Geoderma 158 (2010) 352–358

Contents lists available at ScienceDirect

Geoderma

journal homepage: www.elsevier.com/locate/geoderma

Ordination as a tool to characterize soil particle size distribution, applied to an elevation gradient at the north slope of the Middle Kunlun Mountains

Dongwei Gui [a,b,c], Jiaqiang Lei [a,c,*], Fanjiang Zeng [a,c], Michael Runge [d], Guijin Mu [a,c], Faxiang Yang [a,c], Juntao Zhu [a,b,c]

[a] Xinjiang Institute of Ecology and Geography ,CAS ,Urumqi, 830011, China
[b] Graduate School of the CAS, Beijing, 10039, China
[c] Cele National Station of Observation & Research for Desert-Grassland Ecosystem in Xinjiang, Cele, Xinjiang, 848300, China
[d] Department of Plant Ecology, Albrecht von Haller Institute of Plant Sciences, University of Göttingen, Untere Karspüle 2, 37073 Göttingen, Germany

ARTICLE INFO

Article history:
Received 1 July 2009
Received in revised form 26 May 2010
Accepted 3 June 2010
Available online 6 July 2010

Keywords:
Particle-size distributions (PSDs)
Ordination
CCA
Fractal dimension
Arid soils

ABSTRACT

Soil particle-size distribution (PSD) is one of the most fundamental physical attributes of soil due to its strong influence on other soil properties related to water movement, productivity, and soil erosion. Characterizing variation of PSD in soils is an important issue in environmental research. Using ordination methods to characterize particle size distributions (PSDs) on a small-scale is very limited. In this paper, we selected the Cele River Basin on the north slope of the Middle Kunlun Mountains as a study area and investigated vegetation and soil conditions from 1960 to 4070 m a.s.l. Soil particle-size distributions obtained by laser diffractometry were used as a source data matrix. The Canonical Correspondence Analysis (CCA) ordination was applied to analyse the variation characteristics of PSDs and the relationships between PSDs and environmental factors. Moreover, single fractal dimensions were calculated to support the interpretation of the ordination results. Our results indicate that a differentiation of 16 particle fractions can sufficiently characterize the PSDs in CCA biplots. Elevation has the greatest effect on PSDs: the soil fine fractions increase gradually with increasing elevation. In addition, soil pH, water and total salt content are significantly correlated with PSDs. CCA ordination biplots show that soil and vegetation patterns correspond with one another, indicating a tight link between soil PSDs and plant communities on a small scale in arid regions. The results of fractal dimensions analysis were rather similar to CCA ordination results, but they yielded less detailed information about PSDs. Our study shows that ordination methods can be beneficially used in research into PSDs and, combined with fractal measures, can provide comprehensive information about PSDs.

1. Introduction

Soil particle-size distribution (PSD) is one of the most fundamental physical attributes of soil due to its strong influence on other soil properties related to water movement, productivity, and soil erosion (Perrier et al., 1999; Bird et al., 2000; Huang and Zhang, 2005; Montero, 2005; Fooladmand and Sepaskhah, 2006). In a conventional particle-size analysis the mass fractions of clay, silt, and sand are differentiated. However, the size definitions of these main particle fractions are rather arbitrary, and this rough differentiation provides incomplete information (Bittelli et al., 1999) and is unsuitable to establish small-scale differences in soil PSDs (Wang et al., 2008).

Characterizing variation of PSDs in soils is an important issue in environmental research. The latest developments in the study of PSDs have focused on the use of fractal geometry (Turcotte, 1986; Tyler and Wheatcraft, 1992; Wu et al., 1993; Bittelli et al., 1999; Millan et al., 2003; Filgueira et al., 2006). Many single fractal and multifractal measures have been used to characterize the PSDs based on the need to obtain more data regarding particle fractions (Grout et al., 1998; Posadas et al., 2001; Montero and Martín, 2003; Montero, 2005). Most fractal measures attempt to characterize PSDs with parameters (i.e. fractal dimensions, D) that retain the most information. These parameters are then used to compare differences in the PSDs of soil samples. However, little attention has been paid to comparisons of changes in fraction content between soil samples and to quantitatively analyze the relationship between PSDs and environmental factors.

Quantitative methods have been used increasingly in ecological investigations since the 1950s (Zhang et al., 2008). Ordination and classification, which are effective multivariate techniques, have been

* Corresponding author. Xinjiang Institute of Ecology and Geography, Chinese Academy of Sciences, 818 Beijing South Road, Urumqi, 830011, China. Tel.: +86 991 7885443; fax: +86 991 7885503.
E-mail address: desert@ms.xjb.ac.cn (J. Lei).

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doi:10.1016/j.geoderma.2010.06.002

Table 1
Community characteristics along the altitude gradient on the north slope of the Middle Kunlun Mountains.

	Dominant species	Distribution range	Vegetation coverage	Vegetation type
Community I	*Calligonum roborovskii* + *Reaumuria soongonica* + *Sympegma regelii* + *Halogeton glomeratus*	1960–2800 m	Lower than 5%	Mountain desert
Community II	*Seriphidium rhodanthum* + *Stipa roborowskyi* + *Allium przewalskianum*	2900–3400 m	11–39%	Mountain desert grassland
Community III	*Poa* spp. + *Stipa purpurea*	3500–3600 m	35–73%	Mountain grassland
Community IV	*Kobresia humilis* + *Polygonum viviparum* + *Festuca rubra* + *Trisetum spicatum*	3700–4070 m	20–60%	Alpine steppe

widely used for analyses of community structure in vegetation ecology (ter Braak and Prentice, 1988; Mucina and Maarel, 1989; Mucina, 1997; Leps and Šmilauer, 2003; Zhang et al., 2008) and for research in other disciplines (Furse et al., 1984; Rubio and Escudero, 2000; Kent, 2006; Liu et al., 2007; Claassens et al., 2008). Ordination is useful in order to display the rows and columns of a two-way contingency table as points in a low-dimensional space, such that the positions of the row and column points are consistent with their attributes in the table (Greenacre, 1993; Giraudel and Lek, 2001). Normally, the objective of ordination is to generate hypotheses about the relationships between the composition of objects (e.g. vegetation) and the environmental or other factors which determine it (Greig-Smith, 1983). Various ordination methods are available, some of which have been widely used, e.g. Principal Components Analysis (PCA), Correspondence Analysis (CA), Canonical Correspondence Analysis (CCA) and Detrended Correspondence Analysis (DCA) (ter Braak and Prentice, 1988; Leps and Šmilauer, 2003). However, these methods have been mainly used in vegetation ecology and the application of ordination methods in studies of soil PSDs should be further discussed.

Because studies of small scale soil patterning in arid regions are rare (Rubio and Escudero, 2000), a typical arid mountain region, the north slope of the Middle Kunlun Mountains, Xinjiang, China, was selected as the research area for this study. CCA ordination was primarily employed to analyze the variations in the characteristics of PSDs and the relationships between the PSDs and environmental factors. Thus, the objectives of this study were to discuss the application of the ordination method to soil PSDs while analyzing the small scale soil patterning in a typical arid mountain region based on the results of the ordination. In addition, fractal dimensions (single dimension), which have been shown to be effective parameters in previous studies of PSDs, were used to support the interpretation of the ordination results.

2. Materials and methods

2.1. Site description

The Kunlun Mountains are located at the northern fringe of the Qinghai–Tibetan Plateau. The northern slope of the mountains is positioned above the Tarim Basin, constituting the natural boundary between the two physiogeographic regions (Guo et al., 1997). The Middle Kunlun Mountains are positioned between 77°24′ and 84° E and are extremely arid. Forests are scarce and the number of plant species is low (Cui et al., 1988). In this region, we selected the Cele River Basin (35°17′–37°07′N, 80°03′–81°07″E) as the main study area because of its relatively high plant species richness and its broad distribution of alpine meadows (Cui et al., 1988).

In the Cele River Basin, the elevation varies between 1300 and 5500 m a.s.l. Oases are mainly distributed between 1300 and 1900 m a.s.l. with a typical arid continental climate—an average annual temperature of 11.9 °C and annual precipitation of less than 35 mm. The elevation range between 2000 m and 3600 m has an alpine climate with an average annual temperature of 3.6 °C. Above 3600 m in elevation the temperature decreases gradually with increasing altitude and the precipitation increases, reaching 350 mm at an altitude of 4000 m (Gui et al., 2009).

2.2. Sampling and treatment

Sampling along the Cele River Basin was carried out from July to September 2008. Along the elevation gradient of 1960–4070 m, the main range of the natural vegetation, a sequence of 21 sample plots were established, most joined plots were separated by about 100 m in altitude, with the longest altitude separation of joined plots being 247 m and the shortest being 49 m based on changes in vegetation. Three squares were established randomly in each plot. The square size was 10 × 10 m for shrubs, which occur mainly in the range from 1960 to 2800 m a.s.l., and 1 × 1 m for herbs (2900 to 4070 m). The cover, height, and individual number of shrubs, and the cover and height of herbs were measured in each square. Altogether, 67 plant species were recorded in 63 squares. Soil samples (0–20 cm) were collected in the center of each square. A small amount of soil was sealed hermetically in an aluminum box to determine soil water content. Soil material was also placed in zip-lock bags for the measurement of soil PSDs, pH value, organic matter, and total salt content. All measurements were done in a laboratory.

Soil water content (SW) was calculated after drying the soil samples at a temperature of 105 °C until the weight did not change. The other samples were air-dried and hand-sieved through a 2-mm sieve to remove roots, stones and debris, and then analysed by standard soil testing procedures (Editorial Committee, 1996) to measure soil organic matter (SOM), pH value, and total salt (TA).

The particle size distributions of the <2 mm particle fractions was determined using the laser detection technique on a Malvern Mastersizer 2000 (Tate et al., 2007). Soil samples were pretreated by destroying organic matter using H_2O_2 (30%, w/w) at 72 °C. The aggregates were then dispersed using sodium hexametaphosphate (NaHMP) and ultrasonics lasting for 30 s. In all soil samples, the soil

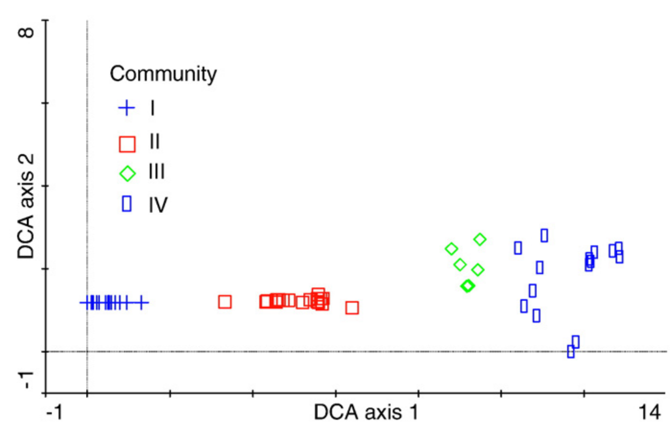

Fig. 1. Two-dimensional DCA ordination diagram of vegetation types (63 squares) along an altitudinal gradient on the north slope of the Middle Kunlun Mountains.

particle diameters were in the range of 0.29 to 1000 µm. The size interval was partitioned into 8, 16, 32, 64 subintervals by the Malvern built-in software, respectively, and PSDs were obtained representing relative volume (%) versus soil particle diameter.

2.3. Data analysis

In order to examine the relationship between PSDs and environmental factors, the canonical correspondence analysis (CCA) was used. CCA is a constrained unimodal ordination method that stresses patterns in relative abundance (Leps and Šmilauer, 2003), and has been widely used to analyze the relationships between plant distribution and environmental factors (ter Braak, 1986; da Silva and Batalha, 2008; Zuo et al., 2009). In particular, the ordination diagram of samples, species, and environmental variables derived from the CCA optimally displays the variation of the object composition in connection with the environmental factors (Zuo et al., 2009). In our analysis, CCA was performed with the particle-size fractions of soil samples as "species" variables, and elevation, vegetation coverage, SOM, pH, SW, TA as environmental variables. In order to clearly reflect the spatial variability of soil PSDs on the resolution of the CCA ordination diagram, the average values of each corresponding particle fraction content (%) in three soil samples of every plot were calculated to represent the information regarding PSDs for each plot, and the average values of environmental variables in every plot were also calculated correspondingly. Therefore, the analysis was carried out on the PSDs data matrix (21 records and 8, 16, 32, 64 "species", respectively) and coupled to the environmental data matrix (21 records and 6 variables). Significance of species–environment correlation was tested by the distribution-free Monte Carlo test (1,000 permutations; Jafari et al., 2004).

For support in explaining the ordination results, the fractal dimension of PSDs, D, was also estimated from the following equation (Tyler and Wheatcraft, 1992):

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

Assuming that densities of all particle fractions are the same, where V is the cumulative volume of particles of ith size r less than R_i, V_T is the total volume, R_i is the mean particle diameter (µm) of the ith size class, and the R_{max} is the mean diameter of the largest particle, respectively. The largest value for i was 64 (that is, the relative volume versus soil particle diameter along 64 subintervals was used to calculate the D value in our analysis). The D value of each soil sample in 21 plots was calculated independently, and the difference in D value between the plots was compared using multiple comparison and one-way analysis of variance (ANOVA) procedures. Results were checked by Tukey's test ($p<0.01$). The Pearson's correlation analysis was used to analyse the relationships between D and environmental variables and the contents of different particle fractions.

The plant communities were classified using the program WinTWINSPAN, version 2.3 (Hill and Šmilauer, 2005), and their distribution patterns in the study area were analysed by Detrended Correspondence Analysis (DCA), which is a general unconstrained ordination method for vegetation pattern analysis. The importance value of each species in each quadrat was used for the DCA analyses. The importance value was calculated using the ordinary formula: shrubs of community IV = (relative abundance + relative height + relative coverage) × 100/3, and herbs of community IV = (relative height + relative coverage) × 100/2 (Zhang et al., 2005a,b). Considering the effects of the dominant species and common species on communities, species whose frequency was less than 5% were removed and species whose frequency was equal or more than 5% were preserved (Leps and Šmilauer, 2003). The remaining species formed an important value matrix (63 quadrats and 49 species).

The ordination analyses (CCA, DCA) were performed using CANOCO 4.5 (ter Braak and Šmilauer, 2002), and the statistical analyses (ANOVA, Tukey's test) were calculated with SPSS (version 13.0).

3. Results

3.1. The spatial patterns of plant communities in the study area

Four plant communities were classified by WinTWINSPAN. Detailed information on each community is depicted in Table 1. The plant community distribution patterns were analysed using DCA. The eigenvalues of four DCA axes were 0.986, 0.334, 0.314 and 0.198, respectively. Fig. 1 shows the DCA ordination diagram based on the

Table 2
The relative volume (%) versus soil particle diameter (µm) along 16 subintervals in 21 plots.

Sample plots	Elevation (m)	PSDs															
		0.29–0.48	0.48–0.80	0.80–1.33	1.33–2.22	2.22–3.70	3.70–6.15	6.15–10.24	10.24–17.03	17.03–28.33	28.33–47.14	47.14–78.43	78.43–130.50	130.50–217.12	217.12–361.24	361.24–601.04	601.04–1000
		sp1	sp2	sp3	sp4	sp5	sp6	sp7	sp8	sp9	sp10	sp11	sp12	sp13	sp14	sp15	sp16
Plot 1	1960	0.07	0.46	0.50	0.52	0.64	1.03	2.24	2.83	3.11	12.65	30.05	28.62	9.50	2.49	4.80	0.51
Plot 2	2177	0.13	0.79	0.90	1.16	1.77	2.57	3.92	4.63	4.90	11.25	21.46	18.92	7.74	7.08	10.79	2.01
Plot 3	2269	0.26	1.01	1.21	1.65	2.42	3.20	4.18	4.48	4.58	9.05	16.07	15.07	8.97	9.73	12.60	5.53
Plot 4	2360	0.23	0.99	1.19	1.59	2.23	3.01	4.65	5.69	5.72	12.35	24.00	20.45	5.47	1.82	6.52	4.11
Plot 5	2467	0.12	0.75	0.92	1.36	2.12	2.83	3.92	4.42	3.78	7.68	16.95	17.14	8.51	8.04	12.85	8.30
Plot 6	2516	0.29	1.28	1.37	1.58	2.37	3.58	6.71	12.71	18.84	20.35	15.67	7.94	2.24	1.69	3.02	0.34
Plot 7	2714	0.09	0.60	0.66	0.74	0.99	1.57	2.97	4.21	6.34	16.18	29.51	25.81	8.50	0.64	1.19	0.00
Plot 8	2800	0.17	1.19	1.47	1.84	2.68	3.97	6.04	8.18	11.43	18.95	24.29	16.44	3.33	0.00	0.00	0.00
Plot 9	2900	0.24	1.05	1.19	1.28	1.66	2.40	3.77	5.36	9.50	20.11	27.82	18.70	4.17	0.70	2.03	0.00
Plot 10	3000	0.27	1.20	1.38	1.54	2.03	2.88	4.29	5.83	10.04	20.73	27.90	18.18	3.73	0.00	0.00	0.00
Plot 11	3100	0.15	0.97	1.09	1.15	1.54	2.34	3.69	5.39	10.39	21.54	27.84	17.56	3.73	0.81	1.79	0.00
Plot 12	3219	0.34	1.43	1.65	1.89	2.62	3.77	5.56	7.67	11.83	19.88	23.55	14.33	2.91	0.79	1.77	0.00
Plot 13	3304	0.28	1.27	1.45	1.62	2.26	3.42	5.35	7.86	12.66	21.03	24.26	14.68	3.64	0.23	0.00	0.00
Plot 14	3400	0.36	1.44	1.57	1.72	2.40	3.61	5.69	8.69	13.84	21.04	22.46	13.07	3.40	0.71	0.00	0.00
Plot 15	3500	0.27	1.26	1.47	1.66	2.34	3.53	5.48	8.30	13.60	21.26	22.95	13.49	3.58	0.81	0.01	0.00
Plot 16	3600	0.30	1.40	1.64	1.93	2.81	4.28	6.72	9.87	14.57	20.77	21.37	11.94	2.35	0.04	0.00	0.00
Plot 17	3700	0.20	1.43	1.68	1.90	2.69	4.05	6.33	9.38	14.21	20.83	22.07	12.81	2.42	0.00	0.00	0.00
Plot 18	3755	0.30	1.34	1.50	1.72	2.56	4.03	6.45	9.64	14.44	20.62	21.18	12.20	3.14	0.75	0.13	0.00
Plot 19	3925	0.32	1.44	1.67	1.96	2.83	4.25	6.55	9.53	14.06	20.22	21.26	12.58	3.09	0.24	0.00	0.00
Plot 20	4000	0.38	1.57	1.84	2.18	3.06	4.39	6.52	9.16	13.05	18.68	20.07	12.21	3.27	1.59	1.84	0.19
Plot 21	4074	0.33	1.53	1.88	2.35	3.37	4.77	6.96	9.62	13.20	18.05	18.99	11.75	3.70	1.88	1.50	0.13

first and second axis. It shows that each association group appears within a limited range and has a clear borderline against other communities. The plant communities change along with the altitude. This indicates that elevation is the main factor that influences vegetation distribution in arid mountain regions. Moreover, vegetation coverage and species richness are also increasing along the altitudinal gradient in our investigation.

3.2. Relationship between PSDs and environmental factors

The CCA was used to analyse the relationship between PSDs and environmental factors based on the PSDs data matrix and an environmental data matrix. Since the size interval was partitioned into 8, 16, 32, 64 subintervals, we first compared the ordination results from calculations with differing particle fractions (8, 16, 32, 64 fractions). The results indicated no difference between 16, 32 and 64 particle fractions as "species" data. Thus, 16 particle fractions sufficiently characterize the PSDs in the CCA analysis. Therefore, the relative volume versus soil particle diameter along 16 subintervals was used (Table 2).

The connection between PSDs of the sample plots and the measured environmental factors in the study area as revealed by CCA is shown in Table 3. The "species"–environmental correlations are higher for the first two canonical axes, explaining 95.3% of the total cumulative variance. These results indicate a strong connection between PSDs and the measured environmental factors presented in the CCA biplots. A Monte-Carlo permutation test indicated a strong collinearity of SOM and vegetation coverage in their dependence on altitude. Therefore, both factors were dropped. The test indicated also that all canonical axes were significant ($p<0.005$). From the intra-set correlations of the environmental factors with the axes of the CCA shown in Table 3 it can be inferred that the selected environmental factors were mainly correlated with the first axis, and that the absolute value of the correlation coefficient of altitude and the first axis is highest. This fact becomes clearer in the CCA ordination biplots (Figs. 2 and 3).

Fig. 2 depicts the particle fraction scores (Table 2) and canonical coefficient scores of the environmental variables from the CCA ordination. The variables are represented by arrows pointing in the direction of maximum variation, with their length proportional to the rate of change (ter Braak, 1986). Each arrow determines an axis on which the particle fraction points can be projected. Generally, these projected points estimate the optimum particle fractions distribution for each environmental variable. Fig. 2 shows that the soil fine fractions were mainly concentrated at high altitude together with higher pH and soil water content, and that the soil coarse fractions were mainly concentrated at low altitude with higher total salt content.

Fig. 3 shows the CCA ordination biplots of 21 sample plots for the first two axes. The 21 sample plots were classified into three groups

Table 3
Intra-set correlations of the environmental variables, eigenvalue, and cumulative percentage variance and "species"–environment correlation coefficients for the first four axes of CCA.

	Axis			
	SPX1	SPX2	SPX3	SPX4
Altitude (ASL)	−0.7253[b]	−0.2202	0.1187	0
Total salt (TA)	0.7173[b]	0.1206	0.2576	0
pH	−0.5667[b]	0.2839	−0.3829[a]	0
Soil water content (SW)	−0.4542[a]	−0.2845	0.3682	0
Eigenvalue	0.104	0.019	0.002	0
"Species"–environment correlation	0.783	0.65	0.74	0.15
Cumulative percentage variance (%)	83.3	95.3	98.1	98.7

[a] Correlation significant at the 0.05 level (2-tailed).
[b] Correlation significant at the 0.01 level (2-tailed).

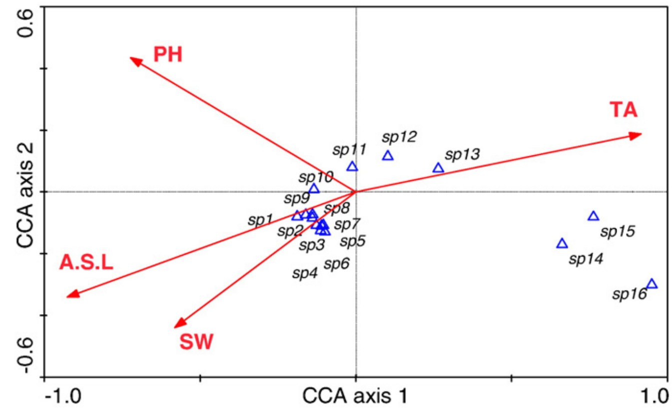

Fig. 2. CCA ordination diagram of the first two axes showing the distribution of the 16 particle fractions and environmental variables (for complete listings of variables, see Tables 2 and 3).

based on characteristics of PSDs. Group I is distributed in the lower altitudinal range, together with high total salt content. Groups II and III are distributed in the higher altitudinal range, together with high pH and high soil water content. The groups do not overlap, indicating clear differences in PSDs and the environmental gradients between them. The plots are aggregated in each group, which shows that these plots are very similar with respect not only to the PSDs but also to the environmental gradients. In combination with Fig. 2, the dominating particle fractions in the PSDs can be identified. As an example, in the group of plots 1 to 8 the soil coarse fractions are dominating.

A comparison of Figs. 3 and 1 shows correspondence between soils and plant communities with regard to spatial patterns: Group I of the soil samples (includes plots 1to 8) corresponds to plant community I (1960 to 2800 m a.s.l.); group II (plots 9 to 14) corresponds to plant community II (2900 to 3400 m a.s.l.), and group III (plots 15 to 21) corresponds to plant communities III and IV (3500 to 4070 m a.s.l.). PSDs and plant communities are apparently connected with each other.

3.3. Fractal dimension of PSDs

Table 4 contains fractal dimensions of PSDs found when Eq. (1) was applied to each soil data set. The average fractal dimensions of the sample plots changed in the range of 2.081 to 2.376. And correlation analysis of all D values and the volume contents of the clay, silt, and sand revealed that a significant positive correlations were found between the D value and the contents of clay and silt ($r=0.913$, $p<0.01$; and $r=0.332$, $p<0.01$, respectively), a significant negative

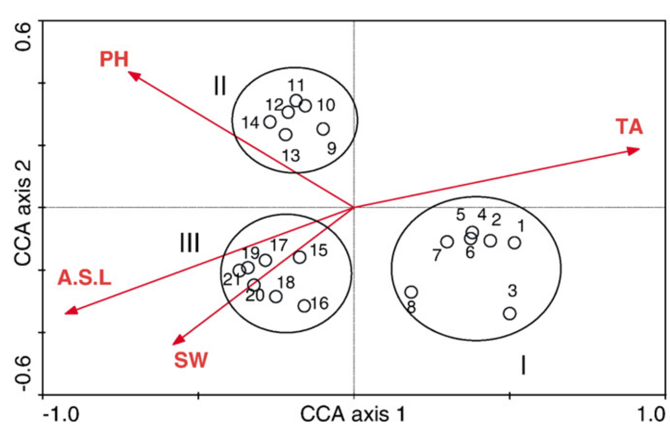

Fig. 3. CCA two-dimensional ordination diagram of the first two axes showing the distribution of 21 plots and environmental variables.

Table 4
Contents of clay, silt and sand and fractal dimension of PSDs in the sample plots.

Sample plots	Elevation (m)	Clay, <2 μm (%)	Silt, 2–50 μm (%)	Sand, 50–1000 μm (%)	Fractal dimension *D*
Plot 1	1960	1.619 ± 0.190	30.785 ± 5.347	67.596 ± 5.537	2.109 ± 0.031 cd
Plot 2	2177	3.548 ± 1.322	30.207 ± 7.415	66.245 ± 8.455	2.247 ± 0.041 ab
Plot 3	2269	4.344 ± 1.009	27.033 ± 3.097	68.623 ± 3.347	2.305 ± 0.045 a
Plot 4	2360	3.700 ± 0.611	30.465 ± 5.646	65.835 ± 5.866	2.259 ± 0.031 ab
Plot 5	2467	6.708 ± 3.389	35.122 ± 8.734	58.170 ± 11.344	2.325 ± 0.082 a
Plot 6	2516	2.393 ± 1.525	43.600 ± 10.903	54.007 ± 22.416	2.147 ± 0.082 bcd
Plot 7	2714	1.574 ± 0.448	29.499 ± 7.621	68.927 ± 8.069	2.105 ± 0.019 d
Plot 8	2800	3.227 ± 0.937	51.022 ± 3.283	45.752 ± 4.218	2.200 ± 0.051 abcd
Plot 9	2900	3.151 ± 0.278	44.419 ± 1.932	52.431 ± 2.139	2.199 ± 0.012 abcd
Plot 10	3000	4.060 ± 0.348	50.492 ± 3.435	45.448 ± 3.771	2.236 ± 0.014 ab
Plot 11	3100	3.142 ± 0.130	47.846 ± 0.637	49.012 ± 0.527	2.206 ± 0.008 abcd
Plot 12	3219	4.055 ± 0.759	54.468 ± 1.505	41.478 ± 1.945	2.234 ± 0.035 abc
Plot 13	3304	3.629 ± 0.551	54.859 ± 0.995	41.512 ± 1.532	2.221 ± 0.016 abcd
Plot 14	3400	4.070 ± 0.597	56.426 ± 1.906	39.503 ± 2.502	2.240 ± 0.028 ab
Plot 15	3500	4.098 ± 0.265	57.214 ± 0.684	38.688 ± 0.645	2.237 ± 0.001 ab
Plot 16	3600	4.432 ± 0.386	60.673 ± 1.689	34.896 ± 2.069	2.249 ± 0.009 ab
Plot 17	3700	4.487 ± 0.334	60.612 ± 0.306	34.901 ± 0.267	2.256 ± 0.010 ab
Plot 18	3755	4.348 ± 0.107	59.874 ± 0.951	35.778 ± 0.989	2.243 ± 0.009 ab
Plot 19	3925	4.611 ± 0.404	60.753 ± 0.303	34.636 ± 0.508	2.258 ± 0.007 ab
Plot 20	4000	4.864 ± 0.637	54.299 ± 3.062	40.837 ± 3.638	2.269 ± 0.028 ab
Plot 21	4074	4.680 ± 0.743	56.138 ± 2.836	39.182 ± 3.396	2.254 ± 0.026 ab

Values with different letters within the column of *D* values are significantly different at $p<0.01$.

correlation with the content of sand ($r=-0.411$, $p<0.01$). Moreover, the determination coefficients, R^2, of the linear regressions (from Eq. (1)) were high and ranged from 0.84 and 0.96, with most being greater than 0.9. This indicates that the fractal model of the accumulative volume-size distribution is appropriate.

The differences of fractal dimensions between sample plots at different elevations were significant as revealed by ANOVA. Tukey's test ($p<0.01$) showed that significant differences occurred mainly in individual plots that were located in the low altitudinal range, such as plots 1, 6, and 7 (Table 4). However, the fractal dimensions between many plots were not significant. The fractal dimensions were especially similar in the range between 2800 and 4070 m a.s.l. and did not reflect the corresponding relation between PSDs of sample plots and plant communities.

Table 5 shown the ranges of vegetation cover, SOM, SW, pH and TA, and their correlations with *D* values using Pearson's correlation anlysis. It indicated significant positive correlations between *D* and vegetation and SOM at 0.05 level, and a significant negative correlation with the TA at 0.01 level. These results are similar with the results of the ordination analysis. However, no correlation was noted between *D* and pH or SW at 0.05 level, but we can see a moderate correlation between *D* and SW (0.098 significance level).

Although the fractal dimension can effectively depict the variation of clay, silt, and sand content, it does not provide detailed information about each particle fraction. In the correlation analysis, no matter whether 8, 16, 32, or 64 particle fractions were considered, there was no correlation between *D* and content of the individual particle fractions. Thus, ordination can obtain more detailed information about PSDs than the calculation of fractal dimensions. Moreover, ordination is superior in establishing correlations between contents of particle fractions and environmental variables. PH or soil water content, for example, was not correlated with D, but CCA ordination indicated that the contents of some particle fractions were correlated with these variables (Fig. 2).

4. Discussion

Characterization of soil particle-size distributions requires the use of mathematical tools such as fractal geometry capable of quantifying the internal structure of such measures (Montero, 2005). Ordination methods, which are considered robust quantitative analysis techniques, are effectively used to analyse entities, their attributes and their correlation with environmental variables (Greenacre, 1993; Giraudel and Lek, 2001). Although ordination methods have been widely used for various research purposes, they have not been used, previously, for investigations into PSDs.

In this study, the volume content of each particle fraction formed the PSDs data matrix, coupled to environmental factors, for a CCA ordination analysis. Theoretically, the more particle-size classes that are used, the more information that should be obtained. However, the results of our comparative analysis indicated that in our case a data set comprising 16 particle-size classes is sufficient to characterize the PSDs.

In all environmental variables collected in our study, the elevation plays the most important role in plant communities and PSD differences. This may be because elevation has an important effect on the amount of precipitation, relative humidity and temperature (Huston, 1994; He et al., 2007), which in turn impacts the local communities and PSDs.

It has long been accepted that interactive soil–plant relationships induce spatial patterning in soil properties, and that individual plant performance and even plant communities may respond to soil heterogeneity (Jackson et al., 1990). It is also known that soil heterogeneity is a basic element for competitive and/or facilitative interactions between plants (Chapin et al., 1994), and consequently may determine patterns in plant and community distribution (Rubio and Escudero, 2000). Our ordination results show a good correspondence between soil and vegetation patterns. This indicates a tight link between soil PSDs and plant communities on a small scale in arid

Table 5
The range of vegetation coverage, SOM, SW, pH and TA, and their correlation with *D* values.

	Vegetation coverage (%)	Soil organic matter (SOM, g/kg)	Soil water content (SW,%)	pH	Total salt (TA, g/kg)
Range	0.04–73	1.205–24.503	3.46–44.22	7.27–8.55	0.38–25.73
Pearson's correlation with *D*	0.255	0.277	0.211	0.052	−0.421
Sig. (2-tailed)	0.04	0.028	0.098	0.687	0.01

regions. Sala et al. (1997) hypothesize that soil PSDs plays a significant role in regulating vegetation pattern, including vegetation composition, functional groups, and structure since PSDs control the dynamics of soil organic matter in many simulation models of organic matter decomposition and formation (Raich et al., 1991) and influence infiltration, moisture retention and the availability of water and nutrients to plants (Sperry and Hacke, 2002). However, it is noteworthy, that soil group III corresponds to plant communities III and IV (3500 to 4070 m a.s.l). Possibly, the effects of PSDs on plant communities decrease with increasing elevation and other environmental factors, such as temperature exert a more decisive effect on communities (Huang et al., 2007).

Fractal theory has been widely applied to soil science and has been proven to be effective in characterizing particle-size distribution, pore-size distribution, and aggregate-size distribution (Su, et al., 2004), and fractal dimensions of soil PSDs has significant correlations with contents of clay, silt and sand.(Wang et al., 2007, 2008). In our study, the single fractal dimension was calculated and used to compare and verify the ordination results. Our results indicate that the *D* value of PSDs is highly significantly correlated with the clay, silt, and sand contents, and the *D* values were lower than that observed in semi-arid areas of China (Wang et al., 2007). These findings indicate that the clay and silt contents were present in lower levels, while the sand contents were higher in the study area than in semi-arid regions of China.

The *D* values is significantly correlated with SOM, vegetation coverage, and total salt content at 0.05 level. The clay contents and the altitudinal gradient are linear correlated ($R^2 = 0.18$) and silt and altitudinal gradient gave a better linear correlation ($R^2 = 0.80$) (Table 4). These results are similar to the CCA ordination results, but compared to the ordination method, the fractal dimension does not give comparably detailed information about PSDs. In other words, *D* does not reflect changes of the individual particle-size classes and does not point to correlations with some environmental factors (e.g. soil water content or pH). Moreover, the fractal dimension does not reveal differences in PSDs between different communities according to ANOVA and multiple-comparison tests. However, in spite of these limitations, we still suggest that the fractal dimension should be used in the process of ordination analysis, since it can simply depict the main information regarding PSDs and can help to explain the ordination results.

On a scale as small as that used in the present study, based on principle of ordination calculation, CCA ordination can effectively reveal the variation characteristics of PSDs and the relationships between PSDs and environmental factors. Therefore, we conclude that ordination methods are well suited for studies of PSDs, and that these methods used in combination with fractal measures can provide comprehensive information regarding PSDs.

Acknowledgements

This project was supported by the National Basic Research Program of China (973 program: 2009CB421302), as well as the National Science and Technology Supporting Program of China (2009BAC54B01, 2006BAD26B0202-1) and program numbers 200633130, 200733144-2 and PT0801. Additionally, the authors are very grateful to the anonymous reviewers for their valuable comments.

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