Fractal features of soil particle size distribution under different land-use patterns in the alluvial fans of collapsing gullies in the hilly granitic region of southern China

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Abstract

Collapsing gullies are among the most severe soil erosion problems in the tropical and subtropical areas of southern China. However, few studies have examined the relationship of soil particle size distribution (PSD) changes with land-use patterns in the alluvial fans of collapsing gullies. Recently, the fractal method has been applied to estimate soil structure and has proven to be an effective tool in analyzing soil properties and their relationships with other eco-environmental factors. In this study, the soil fractal dimension (D), physico-chemical properties and their relationship with different land-use patterns in alluvial fans were investigated in an experiment that involved seven collapsing gully areas in seven counties of southern China. Our results demonstrated that different land-use patterns of alluvial fans had a significant effect on soil physico-chemical properties. Compared to grasslands and woodlands, farmlands and orchards generally contained more fine soil particles (silt and clay) and fewer coarse particles, whereas significant differences were found in the fractal dimension of soil PSD in different land-use patterns. Specifically, the soil fractal dimension was lower in grasslands and higher in orchards relative to that of other land-use patterns. The average soil fractal dimension of grasslands had a value that was 0.08 lower than that of orchards. Bulk density was lower but porosity was higher in farmlands and orchards. Saturated moisture content was lower in woodlands and grasslands, but saturated hydraulic conductivity was higher in all four land-use patterns. Additionally, the fractal dimension had significant linear relationships with the silt, clay and sand contents and soil properties and exhibited a positive correlation with the clay (R² = 0.976, P<0.001), silt (R² = 0.578, P<0.01), organic carbon (R² = 0.777, P<0.001) and saturated water (R² = 0.639, P<0.01) contents but a negative correlation with gravel content (R² = 0.494, P<0.01), coarse sand content (R² = 0.623, P<0.01) and saturated hydraulic conductivity (R² = 0.788, P<0.001). However, the fractal dimension exhibited no significant correlation with pH, bulk density or total porosity. Furthermore, the second-degree polynomial equation was found to be more adequate for describing the correlations between soil fractal dimension and particle size distribution.
The results of this study demonstrate that a fractal dimension analysis of soil particle size distribution is a useful method for the quantitative description of different land-use patterns in the alluvial fans of collapsing gullies in southern China.

Introduction

Soil is a porous medium composed of soil particles of different sizes and shapes [1], and its structure and properties are determined by soil particle size distribution (PSD), which indirectly affects soil moisture characteristics, fertility and soil erosion [2]. During the last few decades, many soil scientists have used the PSD to predict physical properties such as water retention, bulk density, permeability, and porosity [3–6]. To a certain extent, PSD is an important index for the evaluation of soil and its relationship with other soil functions [7–8]. In areas with high soil erosion rates due to rainfall and runoff, fine particle-size fractions (accompanied by nutrients) are selectively removed or deposited during soil erosion processes [9–10]. A number of previous studies have proposed that land use largely influences PSD by promoting or hindering soil erosion [11–14]. Therefore, the characterization of PSD can help to reveal the influence of land use on soil properties.

A quantitative description of soil PSD is important for soil structure research. During the last few decades, several different methods have been established for determining soil PSD [15–17]. Textural analysis is commonly used to characterize soil PSD, but the size definitions of the three main particle fractions (sand, silt and clay) are rather arbitrary and thus cannot provide complete information about the soil PSD. Additionally, in the textural triangle, soils grouped in a textural class exhibit a wide PSD range (e.g., the silt loam in the textural triangle contains soils that roughly vary between 50% and 80% in silt content), thus providing incomplete information regarding PSD [9]. Fractal theory, which is a method of describing systems with non-characteristic scales and self-similarity, was first proposed and established by Mandelbrot (1977) [18]. In recent years, this theory has been utilized for quantitative descriptions of soil PSD characteristics and has attracted the attention of pedologists worldwide. Tyler and Wheatcraft (1992) [19] developed a mass-based distribution to estimate the fractal dimension of PSD and developed the limits of fractal behavior and applications for soil PSD. Based on the mass-based approach, Yang et al. (1993) [20] applied fractal scaling theory in describing soil PSD characteristics of different soil textures in northern China. The results of their studies demonstrated that fractal dimension analysis was very sensitive to clay content. Later, Bittelli et al. (1999) [21] characterized PSD using a fragmentation model based on the mass fractal dimension in three domains: clay, silt, and sand. Huang and Zhan (2002) [22] found that the fractal dimension of PSD increased with clay content but decreased with sand content. Millan et al. (2003) [23] analyzed the relationship between scaling exponents and soil texture on the basis of the fractal model. Their research demonstrated that the fractal dimension of soil PSD was significantly positively correlated with clay content following a linear trend. Su et al. (2004) [24] demonstrated that fractal dimensions of PSD are useful parameters in monitoring soil degradation and desertification processes. Additionally, Prosperinin and Perugini (2008) [25] systematically described the characteristics of soil particle size distribution by utilizing the fractal model in the Umbria region of Italy. More recently, Segal et al. (2009) [26] and Arya et al. (2010) [27] used the fractal method and theory to identify soil PSD as a useful factor for predicting soil hydraulic properties and compared the results with those determined using traditional methods. Furthermore, many multifractal measures have been used to characterize PSD by analyzing the specific data of soil particles [9, 28–31]. Despite extensive research on
soil structure using the fractal theory, to our knowledge, few studies have focused on the influence of land-use patterns on the fractal dimension of soils [32–33].

Water loss and soil erosion pose great threats to China’s environment and economy [34]. In particular, gully erosion is an important indication of land degradation, rendering slopes unfit for agriculture and representing an important source of sediment in a range of environments [35]. First described by Zeng (1960) [36], collapsing gully erosion, a widely distributed erosional phenomenon in the hilly granitic region of southern China, is caused by a combination of intense runoff and gravity in areas that receive more precipitation than the soil is able to absorb [37–40]. These gullies develop quickly and collapse suddenly, with an annual average erosion rate of more than 50 kt km\(^{-2}\) yr\(^{-1}\), which is more than 50 times greater than the erosion rate on gentler slopes or on slopes with high vegetation cover [41]. According to a 2005 survey by the Monitoring Center of Soil and Water Conservation of China, there are hundreds of such degraded ecosystems in the hilly granitic region of southern China, and the number of collapsing gullies is estimated to be 239,100 within an area that extends from 21°01’–32°05’N and 106°49’–120°27’E, including the provinces of Guangdong, Jiangxi, Hubei, Hunan, Fujian, Anhui, and Guangxi (Fig 1) [42–43]. A collapsing gully system consists of five parts: (1) an upper catchment, where a large amount of water is accumulated; (2) a collapsing wall, where mass-soil wasting, water erosion and gravitational erosion are quite severe; (3) a colluvial deposit, where residual material is deposited; (4) a scour channel, where the sediment accumulation and transport is usually deep and narrow; and (5) an alluvial fan, the zone below the gully mouth, where sediments transported by the collapse are deposited (Fig 2) [37, 39, 44].

From 1950 to 2005, collapsing gully erosion affected 1,220 km\(^2\) in the granitic red clay soil region, leading to the loss of more than 60 Mt of soil [43]. The collapsing gullies in turn led to the losses of 360,000 ha of farmland, 521,000 houses, 36,000 km of road, 10,000 bridges, 9,000 reservoirs, and 73,000 ponds, as well as an economic loss of 3.28 billion USD that affected 9.17 million residents [38, 45]. As part of collapsing gully systems, alluvial fans are sedimentary regions and are the most destructive features to farmlands in collapsing gully areas (Fig 3). When collapsing gully erosion occurs, the cultivation layer of farmlands in alluvial fans is covered by a large amount of sediment, which severely affects the physico-chemical properties of

**Fig 1. Number of collapsing gullies in areas of southern China.** Data are from Feng et al. (2009).

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the soil and further diminishes the crop yield. Several researchers have investigated collapsing gully erosion in China, but most studies have focused on the formation mechanism and governance of collapsing gully erosion [46–49]. As a result, few studies have been performed on the effects of land use on the soil quality of these degraded land areas.

In this study, we investigated the PSD and fractal dimensions (D) of soil in seven different alluvial fans of collapsing gullies at different latitudes in the hilly granitic region of southern China.
China. Our objectives were to (i) determine the effect of different land-use patterns on the soil properties and soil PSD of alluvial fans of collapsing gullies in different regions; (ii) describe and assess the status of the fractal dimensions of different land-use patterns in these alluvial fans and investigate the relationship between soil fractal dimensions and soil properties; and (iii) explore the possibility of using the fractal dimension of soil PSD as an integrating index for quantifying soil PSD characteristics and soil degradation extent of these alluvial fans. This study lays a theoretical foundation for further research regarding soil protection, soil recovery mechanisms, and other soil science topics concerning alluvial fans in collapsing gullies.

Materials and methods

Study area

This study was conducted in seven counties of southern China, including Tongcheng County (TC) in Hubei Province, Longhui County (LH) in Hunan Province, Gan County (GX) in Jiangxi Province, Changting County (CT) and Anxi County (AX) in Fujian Province, Wuhua County (WH) in Guangdong Province and Cangwu County (CW) in Guangxi Province. These counties were selected as the study sites because they suffer from the most severe collapsing gully erosion in the hilly granitic region of southern China. The field study does not involve endangered or protected species and these sites do not require specific permission.

TC (29°02′–29°24′N, 113°36′–114°04′E), located in southeastern Hubei Province in central China, has a temperate monsoon continental climate, an average temperature of 15.5–16.7°C, average annual precipitation of approximately 1,550 mm with high variability, and an accumulated temperature (>10°C) of 5,058°C. The region is dominated by granitic red soil, with granites in the area formed during the Yanshanian period. Many granitic joints formed by the Yanshan movement and inherited from the bedrock facilitate slope failure. According to a 2005 survey by the Yangtze River Water Resources Commission of the Ministry of China, TC has 1,102 collapsing gullies that contribute to an annual soil loss of more than 120 million ha, accounting for 58.4% of the total soil erosion loss in the county [50].

LH (27°00′–27°40′N, 110°15′–110°38′E), located in southwestern Hunan Province, is characterized by a subtropical monsoon climate, an annual average temperature of 11–17°C, annual precipitation of 1,427.5 mm, a rainy season from April to September that accounts for 76% of the total annual precipitation, and an annual average frost-free period of 281.2 days. The region is dominated by granitic red soil, with granites in the area formed during the Yanshanian period. Many granitic joints formed by the Yanshan movement and inherited from the bedrock facilitate slope failure. According to a 2005 survey by the Yangtze River Water Resources Commission of the Ministry of China, LH has 1,617 collapsing gullies in the county [51].

GX (25°26′–26°17′N, 114°3′–115°22′E), located in southern Jiangxi Province, has a characteristically warm subtropical humid monsoon climate, a mean annual temperature of 19.3°C, average annual sunshine of 1,092 h, average annual rainfall of 1,394.3 mm, an average of 160 rainy days per year, and a frost-free period of 298 days. The region is dominated by granitic red soil, with granites in the area formed during the early Caledonian and Yanshanian periods. Soil erosion is severe in this area, and there are 4,138 collapsing gullies in the county [52].

CT (25°18′–26°02′N, 116°0′–116°39′E), located in western Fujian Province, belongs to the subtropical monsoon climate zone; the climate is warm, the mean annual temperature is 18.3°C, the average annual sunshine is 1,685.6 mm, and the frost-free period is 260 days. The dominant soil type is red soil, and the granites in the area were formed during the early Caledonian and Yanshanian periods. CT has 1,592 collapsing gullies [53].

AX (24°50′–25°26′N, 117°35′–118°17′E), located in southeastern Fujian Province, is characterized by a typical subtropical maritime monsoon climate, an annual average sunshine of 2,069 h, an annual average temperature of 16–22°C, and an accumulated temperature
of 5,000–7,700˚C. The average annual precipitation is 1,600 mm, with 81% occurring between March and September and an average of 160 rainy days per year. The average frost-free period is 350 days. The dominant soil type is red soil, and the granites in the area were formed during the Yanshanian period. AX has 4,744 collapsing gullies, the most of all counties in Fujian Province [54].

WH (23˚23’–24˚12’N, 115˚18’–116˚02’E), located in northeastern Guangdong Province, is characterized by a subtropical monsoon climate, an annual average temperature of 20˚C, and annual precipitation of 1,547.5 mm, and the rainy season is concentrated between April and September, accounting for 76% of the total annual precipitation. The granites in the area were formed during the Yanshanian period. There are a total of 22,117 collapsing gullies in WH, representing a serious threat to the local economy [55].

CW (22˚58’–24˚10’N, 110˚51’–111˚40’E), located in the eastern part of the Guangxi Zhuang autonomous region, is characterized by a subtropical monsoon climate, an average annual temperature of 21.12˚C and average precipitation of 1,500 mm. CW has 1,592 collapsing gullies, 580 of which are in the town of Longxu [56].

**Soil sampling**

Extensive alluvial fans form at the mouth of most gullies in the study area. Most valleys are covered by alluvial fans, and essentially all previous farmlands have been abandoned. However, some alluvial fans are used as farmland areas by local farmers due to a shortage of agricultural land. This study was conducted to investigate the expansion of seven collapsing gully areas in southern China, including TC, LH, GX, CT, AX, WH and CW. These regions are all experiencing an expansion in collapsing gullies, resulting in the accumulation of alluvial fan sediments. Additionally, four land-use patterns, including farmland, orchard, woodland and grassland, were chosen as areas of focus among the alluvial fans of the collapsing gullies in the study area. All soil types in the study area are granitic red soils (Ultisols). Soil samples were collected from the four different land-use patterns at a total of 28 sampling sites (i.e., 7 locations x 4 land uses). At each of these sites, we removed the litter and selected 10–20 points in the tillage layer in an S-pattern under different land-use patterns. Then, the soil collected from several points was combined into a single sample, and approximately 1–2 kg of soil samples was transferred to the laboratory after a four-way division of all samples. Additionally, bulk density, porosity and soil moisture were determined by using metal cylinders whose volumes were approximately 100 cm³ (5.02 cm diameter and 5.05 cm height).

**Soil analysis**

Each soil sample was dried at laboratory room temperature (25˚C) to a constant weight and then sieved through a 2-mm mesh to remove roots, stone and other debris for experimental analysis. According to the United States Department of Agriculture classification of soil particle size, soil PSD was described in terms of the percentages of gravel (1–2 mm), coarse sand (0.5–1 mm and 0.25–0.5 mm), fine sand (0.1–0.25 mm and 0.05–0.1 mm), silt (0.002–0.05 mm) and clay (<0.002 mm). Sand fractions were obtained using the wet sieving method, and silt and clay fractions were determined using the pipette method after the removal of organic matter using hydrogen peroxide and heat treatment with sodium hexametaphosphate as the dispersing agent. Each PSD sample was measured in triplicate to minimize the underestimation of primary silt and clay particles and to achieve good reproducibility.

The soil physical and chemical properties were tested according to the procedures described by the Institute of Soil Science of the Chinese Academy of Sciences (ISSCAS, 1978) [57]. Bulk density (BD) was measured by collecting samples from the 0–20 cm soil layer using metal...
cylinders whose volumes were approximately 100 cm$^3$ (5.02 cm diameter and 5.05 cm height), followed by weighing the samples and then drying (105°C) them to a constant weight. Soil porosity was calculated using bulk density (BD) and particle density (PD; 2.65 mg m$^{-3}$) according to the following equation: total porosity (%) = (1-BD/PD)×100. Saturated water content was measured using the gravimetric method, saturated hydraulic conductivity was measured according to the constant head method, soil pH was determined with the potentiometric method on a soil/water suspension (1:2.5 ratio), and soil organic matter (SOM) was quantified with the K$_2$Cr$_2$O$_7$–H$_2$SO$_4$ oxidation method of Walkey and Black [58].

Measurement of soil fractal dimension

The fractal dimension can be defined by the relationship between number and size in a statistically self-similar system (Mandelbort 1982) [59]:

$$N(X > x_i) = k x_i^{-D}$$  \hspace{1cm} (1)

where $N(X > x_i)$ is the cumulative number of objects or fragments greater than a characteristic size $x_i$, $k$ is the number of elements at a unit length scale, and $D$ is the fractal dimension. The applicability of Eq (1) for PSD analysis, however, is limited due to the incomplete and inaccurate calculations of N from conventional experimental data. To solve this problem, Tyler and Wheatcraft [19] determined $D$ using Eq (2):

$$\frac{M(r < R_i)}{M_T} = \left( \frac{R_i}{R_{max}} \right)^{3-D}$$  \hspace{1cm} (2)

where $M(r < R_i)$ is the cumulative mass of soil particles of the $i^{th}$ size with $r$ less than $R_i$, $M_T$ is the total mass (g) of the soil lower than $R_{max}$, $R_i$ is the soil particle radius, $R_{max}$ is the maximum particle radius, and $D$ is the soil particle fractal dimension. Eq (2) can be rearranged in a log-log scale, providing a method for determining the fractal dimension from the slope of the regression log $[M(r < R)/M_T]$ versus log $[R_i/R_{max}]$. The slope of the graph of log $[M(r < R)/M_T]$ versus log $[R_i/R_{max}]$ is $(3-D)$. Eq (2) was used for analysis in this study.

Statistical analysis

The data were analyzed using one-way analysis of variance (ANOVA) with the SPSS 19.0 software package. The least significant difference (LSD) procedure was used to separate the means of these soil properties at a significance level of $P<0.05$, and all of the results are reported as the mean±SD (standard deviation). Regression analysis was used to analyze the relationship of the fractal dimension ($D$) with the content of soil particles and soil physico-chemical properties.

Results

Soil particle-size distributions

As shown in Table 1, there were considerable differences in soil PSD under the four land-use patterns in the seven alluvial fans of collapsing gullies. The predominant soil particle sizes were found to be silt (0.002–0.05 mm) and coarse sand (0.25–1.0 mm), followed by gravel (1.0–2.0 mm), fine sand (0.05–0.25 mm) and clay (<0.002 mm). The percentages of silt ranged between 18.77% in grasslands and 28.62% in woodlands of TC, 28.14% in grasslands and 36.59% in woodlands of LH, 20.46% in farmlands and 28.35% in grasslands of GX, 16.72% in woodlands and 32.85% in farmlands of CT, 17.66% in farmlands and 37.61% in orchards of AX, 15.83% in woodlands and 30.13% in orchards of WH, and 25.36% in woodlands and 28.58% in grasslands of CW. The concentration of coarse sand and gravel for the soils of the four land-use patterns...
| Code | Soil particle-size distribution (mm) | Soil texture |
|------|-----------------------------------|--------------|
|      | Gravel 2.0–1.0 | Coarse sand 1.0–0.5 | Total of coarse sand 0.5–0.25 | Fine sand 0.25–0.1 | Total of fine sand 0.1–0.05 | Silt 0.05–0.002 | Clay <0.002 |
| TC   | Farmland 18.02 ±0.20b | 14.16 ±0.14a | 8.64±0.31c | 22.80 | 11.39 ±0.73a | 11.64 ±1.37b | 23.03 | 23.02 ±0.69c | 13.13 ±0.55b | Sandy loam |
|      | Orchard 19.35 ±0.11ab | 13.21 ±0.24ab | 9.32±0.22c | 22.53 | 7.34 ±0.30b | 7.79±1.18c | 15.12 | 26.46 ±1.34b | 16.54± 0.46a | Sandy clay loam |
|      | Woodland 19.22 ±0.11ab | 11.04 ±0.67c | 13.52 ±0.42a | 24.56 | 5.79 ±0.23c | 10.97 ±0.77b | 16.76 | 28.62 ±2.18a | 10.84 ±1.51c | Sandy loam |
|      | Grassland 20.11 ±0.19a | 14.41 ±0.90a | 11.72 ±0.58b | 26.12 | 10.39 ±0.60a | 14.95 ±3.51a | 25.34 | 18.77 ±2.32d | 9.67 ±0.69c | Sandy loam |
| LH   | Farmland 17.57 ±0.52c | 9.55±0.38c | 9.41±1.35a | 18.97 | 9.82 ±0.19b | 8.95 ±1.24b | 18.77 | 29.60 ±1.57b | 15.09 ±0.97b | Sandy clay loam |
|      | Orchard 19.24 ±0.76b | 10.71 ±0.85b | 5.29±0.23b | 16.01 | 4.82 ±0.34c | 9.72 ±1.55a | 14.54 | 30.22 ±1.39b | 19.99 ±1.20a | Clay loam |
|      | Woodland 15.47 ±0.37d | 10.05 ±0.91b | 9.89±1.28a | 19.94 | 3.68 ±0.81c | 8.86 ±0.70b | 12.54 | 36.59 ±2.29a | 15.47 ±0.76b | Clay loam |
|      | Grassland 21.69 ±1.76a | 12.61 ±0.57a | 6.93±0.36b | 19.55 | 11.38 ±0.55a | 7.32±0.34c | 18.71 | 28.14 ±1.91c | 11.92 ±1.31c | Sandy loam |
| GX   | Farmland 18.49 ±0.68ab | 14.44 ±1.22b | 8.14±0.33b | 22.58 | 12.49 ±1.22a | 16.46 ±1.64a | 28.95 | 20.46 ±1.08c | 9.53 ±0.50bc | Sandy loam |
|      | Orchard 10.56 ±0.48ab | 13.94 ±0.53b | 10.46 ±0.55a | 24.40 | 8.30 ±0.42c | 13.62 ±0.89b | 21.92 | 25.83 ±2.01b | 17.29 ±2.51a | Sandy clay loam |
|      | Woodland 21.37 ±0.64a | 17.63 ±0.79a | 4.44±0.39c | 22.07 | 10.80 ±0.56b | 11.07 ±0.76c | 21.87 | 25.70 ±3.12b | 8.99 ±1.57c | Sandy clay loam |
|      | Grassland 20.21 ±0.66a | 13.02 ±0.87b | 10.05 ±0.24a | 23.07 | 10.14 ±0.76b | 7.69 ±1.00d | 17.83 | 28.35 ±1.69a | 10.54 ±1.20b | Sandy clay loam |
| CT   | Farmland 12.76 ±1.54d | 8.48±0.63c | 8.13±0.30b | 16.61 | 7.58 ±0.50c | 10.64 ±3.19b | 18.22 | 32.85 ±1.95a | 19.56 ±0.62a | Clay loam |
|      | Orchard 18.70 ±1.05c | 10.06 ±1.17b | 5.93±0.29c | 16.00 | 7.12 ±0.47c | 13.02 ±0.65a | 20.14 | 30.06 ±3.62ab | 15.10 ±0.50b | Clay loam |
|      | Woodland 20.57 ±0.64b | 16.61 ±1.15a | 11.16 ±0.96a | 27.78 | 10.52 ±0.73b | 14.59 ±1.85a | 25.12 | 16.72 ±0.32c | 9.81 ±1.24d | Sandy clay loam |
|      | Grassland 23.23 ±2.2a | 15.87 ±1.90a | 5.94±0.27c | 21.80 | 14.19 ±0.04a | 9.11 ±1.07b | 23.30 | 20.47 ±2.13b | 11.20 ±0.63c | Sandy clay loam |
| AX   | Farmland 24.29 ±1.11a | 15.45 ±0.86b | 12.84 ±0.75b | 28.29 | 10.45 ±0.59b | 11.17 ±1.87a | 21.62 | 17.66 ±0.31c | 8.14 ±1.92c | Sandy clay loam |
|      | Orchard 11.03 ±0.97c | 8.35 ±0.39d | 6.41±0.28d | 14.76 | 12.99 ±0.05a | 5.54±0.38c | 18.54 | 37.61 ±0.65a | 18.06 ±0.68a | Clay loam |
|      | Woodland 21.58 ±1.64b | 12.30 ±0.90c | 9.35±0.28c | 21.65 | 10.35 ±0.47b | 10.57 ±0.20a | 20.93 | 22.55 ±1.21b | 13.29 ±0.37b | Sandy clay loam |
|      | Grassland 19.85 ±0.25bc | 17.66 ±0.40a | 14.44 ±0.16a | 32.10 | 9.31 ±0.01c | 9.21 ±0.59b | 18.52 | 20.83 ±1.49bc | 8.70 ±0.41c | Sandy clay loam |
| WH   | Farmland 17.70 ±0.77c | 12.56 ±0.43c | 8.76±0.21b | 21.32 | 10.74 ±1.27a | 10.02 ±0.59a | 20.76 | 27.65 ±1.15ab | 12.57 ±0.86b | Sandy clay loam |
|      | Orchard 14.74 ±0.71d | 14.69 ±0.49b | 7.27±0.28c | 21.96 | 3.50 ±0.22c | 11.70 ±3.00a | 15.20 | 30.13 ±2.05a | 17.98 ±1.85a | Clay loam |
|      | Woodland 26.25 ±2.86b | 21.24 ±1.05a | 11.63 ±1.23a | 32.87 | 9.54 ±0.44b | 6.01 ±1.87b | 15.55 | 15.83 ±0.86b | 9.49 ±1.74c | Loamy sand |
|      | Grassland 30.03 ±0.33a | 21.18 ±1.13a | 8.37±0.35b | 29.54 | 9.02 ±0.29b | 6.90 ±0.89b | 15.92 | 16.37 ±2.48b | 8.14 ±0.19c | Loamy sand |

(Continued)
showed significant group characteristics, and the coarse sand concentration was higher than that of gravel in TC, GX and AX. The fine sand concentration was greater in farmland than in the other land-use patterns in LH, AX and WH. The highest concentrations of clay in TC, LH, GX, CT, AX, WH and CW were 16.54% in orchards, 19.99% in orchards, 17.29% in orchards, 19.56% in farmlands, 18.06% in orchards, 17.98% in orchards and 20.22% in farmlands, respectively. We can conclude from the texture classification that the soil texture varies under the four land-use patterns in the seven alluvial fans. The soil texture is sandy loam for farmlands, woodlands and grasslands in TC; grasslands in LH; and farmlands in GX. It is sandy clay loam for the orchards in TC; farmlands in LH; orchards, woodlands and grasslands in GX; woodlands and grasslands in CT; farmlands, woodlands and grasslands in AX; farmlands in WH; and all the land-use patterns in CW. The soil texture is clay loam for the orchards and woodlands in LH, farmlands and orchards in CT, orchards in AX, and orchards in WH.

**Soil fractal dimension**

According to the double-logarithmic model of the soil PSD fractal dimension from Eq (2), \( \lg \left( \frac{M(r)}{M_i} \right) \) and \( \lg \left( \frac{r}{R_{max}} \right) \) were linearly fitted utilizing the least-squares method to obtain the soil mass fractal dimension values of the land-use patterns in the alluvial fans of collapsing gullies in TC, LH, GX, CT, AX, WH and CW. The relevant parameters of calculation are shown in Table 2. The highest fractal dimension values for the land-use patterns in each of the alluvial fans were orchards in TC (2.748), orchards in LH (2.779), orchards in GX (2.745), farmlands in CT (2.769), orchards in AX (2.759), orchards in WH (2.705) and farmlands in CW (2.777). The soil particle fractal dimension was higher when the soil texture was finer, corresponding to the soil PSD. The results demonstrated that the fractal dimensions of woodlands and grasslands are smaller than those of the other land-use patterns in most cases, and a lower fractal dimension leads to a higher concentration of both gravel (1.0–2.0 mm) and coarse sand (0.25–1.0 mm), indicating that the soil texture is coarser in the land-use patterns of the alluvial fans. As shown in Table 2, soil D was determined to range between 2.631 and 2.829 in TC, 2.571

| Code | Soil particle-size distribution (mm) | Soil texture |
|------|----------------------------------|--------------|
|      | Gravel | Coarse sand | Total of coarse sand | Fine sand | Total of fine sand | Silt | Clay |       |
| CW   | Farmland | 17.38 ±0.54 | 11.28 ±0.33 | 4.71±0.28 | 15.99 | 6.24 ±0.21 | 12.09 ±0.26 | 18.32 | 28.09 ±0.23 | 20.22 ±0.68 | Sandy clay loam |
|      | Orchard | 14.33 ±0.69 | 9.08 ±0.79 | 10.16 ±0.12 | 19.24 | 10.43 ±0.23 | 9.92 ±0.67 | 20.35 | 26.69 ±0.25 | 19.38 ±1.92 | Sandy clay loam |
|      | Woodland | 25.24 ±1.45 | 8.37 ±0.69 | 14.39 ±0.33 | 22.76 | 5.24 ±0.22 | 11.34 ±2.23 | 16.58 | 25.36 ±0.44 | 10.06 ±1.74 | Sandy clay loam |
|      | Grassland | 19.67 ±0.63 | 12.70 ±0.26 | 8.38±0.43 | 21.08 | 3.85 ±0.36 | 12.26 ±0.72 | 16.11 | 28.58 ±2.07 | 14.55 ±0.44 | Sandy clay loam |

| Soil sample | TC | LH | GX | CT | AX | WH | CW |
|-------------|----|----|----|----|----|----|----|
| Farmland    | 2.708 | 0.994 | 2.733 | 0.979 | 2.658 | 0.985 | 2.769 | 0.964 | 2.639 | 0.998 | 2.705 | 0.982 | 2.777 | 0.976 |
| Orchard     | 2.748 | 0.990 | 2.779 | 0.969 | 2.745 | 0.988 | 2.736 | 0.965 | 2.757 | 0.950 | 2.76 | 0.971 | 2.764 | 0.991 |
| Woodland    | 2.687 | 0.974 | 2.741 | 0.945 | 2.661 | 0.978 | 2.662 | 0.994 | 2.713 | 0.995 | 2.666 | 0.991 | 2.679 | 0.981 |
| Grassland   | 2.661 | 0.993 | 2.703 | 0.981 | 2.683 | 0.98 | 2.688 | 0.997 | 2.649 | 0.997 | 2.649 | 0.992 | 2.732 | 0.972 |

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**Table 2. Soil fractal dimension of different land-use patterns in the alluvial fans of collapsing gullies.**

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General soil characteristics of alluvial fans

Our data analysis demonstrated that soil layers had a significant effect (P<0.05) on soil physical and chemical properties (Fig 4). Specifically, the soil BD varied greatly among the four land-use patterns in the seven alluvial fans. The highest soil BD for the land-use patterns in each county was found in the farmlands in TC (1.44 g cm$^{-3}$), woodlands in GH (1.48 g cm$^{-3}$), woodlands in GX (1.47 g cm$^{-3}$), orchards in CT (1.37 g cm$^{-3}$), grasslands in AX (1.43 g cm$^{-3}$), orchards in WH (1.51 g cm$^{-3}$) and farmlands in CW (1.53 g cm$^{-3}$), and the lowest was in the orchards in TC (1.33 g cm$^{-3}$), orchards in LH (1.26 g cm$^{-3}$), grasslands in GX (1.37 g cm$^{-3}$), woodlands in CT (1.37 g cm$^{-3}$), farmlands in AX (1.31 g cm$^{-3}$), farmlands in WH (1.40 g cm$^{-3}$) and woodlands in CW (1.37 g cm$^{-3}$). However, the soil total porosity (TP) exhibited an opposite trend to the soil bulk density in the corresponding samples. Our data analysis revealed that the highest soil TP for the four land-use patterns in each of the seven regions was found in the orchards in TC (49.77%), orchards in LH (52.37%), grasslands in GX (48.16%), woodlands in CT (50.13%), farmlands in AX (50.74%), farmlands in WH (47.18%) and woodlands in CW (48.29%). Differences were found in the soil-saturated water contents of the four land-use patterns (Fig 4). The range in the soil-saturated water content was 25.53–34.28% in TC, 28.98–33.83% in LH, 28.52–34.42% in GX, 23.95–38.03% in CT, 25.0–38.14% in AX, 24.65–38.14% in WH, and 30.32–38.86% in CW. Compared with that in the other land-use patterns of alluvial fans, the saturated hydraulic conductivity was significantly higher for grasslands in TC (2.15 mm min$^{-1}$), grasslands in LH (1.57 mm min$^{-1}$), woodlands in GX (2.16 mm min$^{-1}$), woodlands in CT (2.16 mm min$^{-1}$), grasslands in AX (2.60 mm min$^{-1}$), grasslands in WH (2.33 mm min$^{-1}$) and woodlands in CW (1.72 mm min$^{-1}$).

As shown in Fig 4, pH values ranged from 4.78 to 5.34, indicating that the pH values of alluvial fan soils are relatively low, possibly due to the acidic nature of the granite parent materials. For the four different land-use patterns of all the collapsing gullies, the lowest pH values were 4.97, 4.94, 4.90, 4.92, 4.78, 4.90 and 4.88 for TC, LH, GX, CT, AX, WH, and CW, respectively. There were significant differences in the soil organic carbon content of the various land-use patterns in the order grasslands (4.50 g kg$^{-1}$)< farmlands (8.86 g kg$^{-1}$)< woodlands (10.25 g kg$^{-1}$)< orchards (11.69 g kg$^{-1}$) in TC; grasslands (8.68 g kg$^{-1}$)< woodlands (9.06 g kg$^{-1}$)< farmlands (12.49 g kg$^{-1}$)< orchards (14.76 g kg$^{-1}$) in LH; woodlands (3.94 g kg$^{-1}$)< grasslands (5.10 g kg$^{-1}$)< farmlands (8.52 g kg$^{-1}$)< orchards (12.65 g kg$^{-1}$) in GX; woodlands (4.58 g kg$^{-1}$)< grasslands (6.81 g kg$^{-1}$)< orchards (10.14 g kg$^{-1}$)< farmlands (14.26 g kg$^{-1}$) in CT, farmlands (5.54 g kg$^{-1}$)< grasslands (7.12 g kg$^{-1}$)< woodlands (11.11 g kg$^{-1}$)< orchards (15.79 g kg$^{-1}$) in AX; woodlands (4.94 g kg$^{-1}$)< grasslands (6.71 g kg$^{-1}$)< farmlands (6.88 g kg$^{-1}$)< orchards (11.38 g kg$^{-1}$) in WH; and woodlands (8.29 g kg$^{-1}$)< grasslands (10.69 g kg$^{-1}$)< farmlands (13.71 g kg$^{-1}$)< orchards (15.92 g kg$^{-1}$) in CW.
Relationship between fractal dimension and soil particle-size distribution

Linear and nonlinear regression analyses were performed to determine the strength of the relationships between D values and the contents of gravel, coarse sand, fine sand, silt and clay as well as the relationships between D values and general soil characteristics in the soil of alluvial fans of collapsing gullies.
fans of collapsing gullies (Fig 5). The linear regression analysis showed that the fractal dimension of PSD had a strong positive correlation with the clay content ($R^2 = 0.976, P<0.001$), a weak positive correlation with the silt content ($R^2 = 0.578, P<0.01$), a remarkable negative correlation with the content of gravel ($R^2 = 0.494, P<0.01$) and the total content of coarse sand and fine sand ($R^2 = 0.685, P<0.01$), and a weak negative correlation with the contents of coarse sand ($R^2 = 0.623, P<0.01$) and fine sand ($R^2 = 0.171, P<0.01$). Additionally, as shown in Table 3, all the correlation coefficients of the linear regression equation were lower than those of the second-degree polynomial regression equation, especially the correlation coefficient (0.578) of the linear regression equation and the correlation coefficient (0.615) of the second-degree polynomial regression equation based on the silt content.

Relationship between fractal dimension and soil characteristics

The occurrence of collapsing gullies severely affected the physical and chemical properties of alluvial fan soils. The linear regression results in Fig 6 clearly show that the fractal dimension of PSD had a significant positive correlation with the SOC ($R^2 = 0.777, P<0.001$) and saturated water content ($R^2 = 0.639, P<0.01$) and a weak positive correlation with pH ($R^2 = 0.064, P<0.05$) but a strong negative correlation with saturated hydraulic conductivity ($R^2 = 0.788, P<0.001$). However, the results revealed no significant correlation with bulk density and total porosity. Accordingly, an association of D values with the physico-chemical properties of the studied soil was established, indicating that the lower the D value, the worse the physico-chemical properties of the soil will be. Therefore, the characteristics of D reveal a physical degradation process of soils in the expansion of land desertification and soil nutrient reduction in the alluvial fans of collapsing gullies.

Discussion

Soil PSD, a key determiner of soil particles and pore characteristics (such as size, number, and geometry), is commonly used in soil classification and the estimation of various related soil properties due to its relationship to soil water movement, structure, productivity, and erosion [10, 39, 60]. Thus, identifying changes in soil PSD may provide useful information for further research regarding soil protection, soil recovery mechanisms, and other soil science topics of alluvial fans of collapsing gullies in hilly granitic regions. Fractal geometry is increasingly applied as an effective tool to describe soil structure, dynamics, and physical processes, facilitating a better understanding of the performance of a soil system [7, 61–62]. The current study demonstrates that the fractal dimension of PSD increases as soil becomes finer in texture [23, 63–65].

Soil particle-size distribution and fractal dimension

In this study, land-use pattern was found to produce highly significant effects on the fractal dimensions of PSD, indicating that it is a primary factor influencing the PSD of alluvial fans in collapsing gullies. Collapsing gullies develop quickly and suddenly erupt, depositing a large amount of gravel and sand in alluvial fans [37–38, 40, 46]. Most of these deposits are composed of quartz, feldspar and mica, exhibiting signs of hard weathering [66]. Land-use patterns in alluvial fans significantly affected the extent of water loss and soil erosion, resulting in variations in PSD and other soil properties. In the present study, soil PSD varied greatly among the four land-use patterns of the seven alluvial fans of collapsing gullies. Compared with other land-use patterns, orchards and farmlands generally had higher concentrations of fine particles (silt and clay), but their gravel contents were lower, whereas the gravel content in grasslands was greater than 20% for the four land-use patterns, except in AX and CW. These results indicate that agricultural land use is an effective means for soil recovery in alluvial fans, possibly
because land-use patterns, especially orchards and farmlands in this study, can accelerate the weathering of minerals such as feldspar [40], leading to a reduction in the concentration of coarse particulate matter in the soil and an increase in the concentration of fine particles. In addition, different fertilization measures and vegetative litter contribute to the formation of humus in orchards and farmlands during the planting process, which increases the percentage of clay particles and changes the soil particle distribution.
Gravel content

Table 3. Regression and correlation analysis of the soil fractal dimension with soil physico-chemical properties.

|                      | Regression equations | R²   | Regression equations | R²   |
|----------------------|----------------------|------|----------------------|------|
| Gravel content       | $y = 69.688x + 208.02$ | 0.494 | $y = 126.46x^2 - 755.07x + 1136.4$ | 0.496 |
| Coarse sand content  | $y = 84.092x + 250.17$ | 0.623 | $y = 362.18x^2 - 2047x + 2909.2$ | 0.637 |
| Fine sand content    | $y = 34.987x + 114.09$ | 0.171 | $y = 82.379x^2 + 411.49x - 490.71$ | 0.172 |
| Coarse and fine content | $y = 119.08x + 364.26$ | 0.685 | $y = 279.8x^2 - 1635.5x + 2418.4$ | 0.690 |
| Silt content         | $y = 99.421x - 243.65$ | 0.578 | $y = -725.15x^2 + 4029.6x - 5567.4$ | 0.615 |
| Clay content         | $y = 89.345x - 228.63$ | 0.976 | $y = 318.89x^2 - 1639x + 2112.6$ | 0.991 |
| Soil organic carbon  | $y = 71.735x - 184.89$ | 0.777 | $y = 284.01x^2 - 1467.5x + 1900.2$ | 0.792 |
| pH value             | $y = 6.844x + 3.1643$ | 0.063 | $y = 16.939x^2 - 91.12x + 127.52$ | 0.110 |
| Bulk density         | $y = 0.033x + 1.3169$ | 0.001 | $y = -1.1636x^2 + 6.3394x - 7.2258$ | 0.001 |
| Saturated water content | $y = 79.352x - 184.49$ | 0.639 | $y = 11.141x^2 - 18.968x - 102.69$ | 0.639 |
| Total porosity       | $y = 1.246x + 50.307$ | 0.001 | $y = 43.909x^2 - 239.22x + 372.67$ | 0.001 |
| Saturated hydraulic conductivity | $y = -11.775x + 33.274$ | 0.788 | $y = 8.9556x^2 - 60.312x + 99.022$ | 0.789 |

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The diversity of PSD due to different land-use patterns and positions in alluvial fans results in differentiated fractal dimensions. In this study, the D values are relatively low compared to those reported in several previous studies [10, 39], which is in agreement with the report by Cheng et al. (2007) [67], who found that the fractal dimension of the soil originating from granite was lower than that of the soil from other parent materials. However, higher soil D values from certain land-use patterns, especially farmlands and orchards, correspond well to improved soil conditions. Previous studies indicated that natural grasslands, woodlands and shrublands typically had higher fractal dimensions of PSD than farmlands in the surface soil profile. The high D values of these land-use types can be attributed to greater vegetation cover [32, 62] and reduced human activities [68], which decreases soil erosion and increases the soil clay content. However, in this study, most of the woodlands and grasslands had lower fractal dimensions than farmlands (Table 2), possibly due to the large quantity of gravel and sand in the sediments of alluvial fans, which are resistant to erosion. Thus, grasslands are not an effective land-use type for soil restoration. However, it can also be inferred from the low soil fractal dimensions that the sand concentrations of alluvial fan soils increase after gullies collapse. Agricultural land can minimize soil erosion and retain fine soil particles, indicating that reasonable planning is important for the recovery of soil productivity in alluvial fans. In addition, we assessed the determination coefficient of the linear fitting for the fractal model (Eq 2) when it was applied to the different land-use patterns in the alluvial fans. As shown in Table 2, there is a strong linear trend in the data for each of the land-use patterns and the presence of strong correlations as indicated by R² values greater than 0.90 in all cases. These results are similar to those of Liu et al. (2009) [62] and Xiao et al. (2014) [33], suggesting the effectiveness of using the fractal dimension of PSD as a descriptor for soils.

General soil characteristics of alluvial fans

Land-use patterns were also found to have significant effects on the soil physico-chemical properties of alluvial fans in collapsing gullies. Soil bulk density (BD), an important physical property of soil, directly affects soil porosity, pore size distribution, soil water, and fertilizer gas thermal change [69]. In this study, no significant consistency was found for the four land-use patterns. Soil BD was highest for farmlands in TC and CW but lowest in AX and WH, whereas soil total porosity (TP), an indicator of the response of soil structure [70], exhibited a contrasting trend at the corresponding locations. A higher soil TP implies better soil structure in the alluvial fans; thus, we can conclude that the soil structure of orchards is better in TC, LC and...
GX. Soil saturated water content is the maximum amount of water a soil can hold against gravity. Increasing the soil saturated water content is an important method to combat drought in granite soil [71]. The soils of orchards had the highest saturated water content except in CT and CW, suggesting that orchards increased the water holding capacity in alluvial fans. However, the saturated water content of woodlands and grasslands was relatively lower, suggesting the soils in these areas can easily become arid and require frequent irrigation. Saturated

Fig 6. Correlations between soil fractal dimension and soil physical and chemical properties. https://doi.org/10.1371/journal.pone.0173555.g006
hydraulic conductivity is a challenging soil hydraulic property to describe because it can change by many orders of magnitude over short distances [72]. Contrary to the general trend of saturated water content, the saturated hydraulic conductivity of grasslands and woodlands is relatively higher. This difference may be due to the high content of gravel and sand in the soils of these land-use patterns, which leads to increased soil macropore size, facilitating the generation of preferential flow and an increase in Ks with an increased water penetration rate in the soil. The organic carbon content was significantly higher in farmlands and orchards than in woodlands and grasslands. As a key attribute of soil fertility and productivity, the generally high levels of organic carbon can primarily be attributed to the massive return of crop residues to agricultural fields and the increased application of organic fertilizer. Therefore, agricultural land may contain more organic carbon, which is consistent with the study by Deng et al. (2015) [40].

Relationship of fractal dimension with soil particle-size distribution and soil characteristics

Numerous studies have demonstrated that the fractal dimension of PSD increases as the soil becomes finer in texture (i.e., from sand to loam to clay) [32–33, 64–65]. In this study, the results of the linear regression equation showed that D values had a significant and positive correlation with soil clay and silt content and a remarkable negative correlation with soil gravel, coarse sand and fine sand. These results illustrate that a higher clay or silt content in an alluvial fan would lead to a higher fractal dimension, whereas a higher sand content would lead to a lower fractal dimension. These observations are consistent with a previous study by Song et al. (2015) [64]. In the process of a collapsing gully, soil clay often accounted for the largest proportion of material loss. Decreased clay concentration is an indication of severe soil erosion, and the fractal dimension of soil PSD decreases with a decrease in clay concentration, indicating that the soil fractal dimension can reflect soil erosion to a certain extent and can be used as an indicator of soil erosion, including collapsing gully events. Additionally, land-use patterns can effectively demonstrate the use value of soils in alluvial fans. In the present study, with an increase in fine soil particles (clay and silt) in farmlands and orchards, the fractal dimension increased, whereas the soil fractal dimension in woodlands and grasslands remained low, indicating that agricultural land is more conducive to the formation of fine particles.

Based on the results of a linear regression equation and second-degree polynomial regression equation, D values had no correlation with bulk density and porosity, which is similar to the findings of Xia et al. (2015) [39]. Several previous reports state that D reflects the spatial filling capacity of soil based on the distribution of soil particles [21–22]. In other words, the smaller the soil particle diameter is, the greater the spatial filling capacity of the soil will be, which corresponds to higher fractal dimension values of PSD. However, the bulk density and porosity are also affected by other factors in addition to the soil particle size distribution in the present study. D values exhibited a significant positive correlation with saturated moisture content, which implies that the greater the D value is, the stronger the water holding capacity will be in the soil of the alluvial fan. Additionally, there was a significant negative correlation between D and the soil saturated hydraulic conductivity. This finding implies that the greater the concentration of fine soil particles, the slower the water infiltration will be, which is beneficial to soil and water conservation.

Soil grain size can reflect the ability to maintain plant nutrition. The chemical composition of fine particles involves many plant nutrient elements, and some of them can be released slowly into the plant. A significant positive correlation was observed between soil organic carbon and D values, implying that finer soil particles promote the binding of soil organic matter [73]. Soil organic carbon content is one of the most important indexes in soil quality
assessment and soil structure stability [74–75]. In this study, the correlation between D and SOC indicates that the D values can be used to assess changes in the soil quality and soil structure of alluvial fans with different land-use patterns.

In addition, as shown in Fig 4, all the $R^2$ values of the second-degree polynomial regression equation were higher than those of the linear regression equation, indicating that the second-degree polynomial equation is more adequate for describing the correlations between soil fractal dimensions and soil particle size distribution. Our results also indicate that D can be used to characterize the uniformity of soil texture among different land-use patterns.

Conclusions

Based on our analyses of PSD, D and the relationships of D values with soil physico-chemical properties for different land-use patterns in the alluvial fans of collapsing gullies, the following conclusions are summarized:

1. The four land-use patterns in the alluvial fans studied exhibit a significant effect on soil PSD and physico-chemical properties. Compared to grasslands and woodlands, farmlands and orchards generally contain more fine soil particles (silt and clay) and fewer coarse particles.

2. The four land-use patterns vary significantly in the fractal dimension of soil PSD. The soil fractal dimension is lower in grasslands but higher in orchards relative to the other two land-use patterns. The average soil fractal dimension of grasslands is 0.08 units less than that of orchards. Additionally, farmlands and orchards are lower in bulk density but higher in porosity, whereas woodlands and grasslands are lower in saturated moisture content. All four land-use patterns have high saturated hydraulic conductivity.

3. Fractal dimension exhibits significant linear relationships with the silt, clay and sand contents and soil properties; it also shows positive correlations with the contents of clay ($R^2 = 0.976, P < 0.001$), silt ($R^2 = 0.578, P < 0.01$), organic carbon ($R^2 = 0.777, P < 0.001$) and saturated water ($R^2 = 0.639, P < 0.01$) but negative correlations with the contents of gravel ($R^2 = 0.494, P < 0.01$) and coarse sand ($R^2 = 0.623, P < 0.01$) as well as saturated hydraulic conductivity ($R^2 = 0.788, P < 0.001$). However, fractal dimension has no significant correlation with pH, bulk density and total porosity. Thus, higher contents of silt and clay and a lower content of sand result in higher fractal dimension values.

The results of this study demonstrate that fractal dimension analysis of soil particle-size distribution is a useful approach for the quantitative evaluation of different land-use patterns in the alluvial fans of collapsing gullies in southern China. The correlation of fractal dimension with soil structure (bulk density and total porosity), soil moisture (saturated water content and saturated hydraulic conductivity) and soil nutrients (pH and organic carbon) provides a novel method for quantifying aggregation and the effects of land use on soil quality.

Supporting information

S1 Table. Soil physical and chemical properties of different land-use patterns in the alluvial fans of collapsing gullies.

(XLSX)

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References

1. Ding F, Huang Y, Sun W, Jiang G, Chen Y. Decomposition of organic carbon in fine soil particles is likely more sensitive to warming than in coarse particles: an incubation study with temperate grassland and forest soils in northern China. Plos One. 2014; 9: 4703–6.
2. Sarkar S, Leo BF, Carranza C, Chen S, Rivassantiago C, Porter AE, et al. Modulation of human macrophage responses to mycobacterium tuberculosis by silver nanoparticles of different size and surface modification. Plos One. 2015; 10.
3. Clapp RB, Hornberger GM. Empirical equations for some soil hydraulic properties. Water Resour. Res. 1978; 14: 601–604.
4. Tyler SW, Wheatcraft SW. Fractal scaling of soil particle size distributions: analysis and limitations. Soil Sci. Am. J. 1992; 56: 362–369.
5. Yang PL, Luo YP, Shi YC. Soil fractal character token by particle-mass distribution. Sci. Bull. J. 1993; 38: 1896–1899 (in Chinese).
6. Huang GH, Zhan WH. Fractal property of soil particle-size distribution and its application. Acta Pedol. Sin. 2002; 39: 490–497 (in Chinese).
7. Filgueira RR, Fournier LL, Sarli GO, Aragon A, Rawls WJ. Sensitivity of fractal parameters of soil aggregates to different management practices in a Phaeozem in central Argentina. J. Soil Till. Res. 1999; 36: 217–222.
8. Wei YJ, Wu XL, Cai CF. Splash erosion of clay-sand mixtures and its relationship with soil physical properties: the effects of particle size distribution on soil structure. Catena. 2015; 135: 254–262.
9. Wang D, Fu BJ, Zhao WW, Hu HF, Wang YF. Multifractal characteristics of soil particle size distribution under different land-use types on the Loess Plateau, China. Catena. 2008; 72: 29–36.
10. Xu GC, Li ZB, Li P. Fractal features of soil particle-size distribution and total soil nitrogen distribution in a typical watershed in the source area of the middle Dan River, China. Catena, 2013; 101:17–23.
11. Martínez-Casanovas JA, Sánchez-Bosch I. Impact assessment of changes in land use/conservation practices on soil erosion in the Penedès Anoia vineyard region (NE Spain). Soil Tillage Res. 2000; 57: 101–106.

12. Islam KR, Weil RR. Land use effects on soil quality in a tropical forest ecosystem of Bangladesh. Agr. Ecosyst. Environ. 2000; 79:9–16.

13. Gao GL, Ding GD, Wu B, Zhang YQ, Qin SG, Zhao YY, et al. Fractal scaling of particle size distribution and relationships with topsoil properties affected by biological soil crusts. Plos One. 2014; 9:1–10.

14. Lyu X, Yu JB, Zhou M, Ma B, Wang GM, Zhan C, et al. Changes of soil particle size distribution in tidal flats in the yellow river delta. Plos One. 2015; 10.

15. Buchan GD, Grewal KS, Robson AB. Improved models of particle size distribution: an illustration of model comparison techniques. Soil Sci. Soc. Am. J. 1993; 57: 901–908.

16. Skaggs TH, Arya LM, Shouse PJ, Mohanty BP. Estimating particle-size distribution from limited soil texture data. Soil Sci. Soc. Am. J. 2001; 65: 1038–1044.

17. Birkhofer K, Schöning I, Alt F, Herold N, Klamer B, Marau M, et al. General relationships between abiotic soil properties and soil biota across spatial scales and different land-use types. Plos One. 2012; 7: 1–8.

18. Mandelort BB. Fractals: form, chance and dimension. San Francisco: Freeman; 1977.

19. Tyler SW, Wheatcraft SW. Fractal scaling of soil particle size distributions: analysis and limitations. Soil Sci. Soc. Am. J. 1992; 56:362–369.

20. Yang PL, Luo YP, Shi YC. Soil fractal character token by particle-mass distribution. Sci. Bull. J. 1993; 38: 1896–1899 (in Chinese).

21. Bittelli M, Campbell GS, Flury M. Characterization of particle-size distribution in soils with a fragmentation model. Soil Sci. Soc. Am. J. 1999; 63: 782–788.

22. Huang GH, Zhan WH Fractal property of soil particle-size distribution and its application. Acta Pedol. Sin. 2002; 39: 490–497 (in Chinese).

23. Millan H, Gonzalez-Posasa M, Aguilar M. On the fractal scaling of soil data. Particle-size distributions. Geoderma. 2003; 122: 43–49.

24. Su YZ, Zhao HL, Zhao WZ, Zhang TH. Fractal features of soil particle-size distribution and the implication for indicating desertification. Geoderma. 2004; 122: 43–49.

25. Prosperini N, Perugini D. Particle size distributions of some soil from the Umbria Region (Italy): fractal analysis and numerical modeling. Geoderma. 2008; 145:185–195.

26. Segal E, Shouse PJ, Bradford SA, Skaggs TH, Corwin DL. Measuring particle size distribution using laser diffraction: implications for predicting soil hydraulic properties. Soil Sci. 2009; 174:639–645.

27. Arya LM, Heiman JL, Thapa BB, Bowman DC. Predicting saturated hydraulic conductivity of golf course sands from particle size distribution. Soil Sci. Am. J. 2010; 74: 33–37.

28. Grout H, Tarquis AM, Wiesner MR. Multifractal analysis of particle size distributions in soil. Environ Sci. Tech. 1998; 32: 1176–1182.

29. Martin MA, Montero E. Laser diffraction and multifractal analysis for the characterization of dry soil volume-size distribution. Soil Tillage Res. 2002; 64: 113–123.

30. Posadas AND, Giménez D, Quiroz R, Protz R. Multifractal characterization of soil pore spatial distributions. Soil Sci. Soc. Am. J. 2003; 67: 1361–1369.

31. Bird N, Díaz MC, Saa A, Tarquis AM. Fractal and multifractal analysis of porescale images of soil. J. Hydrology. 2006; 322: 211–219.

32. Wang XD, Li MH, Liu SZ, Liu GC. Fractal characteristics of soils under different land-use patterns in the arid and semiarid regions of the Tibetan plateau, China. Geoderma. 2006; 134: 56–61.

33. Xiao L, Xue S, Liu GB, Zhang C. Fractal features of soil profiles under different land use patterns on the Loess Plateau, China. J. Arid Land. 2014; 6: 550–560.

34. Zhang J, Wang TM, Ge JP. Assessing Vegetation Cover Dynamics Induced by Policy-Driven Ecological Restoration and Implication to Soil Erosion in Southern China. Plos One. 2015; 10.

35. Poessen J, Nachtergaele J, Verstraeten G, Valentijn C. Gully erosion and environmental change: importance and research needs. Catena. 2003; 50: 91–133.

36. Zeng ZX. Rock topography. Geological Publishing House (in Chinese). 1980.

37. Xu JX. Benggang erosion: the influencing factors. Catena. 1996; 27: 249–263.

38. Jiang FS, Huang YH, Wang MK, Lin JS, Zhao G, Ge HL. Effects of rainfall intensity and slope gradient on steep colluvial deposit erosion in southeast China. Soil Sci. Soc. Am. J. 2014; 78: 1741–1752.
39. Xia D, Deng YS, Wang SL, Ding SW, Cai CF. Fractal features of soil particle-size distribution of different weathering profiles of the collapsing gullies in the hilly granitic region, south China. Nat. Hazards. 2015; 79: 455–478.

40. Deng YS, Xia D, Cai CF, Ding SW. Effects of land uses on soil physico-chemical properties and erodibility in collapsing-gully alluvial fan of Anxi County, China. J. Integr. Agr. 2015; 15: 1863–1873.

41. Zhong BL, Peng SY, Zhang Q, Ma H, Gao SX. Using an ecological economics approach to support the restoration of collapsing gullies in southern China. Land. Use Policy. 2013; 32: 119–124.

42. Feng MH, Liao CY, Li SX, Lu SL. Investigation on the present situation of collapsing gully in the south of China. People Yangtze River. 2009; 40: 66–68 (in Chinese).

43. Zhang XJ. The practice and prospect of hill collapsing improving and development in southern China. China Water Res. 2010; 4: 17–22 (in Chinese).

44. Sheng JA, Liao AZ. Erosion control in south China. Catena. 1997; 29: 211–221.

45. Liang Y, Ning DH, Pan XZ, Li DC, Zhang B. Characteristics and treatment of collapsing gully in red soil region of southern China. Soil water conserve. China. 2009; 1: 31–34.

46. Xu JX, Deng YS, Liu XZ, He YG, Huang SM. Environmental analysis of soil erosion in Guangdong province: a Deqing case study. Catena. 1997; 29: 97–113.

47. Deng YS, Ding SW, Qiu XZ, Xia D, Zhu Y, Guo SW. Spatial distribution of collapsing gully alluvial soil fertility in Ganxian County, Jiangxi Province. Sci. Soil Water Conser. 2015; 1: 47–53 (in Chinese).

48. Chen ZM, Xu YM, Li CL. Governance mode and effect of the collapsing gully of Anxi County. Soil water conserve. China. 2007; 3: 15–17 (in Chinese).

49. Liu X, Li Z, Li P. Particle fractal dimension and total phosphorus of soil in a typical watershed of Yangtze River, China. Environ. Earth Sci. 2014; 73: 6091–6099.
66. Lan HX, Hu RL, Yue ZQ, Lee CF, Wang SJ. Engineering and geological characteristics of granite weathering profiles in South China. J. Asian Earth Sci. 2003; 21: 353–364.

67. Cheng XF, Zhao MS, Shi XZ, Wang HJ. Fractal dimension of red soil particle and relationship with environmental factors in Xingguo County, China. Trans. China Soc. Agric. Eng. 2007; 23:76–79 (in Chinese).

68. Zou XY, Li S, Zhang CL, Dong GR, Dong YX, Yan P. Desertification and control plan in the tibet autonomous region of china. J. Arid Environ. 2002; 51: 183–198.

69. Wang LL, Sun XY, Li SY, Zhang T, Zhang W, Zhai PH. Application of organic amendments to a coastal saline soil in north china: effects on soil physical and chemical properties and tree growth. Plos One. 2014; 9: 1–9.

70. Zhang X, Wang Q, Gilliam FS, Wang Y, Cha F, Li C. Spatial variation in carbon and nitrogen in cultivated soils in henan province, china: potential effect on crop yield. Plos One. 2014; 9: 1–9.

71. Pinheiro EFM, Pereira MG, Anjos LHC. Aggregate distribution and soil organic matter under different tillage systems for vegetable crops in a Red Latosol from Brazil. Soil Till. Res. 2004; 77: 79–84.

72. Barnes RT, Gallagher ME, Masiello CA, Liu Z, Dugan B. Biochar-induced changes in soil hydraulic conductivity and dissolved nutrient fluxes constrained by laboratory experiments. Plos One. 2014; 9.

73. Haregeweyn N, Poesen J, Deckers J, Nyssen J, Haile M, Govers G, et al. Sediment-bound nutrient export from micro-dam catchments in Northern Ethiopia. Land Degrad. Dev. 2008; 19: 136–152.

74. Schrumpf M, Kaiser K, Schulze ED. Soil organic carbon and total nitrogen gains in an old growth deciduous forest in Germany. Plos One. 2014; 9.

75. Nie XD, Li ZW, Huang JQ, Huang B, Zhang Y, Ma WM, Hu YB, Zeng GM. Soil Organic Carbon Loss and Selective Transportation under Field Simulated Rainfall Events. Plos one. 2014; 9(8): e105927. https://doi.org/10.1371/journal.pone.0105927 PMID: 25166015