particle size fractions were obtained using the geostatistical software GS+ (Version 5, Gamma Design Software, Michigan, USA). The test of normal distribution was carried out using the SPSS package. A t test was used to deduce differences in significance between samples taken from under shrubs and from bare soil between shrubs. $P < 0.05$ was selected as the critical value.

Results and discussion

Statistical features of fractal dimension of soil particle size and PSD

Bittelli et al. (1999) have analyzed experimentally determined D data for soil particles using Eq. 2, i.e., the mass-based fragmentation approach. Hence, based on this precedent, we calculated the fractal dimension in this study in a mass-based form. The fractal dimensions reported by Tyler and Wheatcraft (1992) were obtained by applying Eq. 2 to the entire range of the PSD data. Again, based on this precedent, we calculated the fractal dimensions of soil particle sizes of 200 soil samples collected from the 0–5 cm and 50–70 cm soil layers in this study. The correlation coefficients obtained from regression analysis are all larger than 0.87 and show a significant linear correlation ($P < 0.01$).

The use of the fragmentation model to sort particles by size, results in fractal dimensions that range theoretically between the limits of 0 and 3 (Turcotte 1986). All collected data in this study have fractal dimension values that are consistent with the $0 < D < 3$ predictions of the fragmentation theory. Table 1 shows that soil texture in the 0–5 cm sandy layer in the study area is coarser than that in the 50–70 cm soil layer. The fractal dimension of soil particle size is 1.62–1.89 in the 0–5 cm soil layer and 1.87–2.63 in the 50–70 cm soil layer, indicating that the higher the sand content, the lower the fractal dimension of soil particle size. The difference of D values in this study at the 50–70 and 0–5 cm depths resulted from the sand (>0.1 mm particle diameter) and silt and clay contents (<0.05 mm particle diameter) (Table 3).

This result is consistent with the findings of other researchers (Yang et al. 1993; Li and Zhang 2000; Su and Zhao 2004; Bittelli et al. 1999), i.e., the fractal dimension of particle size increases as soil texture changes from coarse to fine. Studies have shown that the fractal dimension increases with clay content and decreases with sand content (Bittelli et al. 1999; Su and Zhao 2004). However, as seen in Table 3, the mean sand content (particle size > 0.05 mm) of all soil samples in this study site is over 49.56%, and there is a significant difference between the silt and clay contents (particle size < 0.05 mm) in the 0–5 cm and 50–70 cm layers (Table 3).

Tyler and Wheatcraft (1992) reported D values approaching 3.0 in very finely textured soils. $D < 2$ (Table 3) were attributed to the relatively high sand content of the sample. The high value of the coefficient of determination, R^2 (>0.87) also showed that mass-based fragmentation models are good descriptions of the PSD in the size range studied (Table 3). Thus, our results demonstrate that relatively high sand content contributes to the decreasing degree of fractal dimension.

The variation coefficients (CVs) of the fractal dimensions of soil particle size are low in the 0–5 cm and 50–70 cm soil layers of our sandy *A. mongolicus* shrub-land study area. These CVs can be arranged in the following order: clay and silt > very fine sand > sand grains. These differences in the CVs of the fractal dimensions of the soil particle size can be correlated to the changes in clay and silt contents in the study area with psammophytic vegetation due to the action of strong winds. Interestingly, the CVs of sand content are smaller than those for clay, silt and very fine sand due to the spatial differences in deflation and transport capacity of sand grains.

In the study of geological statistics, data with non-normal distribution may cause proportional effects, thereby leading to great fluctuations in the variograms and thus, adversely affect the reliability of the results (Journel and Huijbregts 1978). Therefore, SPSS software and the one-sample Kolomogorov–Smirnov (K–S) method were used to test the soil PSD, fractal dimensions of particle size and the

Table 3 Statistical features of soil particle size distribution and fractal dimensions of particle sizes in the 0–5 cm and 50–70 cm soil layers ($n = 100$)

Depth (cm)	Soil property		Min	Max	Mean	SD	CV	Skew	Kurtosis	Distribution	Transformation model
0–5	Fractal dimension D		1.62	1.89	1.73	0.04	0.02	−0.08	2.56	Non-normal	Power
	% particle size distribution frequency	Sand % >0.1 mm	69.32	92.29	86.45	3.10	0.04	−2.20	9.86	Normal	–
		Fine sand % 0.1–0.05 mm	5.92	20.37	9.94	2.10	0.21	1.79	6.48	Normal	–
		Silt+ clay % <0.05 mm	1.62	10.31	3.61	1.10	0.30	2.44	14.09	Non-normal	Square root
50–70	Fractal dimension D		1.87	2.63	2.25	0.17	0.07	−0.69	−0.43	Non-normal	Power
	% particle size distribution frequency	Sand % >0.1 mm	42.58	83.69	64.80	8.43	0.13	0.58	−0.13	Non-normal	Llogarithm
		Fine sand % 0.1–0.05 mm	6.98	18.05	11.76	2.00	0.17	0.76	0.53	Normal	–
		Silt + clay % <0.05 mm	6.20	47.64	23.44	9.11	0.39	−0.33	−0.58	Non-normal	Power

contents of sand, fine sand, silt and clay in the 0–5 cm and 50–70 cm soil layers. The results resembled normal distribution after transformation and analysis of the non-normal distribution, and satisfied the stationary hypothesis (Table 3); hence, they were used for geostatistical analysis.

Means and coefficients of variation of fractal dimension and PSD

A comparison of the data for fractal dimension and %PSD frequency in Table 4 reveals that sand (particle size > 0.1 mm) is the largest component of the samples taken from both the soil under the shrubs and from the bare soil between the shrubs, from both the top 0–5 cm and deeper 50–70 cm layers. Soil samples from the top 0–5 cm layer contained more fine sand (0.1–0.05 mm) than did the samples from the deeper 50–70 cm layer. In contrast to this, soil samples from the deeper 50–70 cm layer contained more fine sand (0.1–0.05 mm) as well as silt and clay (<0.05 mm) than did the samples from the top 0–5 cm layer. Thus, our results were consistent with those from other studies in demonstrating that fine-grained soils in these arid zones result from the deposition of windblown materials that are captured by the shrub canopy (Elkins et al. 1986; Coppinger et al. 1991). However, we did not find any significant differences in the means of any of the parameters of the samples taken from under the shrubs or from outside the shrub area. In general, all CVs were relatively high, suggesting that these constituents are more variable in shrub-land soil (Table 4).

Relationship between soil particle size composition and fractal dimension of particle size

The ground in arid zones inhabited by *A. mongolicus* communities, is generally covered by a thin layer of sand (Compositive review 1985). Strong winds cause complex wind erosion and deposition processes, and the fractal dimension of soil particle size exhibits an intense linear negative correlation with sand content (>0.1 mm) ($P < 0.0001$, $R^2 = 0.945$) and an intense power-law positive correlation with the clay and silt contents (<0.05 mm) ($P < 0.0001$, $R^2 = 0.984$) but no obvious relationship with very fine sand content (0.1–0.05 mm) (Fig. 2).

This indicates that in areas that are covered by psammophytic vegetation and prone to wind erosion, erodible fine soil particles are transported in the air beyond the desert borders as dust (<0.05 mm) by deflation, (Zhu et al. 1994). The transportation and deposition of clay, silt and sand in these arid zones greatly affect the fractal dimension of soil particle size. The increase in fractal dimension mainly results from the lower contents of sand

Table 4 Soil fractal dimension and particle size distribution in different locations of the study area

Location		0–5 cm				50–70 cm			
		D	% particle size distribution frequency			D	% particle size distribution frequency		
			>0.1 mm	0.1–0.05 mm	<0.05 mm		>0.1 mm	0.1–0.05 mm	<0.05 mm
Under shrub	mean	1.75 a	85.31 a	10.71 a	3.99 a	2.27 a	64.26 a	11.28 a	24.46 a
Bare soil	mean	1.73 a	86.74 a	9.74 a	3.52 a	2.24 a	64.94 a	11.88 a	23.19 a
Under shrub	CV	2.76	5.66	28.63	45.83	7.24	14.08	12.36	39.08
Bare soil	CV	2.12	2.82	18.00	23.20	7.44	12.82	17.80	38.99
Ratio		0.99	1.02	0.91	0.88	0.99	1.01	1.05	0.95

Bare soil is soil from between (not under) shrubs; Ratio = ratio of means of parameters corresponding to bare and under shrub soils

Values in the same column followed by the same letter are not significantly different at $P > 0.05$ according to ANOVA

Fig. 2 The relationship between soil characteristics and the fractal dimension ($n = 200$)
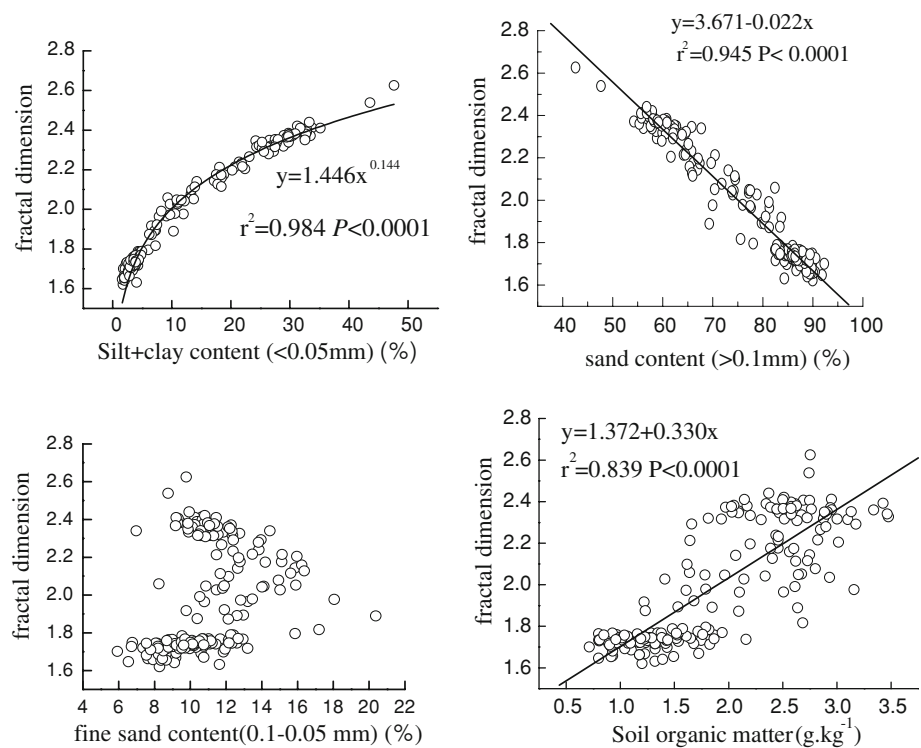
and higher contents of silt and clay, and is more marked when silt and clay contents are really low.

Generally, the clay and silt content is relative low in the arid desert region, hence, its increase due to the deposition of windblown materials that are captured by the shrub canopy plays an important role in the rise of fractal dimension. Therefore, the mobilization, deposition of silt and clay, and movement of sand materials all influence soil texture and fractal dimension. As stated earlier, the higher the fractal dimension, the higher is the content of SOM (Fig. 2). Thus, fractal dimension of particle size of soil samples can be a quantitative indicator of the changes in desertification (Su and Zhao 2004; Zhao et al. 2002).

Analysis of the spatial structure of fractal dimensions of soil particle sizes and contents of different particle size fractions

The ground inhabited by *A. mongolicus* communities is generally covered by a thin layer of sand, mostly in a floating or semi-fixed state (Compositive review 1985). The soil contents of sand, silt and clay continuously change due to wind erosion. Our results show that both the fractal dimensions of the soil particle size in the 0–5 cm and 50–70 cm soil layers and the contents of various particle size fractions exhibit a high spatial heterogeneity in the chosen study area (Table 5). Therefore, a spherical model can be

Table 5 Spatial semi-variogram model and parameters of various soil particle size fractions and fractal features

		C_0	$C_0 + C$	Effective range (m)	C/C_0+C	R^2	RSS	
0–5 cm	Fractal dimension	0.00	0.05	30.99	0.94	0.870	0.00	
	sand	2.26	24.51	24.33	0.91	0.855	17.60	
	fine sand	1.56	9.13	21.19	0.83	0.876	2.22	
	Silt + clay	0.01	0.26	30.20	0.97	0.873	0.00	
50–70 cm	Fractal dimension	380000	3870000	22.30	0.90	0.98	4.828E + 10	
	sand	0.00	0.42	23.11	0.90	0.98	0.00	
	Fine sand	3.21	6.42	30.99	0.50	0.60	0.71	
	Silt + clay	22300	220700	25.92	0.90	0.99	8.745E + 07	

used to describe a variogram of the properties of soil samples from this area.

Calculated results show that the effective ranges of the contents of various particle size fractions and particle fractal dimensions in the 0–5 cm soil layer vary between 21.19–30.99 and 22.3–30.99 m, respectively. An analysis of the variogram clearly shows that the spatial variation scale of various soil properties, fractal dimensions of soil particle sizes in the area with *A. mongolicus,* and the contents of various particle size fractions do not appear to be associated with the mean size of the canopy diameter of any single shrub. The mean diameters of *A. mongolicus*, *Z. xanthoxylon* and *A. ordosica* are 120, 100, and 70 cm, respectively (Compositive review 1985).

This suggests that the spatial distribution of these elements may not be associated with any physical process operating at the scale of the shrub islands. The particle fractal dimensions in the 0–5 cm soil layer are larger than those in the 50–70 cm soil layer; this is related to the long-term effects of surface coarsening factors. Li and Reynolds (1995) claim that spatial heterogeneity consists of two aspects, namely, the random and autocorrelation aspects. The nugget value represents the spatial heterogeneity of the random aspect, while the arch height ($C = C_0 + C–C_0$) represents the spatial heterogeneity of the autocorrelation aspect. The ratio of the nugget to the sill value ($C_0/C_0 + C$) reflects the degree of the spatial heterogeneity of the random part while the ratio of the arch height to the sill value reflects the degree of the spatial heterogeneity of the autocorrelation part.

It can be seen from Table 5 that except for the spatial heterogeneity of the autocorrelation part of very fine sand in the 50–70 cm soil layer that accounts for 50%, the spatial heterogeneity of the autocorrelation part of other soil properties accounts for over 80% of the total spatial heterogeneity. The spatial heterogeneity of the autocorrelation part in the 0–5 cm soil layer reaches a maximum value of 97% (silt and clay content) and a minimum value of 83% (very fine sand content). The spatial heterogeneity of the autocorrelation part in the 50–70 cm soil layer

reaches a maximum value of 90% (fractal dimension of particle size) and a minimum value of 50% (very fine sand content). Relatively speaking, the spatial heterogeneity of the autocorrelation part of various particle size fractions and the fractal dimensions is larger in the 0–5 cm soil layer than in the 50–70 cm soil layer, while the proportion of the autocorrelation part in the two soil layers is in the order of silt + clay > sand > very fine sand.

This shows that the spatial difference in the contents of various particle size fractions in the psammophytic vegetation area is mainly caused by zonal factors (spatial autocorrelation part) such as soil-forming parent material (Aeolian sand) and climate, etc. Under the influences of a strong prevailing wind (the northwesterly wind), secondary prevailing winds (northeasterly and easterly winds) (Li 1991) and long-term wind erosion and deposition processes, the 0–5 cm and 50–70 cm soil layers in the psammophytic vegetation study area had the same spatial autocorrelation variances of fractal dimensions and various particle size fractions. Analyses of the spatial variation scale of various particle size fractions show that it was mainly the factors related to the autocorrelation aspect that caused variations in soil particle size content in the sand-covered area where *A. mongolicus* was the dominant species.

The spatial heterogeneity of the autocorrelation part accounts for up to 83% (except for the very fine sand in the 50–70 cm soil layer where it is 50%), with a spatial variation scale of 21.19–30.99 m, which is larger than the mean diameter of the shrub canopy but does not reflect the local effect of shrubs. The sand-covered ground in this area promotes the infiltration of rainwater and thus, improves the growth environment for *A. mongolicus* (Wang et al. 2004). However, there is no "fertile island" effect on the exposed ground surface because frequent sand movement in this habitat cannot hold the fine-grained materials such as dust deposited under the canopy of shrubs. This is not in agreement with the conclusions of many researchers who have postulated that shrubs in desert ecosystems can intercept dust-fall, reduce raindrop erosion, and increase

the content of fine-grained substances under the canopies of shrubs (Garner and Steinberger 1989; Elkins et al. 1986; Coppinger et al. 1991; Li 2005; Schlesinger et al. 1996).

The non-existence of the "fertile island" effect may also be related to the stability of the surface materials and to the short life-span of plant species in the habitat (Hirobe et al. 2001). Certainly, it is also related to the fact that the coppice dunes formed by *A. mongolicus* shrubs have different degrees of growth and their branches are sparse and heights are high (Yu et al. 2005). In turn, the stable existence of the psammophyte, *A. mongolicus* in the desert zone may also be strengthened by the non-existence of the "fertile island" effect in arid and semiarid desert regions in that the lack of deposition of fine grains of soil under the canopies of shrubs can prevent the invasion of other plant species.

Conclusion

Quantitative analyses of soil texture using the fractal dimensions of soil particle sizes show that the fractal dimensions of soil particle sizes exhibit an intense linear negative correlation with sand content (>0.1 mm) but an intense power-law positive correlation with the clay and silt content (<0.05 mm) ($P < 0.0001$). The increase in fractal dimension resulting from the increase in the contents of silt and clay compared to the sand content is more marked when the silt and clay contents are really low. As the silt and clay contents are very low in arid desert regions, the increase in their contents plays an important role in the accretion of fractal dimension. However, the spatial variability results show that the spatial variation scale of soil particle content is beyond the range of the shrub canopies.

This may be due to frequent wind erosion and deposition of surface materials in these areas in which *A. mongolicus* is the dominant species of psammophytic vegetation. The morphological differences of the branches of *A. mongolicus* and the differences in the degrees of development of these coppice dunes, do not support the "fertile island" effect. This effect is attributed to the interception by shrubs in the desert ecosystem of fine-grained materials such as dust etc, which promotes the growth of other vegetation. We believe that the absence of this "fertile island effect" is due to the high spatial heterogeneity of the soil substrate in these areas inhabited predominantly by the psammophytic *A. mongolicus,* wherein the range of these spatial variations is not restricted to the range of shrub canopies and the shrub interspaces. This spatial heterogeneity does not help in the creation of the soil substrate conditions required for the invasion of other plant species, thus resulting in the stable and dominant existence of *A. mongolicus* communities in this desert region.

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