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# Characterizing variations in soil particle size distribution in oasis farmlands—A case study of the Cele Oasis

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ABSTRACT

Characterizing soil particle size distributions (PSD) and their variation is an important issue in environmental research. In this study, fractal theory was used to analyse the soil PSD and its variations in the Cele Oasis, which is located at the southern margin of the Tarim Basin. The characteristics of the soil PSD were then evaluated to identify the primary factors that influence soil PSD. The results showed that the fractal dimension (*D*) values ranged from 2.11 to 2.27, and that there were significant differences among groups. Furthermore, the *D* values showed a significant positive correlation with fine particles (<50 μm) and soil organic matter contents. According to a comparative analysis of *D* values, the utilization years of farmlands had a significant influence on PSD, while the difference in the spatial distribution of farmlands did not. These results indicated that long-term and effective tillage management of the farmlands will be beneficial to keeping and improving the states of the soil PSD and other soil properties.



## 0. Introduction

Soil particle size distribution (PSD) is one of the most fundamental physical attributes due to its great influence on other soil properties related to water movement, productivity, and soil erosion [1–3]. Accordingly, characterizing variations in the PSDs of soils is an important issue in environmental research [4].

Latest developments in the study of PSDs have focused on the use of fractal geometry [5–7]. Many single fractal or multifractal measures were used to characterize the PSDs based on obtaining more data of particle fractions [3,8]. The common feature of fractal measures is to find a way to characterize PSDs with parameters (i.e. fractal dimensions, *D*) that retain most information. Then the parameters were used to compare differences in the PSDs of soil samples.

Currently, the soil PSD characteristics and their variations with respect to different land use types are commonly investigated. For example, Wang et al. [9] evaluated the soil PSD characteristics under different land use types in the Loess Plateau using the fractal theory, Similarly, Hu et al. [10] evaluated the soil PSD characteristics under different land use types in Inner Mongolia. The results of these studies revealed that soil PSD obviously differed among land use types and demonstrated that the land use types and changes in land cover were the primary factors responsible for variations in the soil PSD.

However, studies conducted to evaluate soil PSD characteristics and their variations under the same land use types in oases in arid areas are limited. As the azonal landscapes on the moderate and small scales under the arid climatic background,

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oases are mostly distributed in piedmonts, where the terrain is generally smooth and simple [11]. Many studies have shown that the oases in Xinjiang have expanded gradually into oasis–desert ecotones over the last 50 years due to population growth and economic pressure [12]. In the process of oasis growth, farmland is still the dominant land use type. Therefore, in this paper, the soil PSD in farmland in an oasis was characterized and then investigated to determine what the primary factors influencing these characteristics were. To elucidate these factors, it is necessary to have a deep understanding of the laws responsible for changes in the PSD properties and other interrelated properties of soils in oases. The soil organic matter content (SOM), as the best surrogate for soil quality influenced by land use [13,14], was selected to be contrasted with fractal parameters.

The oases located on the southern rim of the Taklamakan Desert are extremely arid and frequently subjected to sandstorms [11]. In this study, the Cele Oasis in the Taklamakan Desert was evaluated. The specific objectives of this study were: (1) to characterize the soil PSD in farmland in the oasis using fractal theory; (2) to identify the primary factors responsible for variations in the farmland soil PSD according to the fractal dimension value of the PSD.

## 1. Materials and methods

### 1.1. The study area

The Cele Oasis (35°17′55″–39°30′00″ N, 80°03′24″ E–82°10′34″ E) is located in the central part of the southern marginal zone of the Taklimakan Desert and the northern piedmont of the Kunlun Mountains. The area is characterized by a typical continental arid climate, with an annual precipitation of only 35.1 mm; however, the annual evaporation is as high as 2595.3 mm, and the aridity is 20.8. The diurnal–nocturnal difference in air temperature is high, with an annual range in temperature of greater than 15 °C. Additionally, the study area is perennially windy, with a prevailing wind direction of NW. The Cele River, which originates in the Kunlun Mountains, is the main river in the Cele Oasis. The average annual runoff volume in the oasis is $1.27 \times 10^8$ m$^3$. The oasis is surrounded by natural vegetation in its eastern and western parts, while its southern part connects with mobile dunes and the Gobi desert. The Cele Oasis is a typical desert–oasis ecosystem that is dominated by aeolian soil [11].

### 1.2. Sampling and treatment

The soil samples (0–20 cm) were collected at random from a total of 35 sampling sites throughout the oasis in September 2008. The distance between adjacent sampling sites never exceeded 2 km, and the farmland use situation was surveyed while sampling. Three replicates of each soil sample were collected, which resulted in a total of 105 soil samples being obtained. The soil samples were transported to the laboratory, where they were dried in the shade and then passed through a 2-mm-mesh sieve, after which the stems were removed.

### 1.3. Calculation of the D values based on the volume distribution of the soil particle size

The equation used to determine the mass fractal dimension value ($D_m$) of soil PSD that was developed by Tyler and Wheatcraft [15] has been widely used in agrology. Many studies have demonstrated that $D_m$ values can be used to reveal the structure, property, fertility and degree of degradation of soil [16]. Actually, Tyler and Wheatcraft put forward the volume fractal dimension value ($D_v$) of soil PSD first, but it was difficult to accurately derive the PSD information regarding the particle volume due to limitations associated with the analysis methods available at that time; therefore, they assumed that the density of the same soil particles was the same. However, this assumption is obviously not ideal given the actual situation of soil [17]. Because laser diffraction (LD) technology can be used to obtain the volume information regarding soil PSD in more particle fractions and independently of the soil particle mass, it is ideal for use in studies conducted to evaluate PSD and has therefore been widely used in such studies [3,9,18]. Accordingly, Tyler and Wheatcraft's method [15] was used in the PSD fractal in this study. The equation is expressed as

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

where $r$ is the 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 of the soil particles, $R_{\max}$ is the maximum diameter of the soil particles, and $D$ is the fractal dimension value. According to the equation above, the logarithms are taken for both sides of the equation and the $D$ values of all of the soil samples can be derived based on the slopes of the logarithmic curves that are fit to the data.

### 1.4. Laser diffraction analysis

The soil samples were pretreated with $H_2O_2$ (30%, w/w) at 72 °C to destroy the organic matter. The aggregates were then dispersed by adding sodium hexametaphosphate (NaHMP) and sonicating the samples for 30 s, after which they were analyzed by a laser diffraction technique using a Longbench Mastersizer 2000 (Malvern Instruments, Malvern, England).

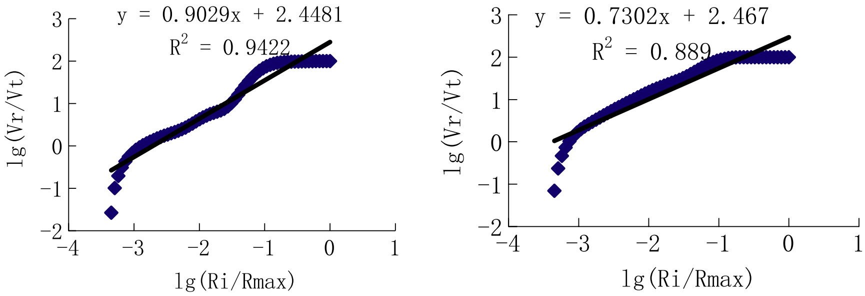


**Fig. 1.** Log–log plots of soil PSD used to calculate the lowest and highest *D* value.

The laser particle analyzer, which can be used to measure PSD values within a range of 0–20 000 μm, gives the continuous volume percentage of particle size during analysis. However, the PSD values in the present study were all found to be in the range of 0.35–1000 μm; therefore, the soil particle sizes in this range were graded into 64 fractions using the software provided with the laser particle analyzer [9].

Soil organic matter was determined by oil bath—$K_2CrO_7$ titration method [19].

### 1.5. Data analysis

The measured distribution data and particle size volumes of all soil samples were imported into EXCEL to calculate the *D* values.The difference in *D* value between the farmlands was compared using the 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 contents of different particle fractions and SOM contents. The *K*-mean quick clustering method was used to find the critical *D* value. All statistical analyses were conducted using the SPSS software (13.0 version).

## 2. Results and discussion

### 2.1. The fractal dimension characteristics of soil PSD

Eq. (1) is used to calculate the *D* values of the soil particle sizes and the *D* values of each of the sampling sites were found to range from 2.11 to 2.27, and ANOVA revealed that the *D* values of farmland soil in the oasis differed significantly (sig = 0). Additionally, the *D* values observed in the oasis were significantly lower than the values observed in other regions [20]. The log–log graph of the minimum and maximum *D* values of soil samples is shown in Fig. 1.

The log–log scatter diagram was used to derive *D* values through the slope of the straight line that best fit the data. Because a single fractal is used, the entire soil PSD extent cannot be contained [21]. Indeed, as shown in Fig. 1, the two ends of the scatter diagram bend downward in the entire scale interval of PSD. Nevertheless, the fitting result was ideal because the primary change occurred close to the straight line of the scatter diagram, and the $R^2$ values were all greater than 0.9.

Correlation analysis of the *D* values and the volume contents of different particle size fractions revealed that there was a significant positive correlation between the volume percentage of the particle size within 50 μm and the *D* value, with a correlation coefficient of 0.68. However, the correlations between the volume percentages of the particle sizes within the 5, 10 and 20 μm fractions and the *D* values were found to be stronger, as indicated by correlation coefficients of 0.824, 0.812 and 0.791, respectively. Furthermore, a significant negative correlation between the volume percentage of the particle size larger than 50 μm and the *D* value was observed, as indicated by a correlation coefficient of −0.75. All correlation analyses passed a two-tailed test when evaluated at $p < 0.01$. These findings demonstrate that the PSD-based volume fractal dimension value (*D*) can be used to reflect the soil PSD characteristics well, and that the higher the *D* value is, the higher the content of soil fine particles will be. Figs. 2 and 3 show the relationship between the change of *D* values and the volume percentage compositions of soil particles <10 μm and >50 μm.

### 2.2. Relationship between the D value of soil PSD and the SOM content

After conducting a typical correlation analysis between the SOM contents in soil samples and the *D* values, a significant positive correlation between SOM and *D* values was observed (Fig. 4). Specifically, the correlation coefficient was 0.65 ($p < 0.01$). This positive correlation can be explained by the because finer soil particles assisted binding of soil organic matter (SOM) and nutrients [22,23]. Soil organic matter content is one of the most important indexes in soil quality assessment [24], and the correlation between the *D* values and SOM of soil shows that the *D* values of soil can be used to objectively identify the changes in soil particle sizes, as well as to reflect changes in the soil quality of farmland.

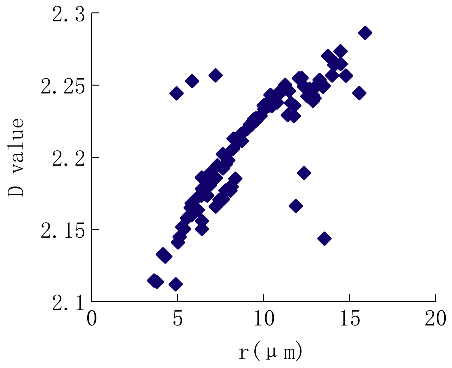


**Fig. 2.** The correlation between $D$ value and soil particle volume ($r < 10$ μm).

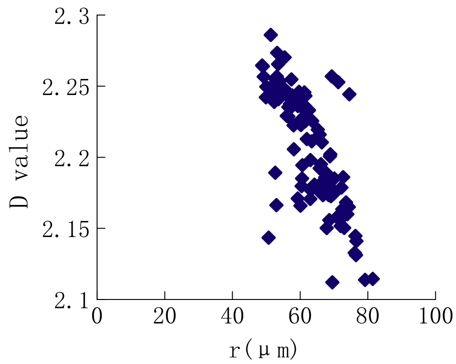


**Fig. 3.** The correlation between $D$ value and soil particle volume ($r > 50$ μm).

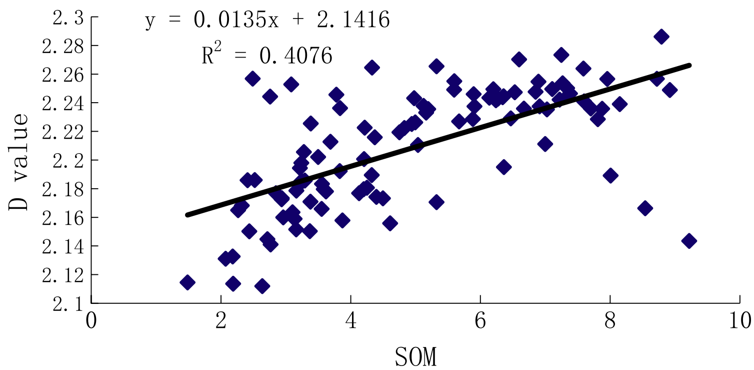


**Fig. 4.** The correlation between $D$ value and SOM.

### *2.3. Characterization of the variation in PSD and evaluation of the affecting factors*

The 35 sampling sites in the oasis were ordinally ranked according to $D$ value (Fig. 5), and the $D$ differencebetween sites was then compared based on ANOVA procedures and LSD multiple comparisons.

Based on evaluation of the farmland use, no obvious differences were observed in the long-term cultivation and tillage management, but the utilization years and distribution locations of the farmland did differ. The farmland in the central (or near central) area of the oasis has been in use for longer periods of time (more than 100 years) than the farmland in the marginal zone of the oasis (less than 30 years) due to differences in the oasis development process.

According to the change of the $D$ values at all the sampling sites, it is found that farmland cultivated for more than 100 years were significantly higher than those of farmland cultivated for less than 30 years. However, there was no significant difference in $D$ values among farmlands cultivated for more than 100 years. Similarly, there was no significant difference in the $D$ values among farmlands that have been cultivated for 30 years. Therefore, the $D$ values were classified into two groups using the $K$-mean quick clustering method to further research the relationship between the change in $D$

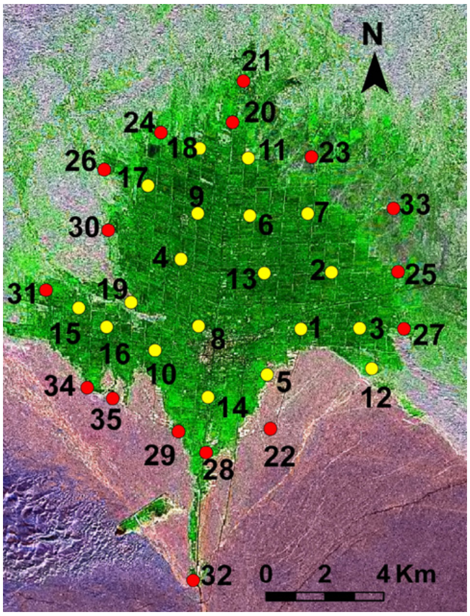


**Fig. 5.** The order of *D* values at sampling sites and the results of the cluster analysis of the *D* values. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

values and the farmland status. The results of the clustering analyses revealed that *D* values $>2.21$ were observed in the first group (20 sampling sites in all), while those $<2.21$ were observed for the second group (15 sampling sites in all).

Based on the classified results, the *D* values of different farmlands are shown in Fig. 5. The red points in the figure indicate *D* values $<2.21$, while the black points indicate *D* values $>2.21$. The figure reveals that the sampling sites with the *D* values $<2.21$ were all distributed in the marginal zone of the oasis, while sampling sites with *D* values $>2.21$ are distributed in the center or near center of the oasis.

The vegetation coverage in the study area differed due to the different spatial locations of farmlands. Furthermore, the response of farmlands to wind erosion also differed because the farmlands were located in areas that were subjected to different perennial prevailing wind [10,11]. Sampling sites 1–18 were all located in farmland that has been cultivated for more than 100 years. This type of farmland covers most of the oasis, and among these sites, sampling sites 15–18 were located in a region close to the marginal zone of the oasis; however, the variance analysis revealed that there were no significant differences in the *D* values among these sites. Sample site 20 was located in an area near the marginal zone of the oasis and windward of the perennial prevailing wind; however, it has been cultivated for more than 30 years. ANOVA revealed that there was no significant difference in the *D* values between sample site 20 and other sampling sites cultivated for over 100 years. Taken together, these findings indicate that there is a trend of homogeneity in soil PSD properties in farmland under long-term cultivation.

Based on the results shown in Fig. 5, some farmlands in the marginal zone of the oasis are located in windward areas, while some are located in leeward areas with respect to the perennial prevailing wind. Additionally, there is a great deal of variation in the vegetation coverage. However, no significant differences in the *D* values were observed between sampling sites. Therefore, it is difficult to reveal the effects of variation in the location of farmland on PSD. Nevertheless, a common characteristic of farmland in the study area is that they have relatively short and similar utilization years. These results further indicate that utilization years were the primary factor influencing the soil PSD in the study area. Correlation analysis revealed a significant positive correlation between the *D* value and the farmland cultivation time, with correlation coefficients as high as 0.85 being observed ($p < 0.01$).

Although the spatial location of farmland had no regular effect on soil PSD in general, the change in *D* values revealed that farmland located in the upstream portion of the oasis near the Gobi desert had an obvious influence on soil PSD. The farmlands located on the leeward portion of the perennially prevailing wind had significantly higher *D* values than farmlands located on the windward farmlands with similar utilization years. For example, the *D* values of sampling sites 29, 34 and 35 were significantly lower than the *D* values of sampling sites 29 and 32.

## 3. Conclusions

Farmland in oases represents an important land use type in extremely arid areas. Accordingly it is important to gain a deep understanding of the changes in soil properties that occur in such areas as well as to develop management strategies for farmland oases in arid areas. To accomplish this, it is important to research the soil PSD characteristics and their variations.

The farmland soil PSD characteristics in the Cele Oasis were evaluated using fractal theory and the results revealed that the volume fractal dimension values of soil could be use to determine the soil PSD characteristics. Additionally, the findings presented in this study indicated that there is a significant positive correlation between the *D* value of soil and the content of soil fine particles, as well as a significant positive correlation between the *D* value and the soil organic matter content. In general, the *D* values of farmland soil in the study area were low, which indicates that the soil texture is poor.

Analysis of the PSD-based volume fractal dimension value of farmland indicated that there is a significant difference in *D* values within the study area. These findings indicate that there is a difference between the soil PSD characteristics in farmland oases.

According to the change in *D* values and the results of *K*-mean quick clustering, 2.21 is the critical *D* value. Farmland cultivation time was found to have an important impact on the soil PSD. Specifically, farmland cultivated for more than 30 years was found to have a more stable PSD, and lands characterized by long-term cultivation and tending were found to have a more heterogeneous PSD. Conversely, the spatial location of farmland had no regular effect on the soil PSD in general, except in areas of the oasis near the Gobi desert.

Taken together, the findings presented here indicate that long-term and rational cultivation patterns and tillage management in oases will be beneficial to the maintenance of the stability of soil PSD, as well as to the maintenance and improvement of other soil properties (such as SOM).

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