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Original Research Paper

Effects of Sand-fixing Vegetation on Topsoil Properties in the Mu Us Desert, Northwest China

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ABSTRACT

Planting vegetation to restore the soil environment is one of the most important methods for combating desertification. Reasonable vegetation type and vegetation coverage has an important role in sand control and the regional ecological security. The objective of this study is to clarify the appropriate type and coverage of sand-fixing vegetation in the Mu Us Desert. We identified changes in the topsoil properties as affected by different types and coverage of sand-fixing vegetation, and assessed the relationship between the soil fractal dimension (*D*) and major soil properties. Our results showed that: (1) with increasing cover of sand-fixing vegetation, fine soil material and soil nutrient content increased, indicating that the soil environment could accelerate restoration after planting or recovery of sand-fixing vegetation; (2) there were significant positive relationships between *D* and soil properties, which indicated that *D* was a sensitive and useful index for evaluating the influence of sand-fixing vegetation on soil physicochemical properties; and (3) recovery of natural vegetation using fencing should be given priority in areas where the soil matrix is not completely destroyed, and plant cover should be maintained at approximately 40% to 60%. We suggest that native shrubs, rather than trees, should be considered when choosing a sand-fixing vegetation.

INTRODUCTION

Planting vegetation to restore the soil environment is a key method for combating desertification (Cao et al. 2011, Le Houérou 2000). Sand-fixing plants, when selected and managed appropriately, can effectively control the expansion of desertification, mitigate soil erosion and sand burial by wind, and promote habitat restoration on small scales (State Forestry Administration 2011). However, large-scale afforestation or reforestation with a single species of shrub or tree is an unsustainable method for controlling desertification because of low soil moisture, groundwater depletion, and degeneration of sand-fixing vegetation (Li et al. 2013). Water availability is the primary factor that limits vegetation restoration in semi-arid areas of China (Cao et al. 2011, Li et al. 2013). An appropriate vegetation cover is not only controlled by the water carrying capacity of the soil (Li et al. 2014), but also can influence the nutrient conditions of the soil. It can also provide certain ecological benefits such as reducing wind erosion. Studies of climate change indicate that warming and drought will seriously affect the arid and semi-arid regions of China in mid-latitude zones (Ji et al. 2014). Therefore, it is important to determine the most appropriate arrangement of plant species and planting density, and to understand how to maintain the stability of restored vegetation, in order to control desertification.

Different types of vegetation restoration can lead to changes in the characteristics of soil which can reflect the effects of recovery efforts (Filgueira et al. 1999). Most studies select a subset of soil characteristics (e.g., soil organic carbon, nutrients, and moisture) when assessing the effects of different types of sand-fixing vegetation on soil conditions (Caravaca et al. 2002). Relevant indicators and methods that can be used to quantify the relationship between soil properties and the type of vegetation used for soil restoration are lacking. The particle size distribution (PSD) of soil is one of the most important indicators of soil physical properties. PSD reflects the soil characteristics such as structure (Díaz-Zorita et al. 2002), water holding capacity, fertility and the degradation processes occurring in soils (Fu et al. 2012). Fractal theory has been applied to soil studies in an attempt to better understand the relationship between soil structure and PSD (Perfect & Kay 1991). Studies incorporating fractal theory have examined ways to improve calculations for measuring fractal dimensions (Tyler & Wheatcraft 1989), the nature of the fractal dimensions themselves (Gui et al. 2010), the response of fractal dimensions

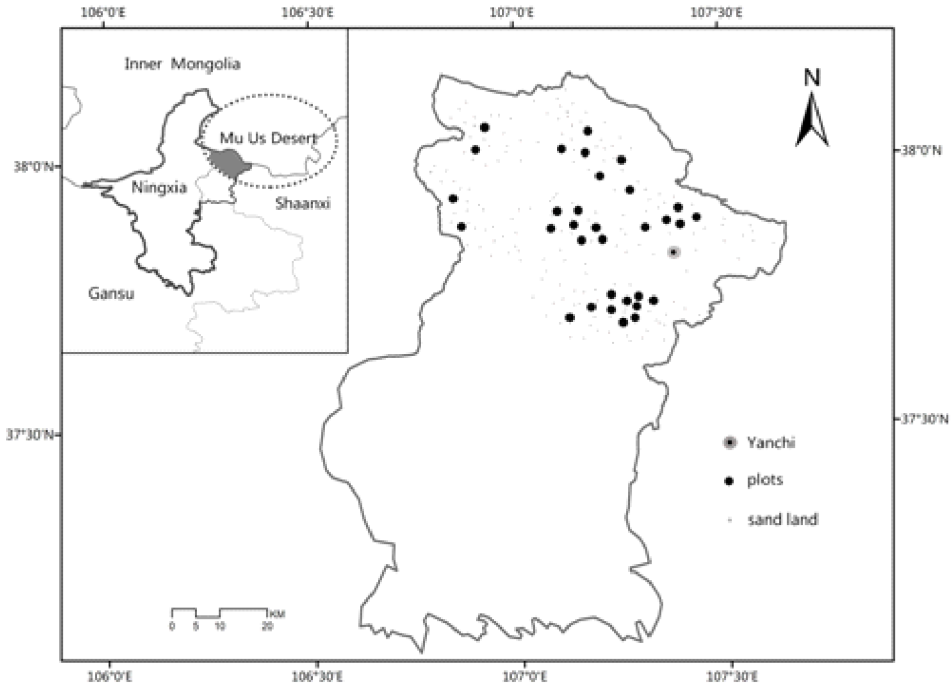

Fig. 1: Map of the distribution of sampling plots.

to plant restoration and land management activities (Filgueira et al. 1999), the relationship between fractal dimensions and the content of the fine-grained material in soil (Millan et al. 2003) and the relationship between fractal dimensions and soil nutrients (Gao et al. 2014). However, few studies have examined the relationship between fractal dimensions and soil physicochemical properties as influenced by different types of sand-fixing vegetation. Further study is needed to determine whether fractal dimensions can effectively represent the effects of soil improvement in relation to sand-fixing vegetation communities.

The objectives of the study are to: (1) analyse changes in PSD, soil nutrients, and fractal dimensions of soil under different types and coverage of sand-fixing vegetation; (2) determine whether the fractal dimensions can effectively characterize soil properties, and (3) determine suitable vegetation types and coverage for sustainably establishing and managing sand-fixing vegetation in a semi-arid desert.

MATERIALS AND METHODS

Study sites: The study area is located in northern Yanchi County on the southern edge of the Mu Us Desert (37°04'-38°10' N, 106°30'-107°41' E; 1400-1800 m above sea level) and is characterized by a mid-temperate semi-arid continental monsoon climate. The mean annual precipitation and potential evapotranspiration (1954-2013) are 275 and 2024 mm, respectively, and the mean annual temperature is 8.1°C (Jia et al. 2014). The dominated soil type in this area is the arenosols type of quartisamment with a pH range of 8.5 to 8.8. Since the 1980s, large-scale afforestation work has been carried out in these areas in order to combat desertification. The main species planted include trees (*Populus simonii*, *Salix mastodons*) and shrubs (*Caragana korshinskii*, *Hedysarum mongolicum*). Natural vegetation is also kept in some regions. After nearly 30 years, the composition of natural vegetation has gradually developed to shrub and herbaceous plants.

Vegetation survey and sample plot selection: Sampling locations representing typical vegetation types were selected in the northern sandy region of Yanchi from July to September 2013 (Fig. 1). Vegetation types were categorized as planted trees, planted shrubs, and natural vegetation. Percentage of vegetation cover was classified as: I, 0-5% vegetation cover (bare sand); II, 5-20%; III, 20-35%; IV, 35-50%; V, 50-65%; and VI, 65-80%. Ten 30 m × 30 m plots for each vegetation type and two bare-sand plots were selected ($n = 32$ plots in total). Vegetation cover (C) was measured using the line transect method (Buckner 1985).

Soil sampling and preparation: Five 5 m × 5 m quadrats were randomly selected within each sampling plot, and five sampling points per quadrat were randomly selected for collection of soil samples. Soil bulk density was measured at each sampling point (0-5 cm depth) using a soil-cutting ring (diameter, 5 cm). Soil samples (0-5 cm) were then collected at each sampling point using a soil auger (diameter, 3 cm). Samples were air-dried and hand-sieved through a 2 mm screen to remove roots and other debris. The contents of soil organic carbon (SOC), total nitrogen (TN), total phosphorus (TP), available nitrogen (Avi-N) and available phosphorus (Avi-P) were measured using the standard soil test procedures (Editorial Committee 1996).

Data Analysis

Vegetation cover: Vegetation cover (C) was calculated using equation (1):

$$C = \left(\frac{\sum D_{plant}}{D_{line}} \right) \times 100 \qquad ...(1)$$

Where, C is vegetation cover (%), D_{plant} is the distance in the line cut by vegetation (cm), and D_{line} is the total length of the sample line (cm).

Soil porosity: Soil porosity was calculated using equation (2):

$$f = (1 - \frac{\gamma_s}{\rho_s}) \times 100 \qquad ...(2)$$

Where, f is soil total porosity (%), γ_s is soil bulk density (g × cm^{-3}), and ρ_s is soil density (g × cm^{-3}), which was generally 2.65 g × cm^{-3}.

Soil fractal dimension: Soil fractal dimension was calculated using the method of Gui (2010) and equation (3):

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

Where, D is the soil fractal dimension, r is the soil particle size (mm), R_i is the soil particle size of class i (mm); R_{max} is the maximum value of soil particle size (mm); $V(r < R_i)$ is the soil volume fraction whose soil particle size was less than R_i (%); and V_T is the sum of the volume fraction of each particle with the same level (%).

Statistical analysis: All statistical analyses were performed using SPSS 17.0. Illustrations were created using Origin 8.1. One-way ANOVA followed by LSD multiple comparison tests ($P < 0.05$) were used to analyse variations in soil physical and chemical properties between different vegetation types and coverage values. Linear regression (R^2) was used to determine the relationship between soil fractal dimensions and physicochemical properties. A Gaussian model was used to determine the fitting relationship between vegetation cover and soil fractal dimensions.

RESULTS AND ANALYSIS

Changes in soil physical and chemical properties: Significant changes in soil physicochemical properties occurred during the process of vegetation restoration (Table 1, Figs. 2 and 3). Soil porosity increased and soil bulk density decreased as plant cover increased (Table 1). No significant differences ($P > 0.05$) in soil bulk density or porosity were observed, where the same percent cover occurred between different vegetation types. Soil structure improved with increasing vegetation cover, which suggested that restoration of vegetation could affect basic soil properties and thereby improve soil structure.

Soil particle size distribution and nutrient content changed significantly with increasing plant cover. On one hand, soil texture became more fine with increasing plant cover: clay and silt content increased to 3.17% and 18.34%, respectively, and sand content fell to its lowest value, 78.49%. On the other hand, for a given type of vegetation, soil organic matter and nutrient contents increased as plant cover increased, indicating that soil quality was improved by plants.

Relationship between soil fractal dimension and physicochemical characters: The relationships between soil fractal dimension (D) and soil properties are shown in Fig. 4. The results showed that a significant negative linear correlation exists between soil bulk density and soil fractal dimension (R^2 = 0.6437), while a significant positive linear correlation exists between soil porosity and soil fractal dimension (R^2 = 0.7176). Fig. 4 (c-e) shows a significant positive linear correlation observed between soil clay, silt content and soil fractal dimension (R^2 = 0.8542 and 0.8321), and a significant negative linear correlation was observed between soil sand content and soil fractal dimension (R^2 = 0.8437). Fig. 4 (f-j) showed the correlation between soil organic matter content, soil nutrient content and soil fractal dimension. Our results showed that with an increase in soil fractal dimension, soil organic matter and nutrient content gradually increased. A significant positive linear correlation was observed between soil fractal dimension and soil organic matter content, soil total nitrogen, soil total phosphorus, soil available nitrogen and soil available phosphorus (R^2 = 0.6242-0.7272).

Soil fractal dimension under different vegetation types and cover: The soil D increased significantly with increasing plant cover (Table 2). The D of sandy soil with natural vegetation was significantly higher than that of sandy soil with planted trees ($P < 0.05$), supporting the suggestion that natural vegetation is advantageous for ecological restoration. We observed that when plant cover increased to grade IV (35-50%), the D value of sandy soil with planted trees was significantly ($P < 0.05$) lower than that of sandy soil with planted shrubs or natural vegetation for a given vegetation coverage. No significant difference ($P > 0.05$) in soil D was observed between natural vegetation and planted

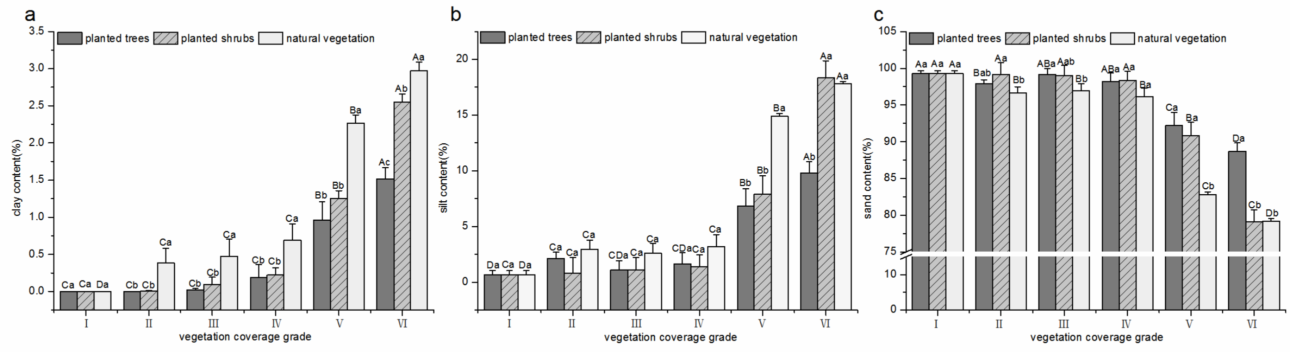

Fig. 2: Soil particle size distribution for different categories of vegetation coverage and different vegetation types.

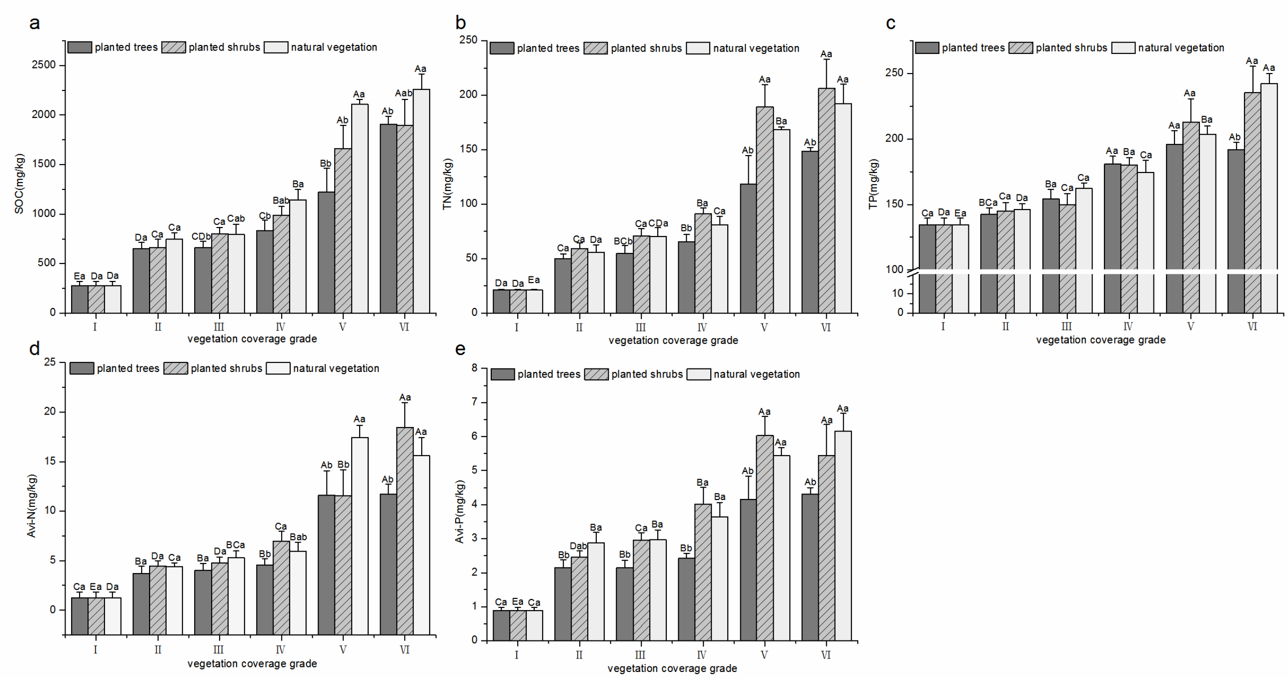

Fig. 3: Soil nutrient content for different categories of vegetation coverage and different vegetation types.

shrubs (except when vegetation coverage was grade V).

Soil fractal dimension and vegetation cover were fitted by Gaussian model (Fig. 5). The practical range of their parameterization is $3^{1/2}$r (Schabenberger & Pierce 2001). We found that the growth rate of soil *D* decreased with further increases in vegetation coverage and the fitting curve tended to flatten when vegetation cover reached $3^{1/2}$r (49.12%).

DISCUSSION AND CONCLUSION

Soil fractal dimension as a comprehensive index: Our results showed that significant changes occurred in the physicochemical properties of the soil during the restoration process of vegetation. The results showed that under different percentages of vegetation cover, significant linear relationships and high correlation existed between soil fractal dimension and its physicochemical properties (Fig. 4). As a porous medium, the structure of soil has self-similarity in statistics, showing obvious fractal characteristics. Soil with a thicker texture has more difficulty in forming a good structure for vegetative growth. The fine-grained material will affect the nutrient status of soil and other soil properties (Delgado-Baquerizo et al. 2013). This suggested that *D* could reflect the development of soil quality in an integrated manner: lower *D* indicates that the soil contains less fine material, while higher *D* indicates that sand-fixing vegetation will promote the improvement of soil conditions, and

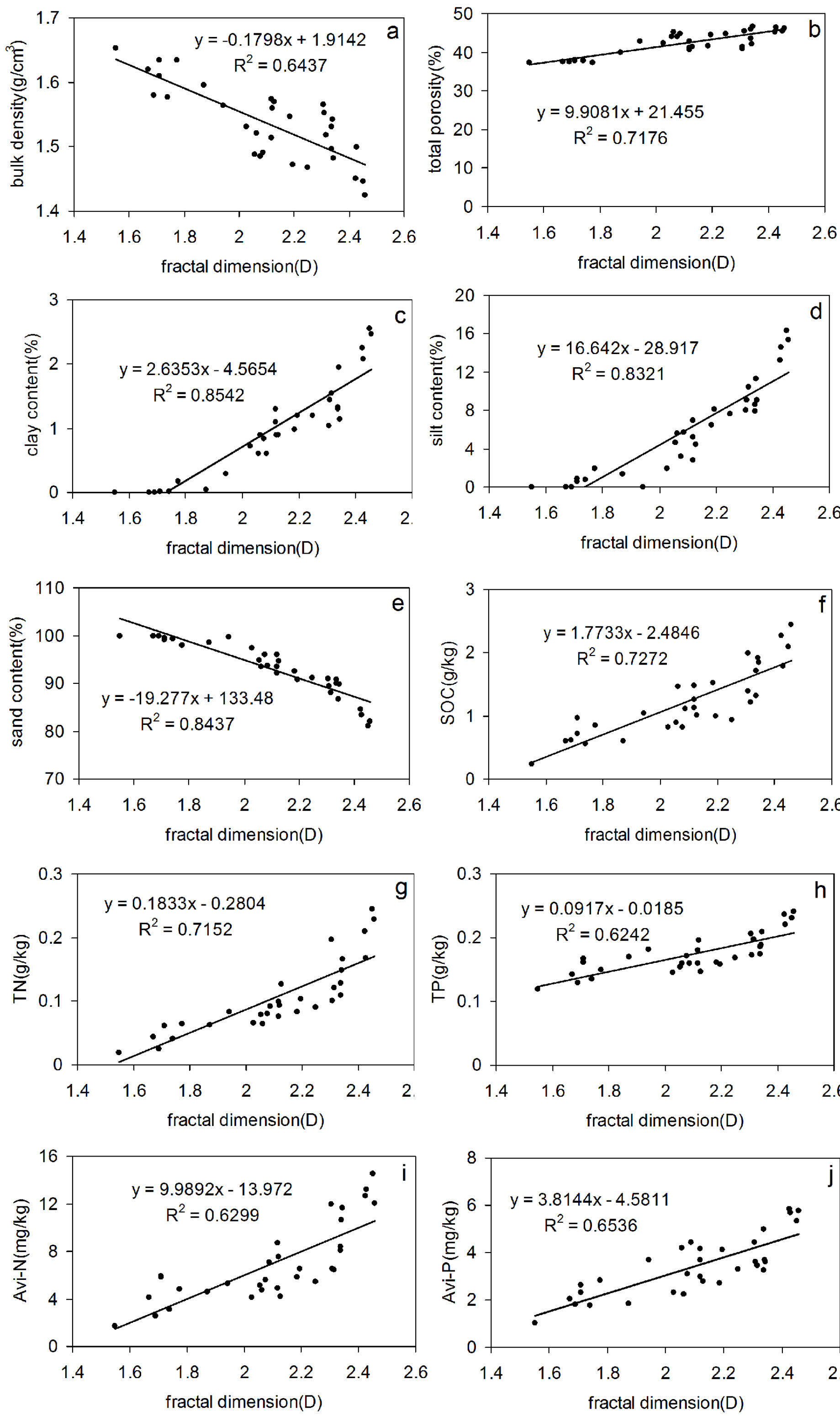

Fig. 4: Relationship between fractal dimension (*D*) values and soil properties: soil bulk density (a), total porosity (b), particle size distribution (PSD; c-e), and nutrient contents (f-j).

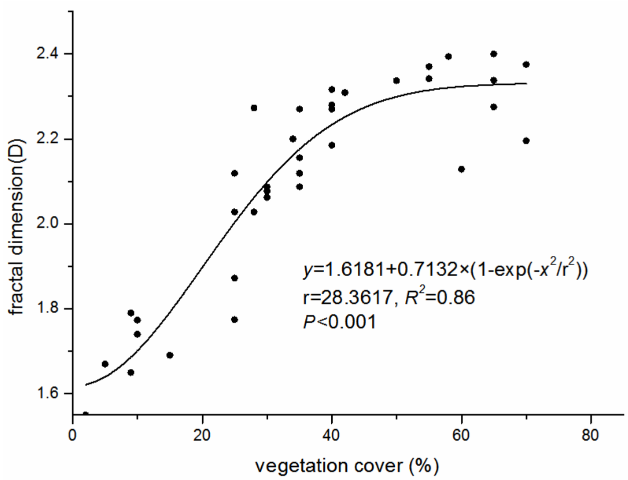

Fig. 5: Relationship between fractal dimension (D) values and vegetation coverage.

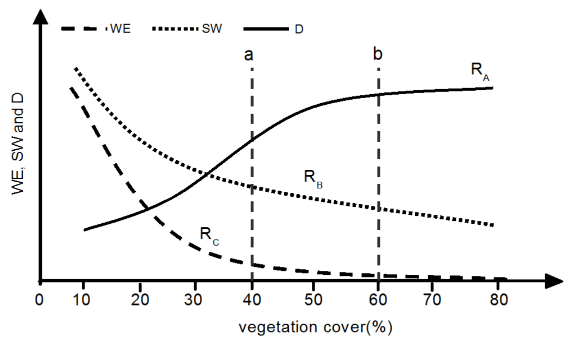

Fig. 6: Theoretical model for selecting plant cover for ecological restoration in a semi-arid desert. (WE, wind erosion; SW, soil water content; D, fractal dimension; R_A, the relationship between D values and vegetation coverage; R_B, the relationship between soil water content and vegetation coverage; R_C, the relationship between relative wind erosion and vegetation coverage.)

it can reflect the effect of vegetation restoration on reducing wind erosion. Therefore, the soil fractal dimension can be used as a comprehensive index to characterize soil texture and nutrient contents, and it will be an appropriate index for evaluating the effect of vegetation restoration on the soil environment.

Further study will be needed to evaluate the soil texture in combination with soil fractal dimension, to discover how to easily and rapidly determine the soil fractal dimension in the field, so it can be practically applied.

Choosing appropriate types and coverage of vegetation: The fractal dimension of soil under artificial vegetation was lower than that under natural vegetation. Natural vegetation has many advantages during ecological restoration efforts such as cost reduction, maintaining species diversity and having a stronger ability to sequester carbon (Jin et al. 2014). In addition, it was shown that the fractal dimension of soil under artificial shrubs was significantly higher than that of soil under artificial trees. The possible explanation for this was that, dense shrub canopies can reduce wind erosion more efficiently than trees, and shrubs have higher stress resistance than could be sustained by trees (Li 2001). Planting large areas of trees for desertification control or ecological restoration in semiarid and arid China is inappropriate (Cao et al. 2011) because of low rainfall and increasing drought under global climate change (Ji et al. 2014). Therefore, based on the efficiency and success of past restoration efforts, shrubs should be appropriate for use, during the restoration of vegetation in sandy areas.

We found that, increased cover helps to improve the soil properties (Fig. 5). In addition, increased vegetation cover can reduce wind speed at the surface, allowing plants to be considered in relation to the control of wind erosion. Besides, the effects of soil moisture, which is the driving force behind all ecological processes in arid areas, cannot be ignored (Li et al. 2014). Therefore, a tradeoff between soil nutrients, soil moisture, and the prevention of wind erosion is needed for determining an appropriate vegetation coverage. Fifty years of continuous observations of soil moisture and vegetation in the Tengger Desert Shapotou region revealed that when the total coverage of sand-fixing vegetation is 40% to 60%, vegetation remains relatively stable in arid and semiarid areas of China (Li et al. 2014). When the coverage of sand-fixing vegetation reached 35% to 40%, there was almost no wind-driven soil erosion (Wasson and Nanninga 1986, Song et al. 2011). From the Gaussian model, we found that the fitting curve of D and vegetation cover tends to flatten when vegetation cover reached 49.12%. Therefore, we can infer the suitable range of plant cover by considering the relationships between vegetation cover, D, soil moisture, and wind erosion (Fig. 6). It is observed that the suitable range of vegetation cover in sandy areas is 40% to 60% (see the region between a, b in Fig. 6). Vegetation is not stable in the situation of area on the left of a (Fig. 6) because it was vulnerable to wind erosion in the absence of appropriate management and protection. High coverage of sand-fixing vegetation (area on the right of b) is unsustainable because, insufficient water is available to support dense plant growth. When vegetation coverage is 40% to 60%, soil nutrients, soil moisture, and control of wind erosion reached a state of equilibrium. Plant cover is stable and thus can be maintained at this level of coverage in the study area.

Of course, the relationship between vegetation, soil properties, soil hydrology and wind erosion in different climate types is very complex. Fig. 6 only provides a theoretical range of vegetation cover. Accurately determining the relationship between vegetation cover and the three parameters in

Table 1: Bulk density and total porosity for different vegetation types and coverage.

	Cover (%)	Natural vegetation	Planted shrubs	Planted trees	Bare sand
Bulk density (g/cm^3)	I	-	-	-	1.61 ± 0.01
	II	1.60 ± 0.01^{Ba}	1.59 ± 0.02^{Ba}	1.64 ± 0.01^{Aa}	
	III	1.56 ± 0.01^{Aab}	1.57 ± 0.01^{Aa}	1.56 ± 0.05^{Aab}	
	IV	1.53 ± 0.02^{Ab}	1.55 ± 0.03^{Aab}	1.54 ± 0.02^{Aab}	
	V	1.49 ± 0.03^{Ab}	1.50 ± 0.02^{Ab}	1.50 ± 0.01^{Abc}	
	VI	1.41 ± 0.01^{Ac}	1.43 ± 0.02^{Ac}	1.45 ± 0.02^{Ac}	
Total porosity (%)	I	-	-	-	39.24 ± 1.31
	II	39.62 ± 1.20^{Ba}	40.00 ± 1.46^{Ba}	38.11 ± 1.10^{Aa}	
	III	41.13 ± 1.34^{Aab}	40.75 ± 0.74^{Aa}	41.13 ± 4.82^{Ab}	
	IV	42.26 ± 2.05^{Ab}	41.51 ± 2.55^{Aab}	43.02 ± 3.11^{Abc}	
	V	43.77 ± 2.30^{Ab}	43.40 ± 1.23^{Ab}	43.40 ± 1.62^{Abc}	
	VI	46.79 ± 0.88^{Ac}	46.04 ± 1.42^{Ac}	45.28 ± 0.67^{Ac}	

Note: Values are means ± SE. Different superscript lowercase letters indicate significant differences between vegetation cover classes for a given vegetation type ($P < 0.05$). Different superscript capital letters indicate significant differences between different vegetation types for a given vegetation cover class ($P > 0.05$). "-" indicates there are no relevant data. Cover classes: I, 0-5% vegetation cover (bare sand); II, 5-20%; III, 20-35%; IV, 35-50%; V, 50-65%; and VI, 65–80%. The following are the same.

Table 2: Variations in D values under different vegetation coverage in different vegetation types.

Cover/%	Natural vegetation	Planted shrubs	Planted trees	Bare sand
I	-	-	-	
II	2.07 ± 0.10^{Ca}	1.94 ± 0.08^{Dab}	1.66 ± 0.10^{Db}	
III	2.29 ± 0.01^{Ba}	2.00 ± 0.15^{DCab}	1.76 ± 0.12^{DCb}	1.63 ± 0.03
IV	2.30 ± 0.01^{Ba}	2.14 ± 0.06^{Ca}	1.82 ± 0.06^{Cb}	
V	2.43 ± 0.01^{Aa}	2.33 ± 0.01^{Bb}	2.29 ± 0.01^{Bc}	
VI	2.45 ± 0.01^{Aa}	2.43 ± 0.01^{Aa}	2.34 ± 0.02^{Ab}	

different bioclimatic regions is a scientific issue that needs to be explored over a long-term.

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