Fractal dimension of soil particles under different plant communities in mountainous area

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Abstract. To explore soil physical property improvement of different plant communities in mountainous area of middle Shandong province, influences of 11 local plant communities on soil particle composition and particle size distribution were studied based on the soil fractal theory and method. First, relative weight contents of different sizes of soil particles were tested by mechanical sieving method. Second, fractal dimension of soil particles were calculated according to mass of soil particles. Results show that: soil particle size under different plant communities ranges between 0.25-1.0mm and the soil structure of stands is significantly better than that of slope wasteland. D of 11 plant communities is between 2.0044-2.4925, showing that mixed forest > pure forest > economic forest > farmland > slope wasteland. Moreover they are most sensitive to soil particles (<0.05mm), showing an evident linear positive correlation (R²= 0.901). The experiment results can provide theoretical references and technical supports to tree species selection and stand structural configuration during vegetation recovery and reconstruction in mountainous area of middle Shandong province.

1. Introduction
As the matrix for vegetation growth, soil has important physiological and ecological functions. Due to complexity of soil structure, some soil properties often present irregularity and randomness (Luo 2015), which couldn’t depicted by conventional statistical methods completely. However, irregularity of soil properties could be studied by using the fractal geometry theory and method, which could provide a new concept to reasonable expression of soil structural features. Moreover plant community directly and indirectly affects soil properties through supplying significant amount of above and belowground litterfall, releasing and recycling nutrients, modifying microclimate, regulating water cycle and altering composition of fauna and flora in soils (Li et al. 2016). This paper analyzed fractal features of soil particles under 11 plant communities in mountainous area of middle Shandong province, to provide theoretical references and technical supports to tree species selection and stand structural configuration during vegetation recovery and reconstruction, thus enabling to provide theoretical references for improving soil structure, soil texture and soil erosion control.

Since the 1980s fractal theory has been applied to soil science (Gao et al., 2014). Subsequently the feasibility of characterizing PSD using fractal theory has been explored since the 1990s (Wei et al., 2016). Moreover fractal dimension (D) becomes a useful method to quantitatively describe soil structure and erodibility (Xia et al., 2015), water permeability and other soil properties (Zhao et al., 2016). Fractal information may facilitate the choice of soil and water conservation measures and vegetation types in plateau and mountainous area (Liu et al., 2009; Wei et al., 2016). However, up to now, there are only few of application reports about fractal theory to analyze soil PSD in mountainous
area of middle Shandong province. In addition, influences of different plant communities on soil particle composition and soil PSD is still unclear.

2. Materials and methods

2.1. Test materials
In the study area, 11 typical plant communities were chosen according to different vegetation types (pure forest, mixed forest, economic forest, crop terrace and slope wasteland) so as to reflect fractal features of soil PSD better and size fraction distribution of soil particles and analyze effect of vegetation type on D of soil particles. Soil samples were collected from Pure Pinus thunbergli forest (PP), Pure Robinia Pseudoacacia forest (PR), Robinia pseudoacacia-Quercus acutissima mixed forest (RP), Pinus densiflora-Pinus thunbergli mixed forest (PD), Castanea mollissima economic forest (CM), Terraced apple (TA), Farmland (Scutellaria baicalensis) (FSB), Terraced crops (TC), Farmland (sweet potato) (FSP), Slope wasteland01 (SW01), Slope Wasteland02 (SW02).

2.2. Test methods

2.2.1. Mechanical composition of soil particles. Soil particle size and weight distributions were tested by mechanical sieving method (dry sieving): 0~40cm soil samples were collected. Soil samples of five sampling points of the same sampling plot were dried and mixed. Chad (>2mm) in soil samples was screened firstly. Next, relative (weights) contents of different sizes of soil particles were tested by the ZBSX−92A jolt impact standard sieve shaker (swing times: 221min⁻¹; impact times: 147min⁻¹; swing stroke: 25mm and motor power: 0.37KW) with 1.00mm, 0.50mm, 0.25mm, 0.10mm and 0.05mm sieve set (Nanjing Soil Research Institute).

2.2.2. Fractal dimension of soil particles. The original soil samples were dry screened. Weights and percentage contents of different sizes of soil particles were weighed and calculated. On this basis, D of soil particles was calculated according to mass (weight) of soil particles under the premise that assuming that soil materials of different sizes have the same density.

In this paper, the quantitative distribution of soil particles was represented by weight (mass) calculated by Yang et al. (1993). Then, the formula of D of soil particles is gained through the method of limits:

\[ D = 3 - \frac{\log(w_i / w_o)}{\log(d_i^* / d_{\max}^*)} \]  \hspace{1cm} (1)

Where D is fractal dimension of soil aggregate, Wi is cumulative weight of particles smaller than \(d_i^*\), W₀ is total weight, \(d_i^*\) is the average soil particle diameter between two adjacent sides \(d_i\) and \(d_{i+1}\), and \(d_{\max}^*\) is the average soil particle diameter of the maximum size. It can be known from Equation (1) that D shall be smaller than 3. When D=3, it meets the hypothesis that soil aggregate is composed of particles with single diameter. When D>3, Equation (1) has no physical significance. Soil is not the medium with ideal fractal features and only has fractal features within certain spatial range. In fact, soil particles that compose soils couldn’t have same diameter. Therefore, D shall be valued between 0 and 3.

3. Results and analysis

3.1 Mechanical composition of soil particles
Most soil particles are irregular, and 3D size of some soil particles differ significantly. Significant size difference was observed among different soil particles. The properties of coarse and fine soil particles differ greatly. For the convenience of studying their properties, soil particles were viewed as a smooth solid balls and divided into several groups (separates of soil or size fraction) according to diameter
(the pore diameter of the round sieve was used as effective diameter of soil particles). Collected sandy soil samples were divided according to China’s standard of soil size fraction (Huang, 2000) (Table 1).

| Particle name | Size (mm) |
|---------------|-----------|
| Gravel        | 2~1       |
|               | 1~0.5     |
| Coarse sand   | 0.5~0.25  |
| Sand          | 0.25~0.1  |
| Fine sand     | 0.1~0.05  |
| powder        | ≤0.05     |

The original soil samples were dry screened by mechanical sieving method. Relative contents of different sizes of soil particles were calculated (Table 2).

It can be seen from Table 1 that soil particle size under different plant communities range between 0.25-1.0mm, indicating that coarse sandy soil is the dominant soil in study area. Local soil structure has characteristic of typical coarse aggregate in rocky hills in Northern China. Lack of fine particles (e.g. powder and clay particles) and with high content of sandy soils, this soil structure often has some prominent problems, such as poor texture, loose structure, strong water permeability and weak water conservation (Deng et al. 2008).

| Sample plot | Codes of plant communities | Percentage composition of different sized soil particles (%) |
|-------------|----------------------------|-----------------------------------------------------------|
|             | 1~2 | 0.5~1 | 0.25~0.5 | 0.1~0.25 | 0.075~0.1 | ≤0.05 |
| 1           | PP  | 21.34 | 28.18    | 14.92    | 19.15    | 6.2   | 10.21 |
| 2           | PR  | 16.51 | 24.05    | 15.48    | 22.02    | 7.45  | 14.48 |
| 3           | RP  | 22.73 | 27.34    | 13.08    | 16.68    | 6.59  | 13.59 |
| 4           | PD  | 19.12 | 28.09    | 14.56    | 17.34    | 5.7   | 15.18 |
| 5           | CM  | 21.57 | 32.54    | 16.87    | 17.94    | 4.49  | 6.59  |
| 6           | TA  | 18.65 | 27.04    | 14.89    | 20.98    | 7.32  | 11.12 |
| 7           | FSB | 20.7  | 32.51    | 18.12    | 18.56    | 4.52  | 5.6   |
| 8           | TC  | 17.5  | 40.2     | 22.55    | 14.05    | 2.19  | 3.51  |
| 9           | FSP | 20.51 | 31.53    | 18.11    | 19.32    | 4.38  | 6.15  |
| 10          | SW01| 25.88 | 34.19    | 14.92    | 16.71    | 3.42  | 2.99  |
| 11          | SW02| 36.69 | 35.08    | 12.1     | 9.35     | 2.26  | 4.52  |

PR, PP and mixed forest have high contents of clay and powder particles. The TA and slope wasteland have high content of fine sandy soils. TC and farmland have high content of sandy soils. The soil structure of stands is significantly better than that of slope wasteland and the soil structure of mixed forest is far better than pure forest. Creating needle-broad leaved forest or broad-leaved mixed forest can increase contents of fine particles (e.g. powder and clay particles) in soil significantly and reduce content of sandy soils, thus improving soil physical structure and water-fertility conservation. Meanwhile, particle contents of terrace and farmland also reflect the declining soil texture, manifested by gradual reduction of fine sandy soils in cultivated lands. This requires prompt improvement of cultivation and irrigation methods.
3.2 Analysis on fractal features of soil particles

3.2.1 Calculation of D of soil particles under different plant communities. D of soil particles was calculated according to the Eq. (1). Based on data in Table 2, a graph that takes \( \log\left(\frac{w_i}{w_i'}\right), \log\left(\frac{d_i}{d_{\max}}\right) \) as the vertical and horizontal axes was drawn. D of soil particles was calculated by linear regression. Calculated D of 11 sampling plots are shown in Table 3.

Table 3 reflects that sandy soil is the main component of all collected soil samples and the calculated D (2.0044-2.4925) is relatively lower, showing slight differences. In general, D is basically within the range of sandy soil in China (1.834-2.641) (Hu et al. 2003). It can be seen from Fig.1 that RP has the highest D, followed by PD, PR, TA, PP, CM, FSB, TC, SW02, SW01, FSP successively.

| Types          | Code | Sample plot | Slope | D    |
|----------------|------|-------------|-------|------|
| Pure forest    | PP   | 1           | 0.98  | 2.3574 |
|                | PR   | 2           | 0.97  | 2.4542 |
| Mixed forest   | RP   | 3           | 0.99  | 2.4925 |
|                | PD   | 4           | 0.99  | 2.4618 |
| Economic forest| CM   | 5           | 0.98  | 2.2908 |
|                | TA   | 6           | 0.97  | 2.3845 |
|                | FSB  | 7           | 0.97  | 2.2002 |
| Farmland       | TC   | 8           | 0.97  | 2.1798 |
|                | FSP  | 9           | 0.97  | 2.0044 |
|                | SW01 | 10          | 0.99  | 2.1152 |
|                | SW02 | 11          | 0.97  | 2.1367 |

3.2.2 Effect of plant community types on D. Effect of plant community types on D is reflected by soil improvement and protection of plant communities. In Table 2, D of 11 plant communities is between 2.0044-2.4925, showing that mixed forest > pure forest > economic forest > farmland > slope wasteland. D of forest land is higher than that of non-forest land, indicating that plant communities can improve soil structure significantly. Among forest lands, mixed forest can improve soil structure mostly (RP > PD), followed by pure forests and economic forest successively. D of forest land is higher than that of non-forest land, which is because forest vegetation is one of influencing factors of soil development. Vegetation recovery is an important measure of ecological reconstruction and can improve soil structure significantly. Soil aggregates under vegetation has characteristics of wide distribution, integration of big and small pores, small particle size as well as good air permeability and water-fertility conservation. Ds of farmland and slope wasteland are similar and small, indicating the coarse soil texture in farmland and crops can improve soil structure slightly. In addition, gravel surface erosion may happen, which will coarsen the soil texture. The surface plant community coverage also can influence D significantly.

3.2.3 The relationship between soil particle size composition and D. Relational graph between soil particle size composition and D was drawn based on Table 2 and Table 3 (D of soil particles under different plant communities). Results are shown in Fig.1.

It can be seen from Fig.1 that contents of different sizes of soil particles are correlated with D to different extents. D is linearly correlated with contents of different sizes of soil particles. It has an evident linear positive correlation with contents of fine sandy soil and coarse powder. The corresponding correlation coefficients (R²) are 0.2888 and 0.901, respectively. However, it shows a
distinct linear negative correlation with content of coarse sandy soil and $R^2$ is 0.7342. The correlation between D and gravel content is not obvious. This reflects that D makes different responses to contents of different sizes of soil particles, which may be related with high contents of other soil particle sizes in the study area. The D couldn’t reflect the non-uniformity of soil texture in the study area correctly, implying that D couldn’t reflect variations of every particle size clearly.

![Graphs showing the relationship between soil particle size composition and D](image)

4. Conclusions
To explore soil physical property improvement of different plant communities in mountainous area of middle Shandong province, this paper analyzed mechanical composition, and fractal features of soil particles under 11 slope plant communities by using ecological and fractal theories and methods of plant community. The main conclusions are drawn as follows:

Viewed from mechanical composition of soil, soil particle size under different plant communities range between 0.25-1.0mm, indicating that coarse sandy soil is the dominant soil in study area. PR, PP and mixed forest have high contents of clay and powder particles. The TA and slope wasteland have high content of fine sandy soils. TC and farmland have high content of sandy soils. The soil structure of stands is significantly better than that of slope wasteland and the soil structure of mixed forest is far better than pure forest.

D of 11 plant communities is between 2.0044-2.4925, RP has the highest D, followed by PD, PR, TA, PP, CM, FSB, TC, SW02, SW01, FSP successively. D of forest land is higher than that of non-forest land, indicating that plant communities can improve soil structure significantly. Among forest lands, mixed forest can improve soil structure mostly, followed by pure forests and economic forest successively.
D of soil is closely related with soil size composition. The linear correlation between D and powder particles (≤0.05mm) is the most obvious one, which is a positive correlation (R²= 0.901). It shows a linear correlation with content of fine sandy soil (R²= 0.2888) and a linear negative correlation with content of coarse sandy soils (R²= 0.7342). However, its relationship with gravel content is not obvious.

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