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Soil fractal features of typical forest stands in Jinyun Mountain, Chongqing City, Southwest China

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Abstract In order to explore the forest soil physical property in the Three Gorges Reservoir areas, the fractal theory was adopted to study the soil fractal features of the four typical forest stands (mixed *Pinus massoniana*-broadleaf forests, evergreen broadleaved forests, *Phyllostachys pubescens* forests and evergreen broadleaved shrub forests) in Jinyun Mountain, Chongqing City, and they were compared with arable land. It has been proposed that the model can be used for the analysis of the relationship between the fractal dimensions and the properties of forest soil. The impacts of fractal dimensions on the soil properties were analyzed with the elasticity analysis and marginal yield analysis. Results showed that the fractal dimension of particle size distribution (PSD), the micro-aggregate size distribution (ASD) and the soil pore size distribution (SPD) can be used as the indices to evaluate the soil structure. In the typical stands of Jinyun Mountain, the fractal dimension of PSD is 2.7–2.9, the ASD is 2.5–2.8, and the SPD is 2.3–2.8. The soil structure of evergreen broadleaved shrub forests performed best in PSD, ASD and SPD, and the soil of *P. pubescens* forests is the worst. There were some relationships among the PSD, ASD, SPD and some soil properties in the different forests and farmland. The related coefficients are over 0.5. Based on the elasticity analysis and marginal yield analysis, the effect of PSD was more than those of ASD and SPD. Obviously, the further study on the fractal theory application in soil structure and soil properties has important significance.

Keywords Jinyun Mountain, typical forest stands, fractal dimension, soil structure, soil properties

1 Introduction

Forestry soil is a basic matter not only in sustainable forest management, but also in environmental sustainability (Jiang,

2005; Liu, 2005). The arrangement of solid components including soil particles and soil pore space, as well their size, shape composition of soil structure, determined the nature and changes of a series soil characteristics.

Since the 1980s, the application of fractal theory in soil science made it possible to quantitatively describe the complex features of soil structure. Falconer (1989) and Arya and Paris (1981) first began to study the fractal phenomenon and calculate fractal dimension of soil particles. Tyler and Wheatcraft (1992) concluded the regulation of the soil particle size distribution. Others also deduced the relations of fractal dimension of soil particle size-quality, particle diameter and surface soil particles size (Friesen, 1987; Pachepsky et al., 1995; Bird et al., 1996; Alexandra and Zhang, 1998).

Yang et al. (1993) deduced the fractal dimension formula of the soil particle size distribution adopting weight distribution instead of quantitative distribution of soil particles, which was more accurate and simple. Therefore, the weight distribution of particle diameter was used to describe the fractal dimension of the soil particles (Particle Size Distribution abridged as PSD) and the aggregate composition (Aggregate Size Distribution abridged as ASD).

After the 1980s, the application of fractal theory in hydraulic parameters became an important field, as well fractal dimension of porosity distribution as one of the important parameters was widely used. Some hydraulic characteristic curve models were deduced, Tyler and Wheatcraft (1989; 1990) reflected the relationship of soil structure and water characteristic curve; Rieu and Sposito (1991) deduced a model attributed by pore volume fractal dimension; Perfect et al. (1996) built parameter fractal model that was similar to experience relationship; and based on Menger spongy structure, and Huang and Zhan (2002) deduced a model reflecting the pore structure characteristics of soil.

Jinyun Mountain, located at the tail end of the Three Gorges reservoir areas, is occupied by complete subtropical evergreen broad-leaved forest community types, so it is the natural laboratory to study water and forest conservation and management (Wang et al., 2005). Based on the Yang's fractal dimension reflecting the soil particle size distribution and Huang's fractal dimension reflecting the pore structure, the soil structure was characterized, which was expected to

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provide new standards and methods for the description of woodland soil structure and to provide basis for vegetation management of the Three Gorges Reservoir areas.

2 Study area

Jinyun Mountain Nature Reserve Region is located at the west bank of Wentang Xia of the Little Three Gorges of Jialing River (29°45'N, 106°22'E). The highest elevation is 951.5 m with 600 m height difference. There soil there is acidic (pH value between 4.0–4.5), occupied mostly by yellow and paddy soil; the horizontal zone belongs to typical mid-subtropical climate, with an average annual temperature 13.6°C, an average annual precipitation 1,611.8 mm, an average annual evaporation 777.1 mm. There are rich plant resources, six major vegetation types of evergreen broadleaved forests, warm-conifer forests, *Phyllostachys pubescens* forests, evergreen broadleaved shrub forests, subtropical bushes and grasses forests and aquatic vegetations. The soil fractal features of the four typical forests (mixed *Pinus massoniana*-broadleaf forests, evergreen broadleaf forests, *Phyllostachys pubescens* forests and evergreen broadleaf shrub forests) were studied as well compared with arable land. Arable land planted with vegetables (*Hemerocallis citrine*, *Daucus carota*, *Brassica chinensis*) in four seasons (Tables 1 and 2).

Table 1 Basic information of standard land of typical forest stand

Stand	Site factor			Stand information					Litter	
	Elevation /m	Slope aspect	Slope /°	Origin	Age class	Canopy density	Undergrowth planting coverage /%	Grass coverage /%	Thickness /cm	Storage /(t·hm ⁻²)
Mixed <i>Pinus massoniana</i> -broadleaf forests	760	NW	16–25	Natural	VI	0.90	40	30	3.5	31.57
Evergreen broadleaved forests	825	NW	26	Natural	VI	0.90	40	20	3.4	58.9
<i>Phyllostachys pubescens</i> forests	800	NW	11	Natural	V	0.85	10	80	1.4	29.11
Evergreen broadleaved shrub forests	860	NW	10	Natural	V	0.95	60	50	4.5	86.85
Arable land (compared)	860	NW	10							

Table 2 Basic compositions of typical forest stands

Stands	Tree species	Undergrowth planting species	Herbaceous species
Mixed <i>Pinus massoniana</i> -broadleaf forests	<i>Gordonia acuminata</i> , <i>Pinus massoniana</i> , <i>Symplocos setchuensis</i> , <i>Adinandra bockiana</i>	<i>Eurya japonica</i> , <i>Adinandra bockiana</i> , <i>Symplocos lancifolia</i> , <i>Neolitea aurata</i> , <i>Diospyros morrisiana</i>	Pteridiaceae, <i>Woodwardia japonica</i> , <i>Diplazium glauca</i> , <i>Lophatherum gracile</i>
Evergreen broadleaved forests	<i>Gordonia acuminata</i> , <i>Neolitea aurata</i> , <i>Adinandra bockiana</i>	<i>Castanopsis carlesii</i> , <i>Rhamnus esquirolii</i> , <i>Symplocos setchuensis</i> , <i>Eurya japonica</i>	Pteridiaceae, <i>Woodwardia japonica</i> , <i>Lophatherum gracile</i>
<i>Phyllostachys pubescens</i> forests	<i>Phyllostachys pubescens</i>	<i>Melastoma indicum</i> , <i>Smilax china</i> , <i>Ficus virens</i>	Pteridiaceae, <i>Pilea pumila</i> , <i>Oplismenus compositus</i> , <i>Commelina communis</i> , <i>Viola tricolor</i>
Evergreen broadleaved shrub	<i>Alniphyllum fortunei</i> , <i>Lindera kwangtungensis</i> , <i>Neolitea aurata</i> , <i>Symplocos caudate</i>	<i>Cunninghamia lanceolata</i> , <i>Eurya japonica</i> , <i>Elaeocarpus japonicus</i> , <i>Machilus nanmu</i> , <i>Camellia japonica</i>	Pteridiaceae, <i>emercocallis fulva</i> , <i>Crassocephalum rabens</i> , <i>Conyza canadensis</i>

3 Methods

3.1 Soil fractal dimension

3.1.1 PSD and ASD

Soil particles size distribution fractal characteristic model put forward by Yang (1993) was applied

$$1 - \left(\bar{d}_i / \bar{d}_{\max} \right)^{3-D_{jt}} = W_i(\delta > \bar{d}_i) / W_0 \quad (1)$$

where \bar{d}_i is the average particles size between d_i and d_{i+1} ; \bar{d}_{\max} is the average diameter of the biggest particles; $W_i(\delta > \bar{d}_i)$ is the accumulated particles weight bigger than \bar{d}_i ; W_0 is the aggregate of soil every particle-weight; D_{jt} is fractal dimension of PSD/ASD.

According to the naturally soil horizon, soil samples of each horizon were taken. The quality weight of soil mechanical composition (<1 mm) and soil micro-aggregates (<1 mm) (machine/crumby) of seven grain size classes (<0.001, 0.001–0.005, 0.005–0.01, 0.01–0.05, 0.05–0.25, 0.25–0.5, 0.5–1.0 mm) were measured using suction method. Soil fractal dimension D can be calculated by (particles size seven samples) regression method (Institute of Soil Science, Chinese Academy of Sciences, 1978).

3.1.2 SPD

Fractal dimension of SPD was determined according to water characteristic curve model deduced by Huang and Zhan (2002)

$$\frac{\theta}{\theta_s} = \left[\frac{\psi}{\psi_a} \right]^{D_k - 3} \quad (2)$$

where D_k is fractal dimension of SPD; θ is soil water ratio (%); θ_s is saturation water ratio (%); ψ is matrix suction of medium (cm); and ψ_a is air admission suction (cm).

Soil samples of each horizon were taken. The soil-water characteristic curve was measured through pressure thin film measurement instrument (the suction of the water is 0.1, 0.3, 0.5, 0.7, 0.9, 1, 3, 5, 10 and 15 bar). D_k can be calculated by regression analysis through reunification water under water suction of ten classes.

3.2 Soil fractal characteristics and soil properties model

Using nonlinear regression equation, the forecast model was built (Liu et al., 2002)

$$\gamma = \alpha D_i^{\beta_1} D_j^{\beta_2} D_k^{\beta_3} \quad (3)$$

where γ is property indices content of forestry soil; D_i , D_j and D_k are fractal dimensions of ASD, PSD and SPD, respectively; α , β_1 , β_2 and β_3 are parameters.

Soil samples of each horizon were taken to measure their properties. Dichromate titration was used to measure organic matter content (O_c). Central cutting techniques were used to measure the soil bulk density (B_d), porosity (e). Natural soil water content (θ_0) and soil moisture absorption coefficient (θ_h) were determined by oven dry. Field moisture capacity (θ_c) was water content corresponding to the soil-water characteristic curve for 0.1 water suction.

$$\text{Wilting coefficient } (\theta_w) = \text{hygroscopic coefficient } (\theta_k) \times 1.5 \quad (4)$$

$$\text{Soil uniform index } (u_{ji}) = (\text{particle diameter corresponding to the 60\% total particle weight}) / (\text{particle diameter corresponding to the 10\% total particle weight}) \quad (5)$$

(Wang et al., 2006)

$$\text{Dispersion rated } (D_r) = (<0.05 \text{ mm micro-aggregates analysis value}) / (<0.05 \text{ mm mechanical composition analysis value}) \times 100\% \quad (6)$$

$$\text{Dispersion coefficient } (D_c) = (<0.001 \text{ mm micro-aggregates analysis value}) / (<0.001 \text{ mm mechanical composition analysis value}) \times 100\% \quad (7)$$

$$\text{Structural coefficient } (S_c) = 100 - D_c \quad (8)$$

$$\text{Aggregate degree } (C_d) = (>0.05 \text{ mm micro-aggregates analysis value}) / (>0.05 \text{ mm mechanical composition analysis value}) \times 100\% \quad (9)$$

(Shen et al., 2000; Liu et al., 2003)

3.3 Effect analysis of fractal dimension on soil properties

3.3.1 Elasticity analysis

Elastic coefficient (EP) in the field of economy (Liu et al., 2002) was introduced to analyze the effect of PSD, ASD and SPD on the soil properties

$$EP = (\Delta\gamma / \gamma) / (\Delta D / D) = (\Delta\gamma / \Delta D) / (\gamma / D) = \beta \quad (10)$$

when $EP > 1$, the effect is at a positive stage; $EP < 0$, at the negative effect stage; $0 < EP < 1$, at the declining stage.

3.3.2 Marginal yield analysis

Marginal yield (MPP) analysis was further introduced to analysis the index increase in additional each units PSD, ASD and SPD on the soil properties (Liu et al., 2002).

$$MPP = \partial\gamma / \partial D = \beta(\gamma / D) = \beta \left(\sum \gamma_i / \sum D_i \right) \quad (11)$$

where MPP is marginal yield; $\sum \gamma_i$ is the sum of each indicator of soil properties in each horizon; $\sum D_i$ is the sum of soil fractal dimension of each horizon.

4 Results and analysis

4.1 Soil fractal characteristics of PSD, ASD and SPD in typical forest stands

4.1.1 Soil fractal characteristics of ASD

The fractal dimension of ASD reflects the impact of soil aggregates on the soil structure and stability, that is, the smaller the fractal dimension, the better the structure and stability of the soil. Fractal dimension of ASD of each horizon in evergreen broadleaved shrub forest is the minimum (2.582), and the largest (2.718) is in the arable land, which indicates that the soil of evergreen broadleaved shrub forests has the best structural and stability, and the arable land is the worst. The soil micro-aggregates structure in forest is better than that in arable land, which is not influenced by soil humus layer and organic matter content, but by different types of plant roots in soil interludes, network effects.

Except *Phyllostachys pubescens* forests, in other forest lands, soil fractal dimensions of A horizon (2.713, 2.714, 2.644, 2.728) was higher than those of other horizons. It indicates that roots played a greater role in soil micro-aggregate formation, compared with the organic matter content and other factors. Because soil in arable land had a shallow root distribution, its fractal dimension (2.674) of AB horizon less than that of A horizon (2.728), which proved that root was beneficial to the formation of soil micro-aggregate.

By regression analysis, the relationship between fractal dimension of ASD and >0.005 mm micro-aggregates content was seen in the following formula:

$$D = -0.012,152x + 3.715,32, \quad R = -0.941 \quad (12)$$

where D is fractal dimension of ASD, x is >0.005 mm micro-aggregates content. The higher the content of >0.005 mm micro-aggregates, the lower the fractal dimension, the better the soil structure.

4.1.2 Soil fractal characteristics of PSD of typical forest stands

For soil mechanical composition, the coarser the soil texture, the smaller the fractal, and the more difficult to create a good soil structure. As is shown in Table 3, in Jinyun Mountain, the fractal dimension of PSD is 2.7–2.9, that is, the soil texture is finer and easy to create a good soil structure, which is directly related with good forest cover (canopy density above 0.8), abundant species and suitable climatic conditions. The fractal dimension of PSD followed the order: *Phyllostachys pubescens* forest (2.770) < evergreen broad-leaved forest (2.802) < evergreen broad-leaved shrub forest (2.818) < mixed *Pinus massoniana*-broadleaf forests (2.843) < arable land (2.852). The texture of *Phyllostachys pubescens* forests is the coarsest and its soil structure is the worst.

In A horizon: the soil texture of evergreen broadleaved shrub forest (fractal dimension of 2.878) is the finest, which related to its thickest litter layer and the largest litter reserves, the thickest humus layer, and the highest organic matter content; in AB and B horizons: the soil texture of mixed *Pinus massoniana*-broadleaf forest (fractal dimension 2.871 and 2.863) was the best, and its root distribution was wider. The roots compression action promoted its good soil structure formation; in C horizon: arable land is the optimal soil texture (fractal dimension 2.813) which is related to the process of development of parent material with the lighter human interruption.

The relationship between fractal dimension of PSD and clay (<0.005 mm) content of typical forestry in Jinyun Mountain is given as

$$D = 0.004,24x + 2.650,56 \quad R = 0.964 \quad (13)$$

where D is fractal dimension of PSD, x is <0.005 mm clay content. The higher the clay content of <0.005 mm, the higher the fractal dimension.

4.1.3 Fractal characteristics of SPD

The greater the fractal dimension of SPD, the more uniform the soil pore space, the better connectivity the soil. Comparing with fractal dimension of PSD and ASD, the SPD had the large variation between horizons (2.3–2.8). The SPD at all horizons is more complex than the PSD. The fractal

Table 3 Soil particle size distribution (PSD), aggregate size distribution (ASD) and soil pore size distribution (SPD) of each soil genetic horizon in different forest stands

Stands	Soil horizons	ASD ^{a)}		PSD ^{b)}		SPD ^{c)}	
		D	R	D	R	D	R
Mixed <i>Pinus massoniana</i> -broadleaf forest	A	2.713	0.98	2.844	0.96	2.678	0.90
	AB	2.644	0.90	2.871	0.92	2.645	0.89
	B	2.645	0.94	2.863	0.99	2.699	0.94
	C	2.664	0.99	2.794	1.00	2.321	0.99
	Average	2.667		2.843		2.586	
Evergreen broad-leaved forest	A	2.714	0.97	2.827	0.96	2.652	0.85
	AB	2.654	0.98	2.810	1.00	2.641	0.93
	B	2.644	0.98	2.764	0.99	2.684	0.97
	C	2.684	0.97	2.805	0.99	2.459	0.90
	Average	2.674		2.802		2.609	
<i>Phyllostachys pubescens</i> forest	A	2.630	0.99	2.735	0.98	2.567	0.93
	AB	2.680	0.99	2.778	1.00	2.485	0.99
	B	2.679	0.99	2.771	0.99	2.371	0.83
	C	2.660	0.96	2.797	1.00	2.442	0.88
	Average	2.662		2.770		2.466	
Evergreen broadleaved shrub forest	A	2.644	0.98	2.878	0.96	2.811	0.98
	AB	2.510	0.93	2.829	0.84	2.799	0.94
	B	2.592	0.98	2.747	0.97	2.747	0.95
	Average	2.582		2.818		2.786	
	Arable land (control)	A	2.728	0.95	2.874	0.92	2.747
	AB	2.674	0.91	2.853	0.85	2.669	0.92
	B	2.746	0.94	2.867	0.97	2.638	0.90
	C	2.725	0.97	2.813	0.99	2.585	0.96
	Average	2.718		2.852		2.660	

Notes: ^{a)}, ^{b)} and ^{c)} were Duncan values, the different letters means the differences are significant.

dimension (2.786) of SPD in evergreen broadleaved shrub forest was the largest, being more uniform porosity and permeability, and followed by arable land soil (2.660), *Phyllostachys pubescens* forest is the lowest (2.466), being the most uneven distribution of porosity and poor permeability. In A, AB and B horizons, evergreen broadleaved shrub forests had optimal porosity connectivity (fractal dimensions 2.811, 2.799 and 2.747), and better water permeability. Previous studies have shown that in broadleaved evergreen shrub forest, the initial infiltration rate (35.3 mm/min) and the steady infiltration rate (10.2 mm/min) were far higher than that in other soils (Wang and Wang, 2006). In C horizon: the composition of pore of *Phyllostachys pubescens* forest was better than the evergreen broadleaved forest, which mainly was affected by the parent material and its coarse texture.

The analysis of variance showed that there are significant difference in PSD, ASD and SPD among different forests soil $F_{(2,54)} = 26.39 > F_{0.01} = 5.02$, and further multiple comparisons indicated that the PSD, ASD and SPD among different forests and different soil horizons were significantly different at $\alpha = 0.05$, so the fractal dimensions of PSD, ASD and SPD should be used as indicators of soil structure.

4.2 Fractal characteristics and properties model of soil

Soil bulk density and porosity characterized the basic physical properties of soil. Soil organic matter is an important indicator for soil fertility evaluation. Soil natural moisture, wilting coefficient and field capacity characterized soil moisture status. Soil uniform index described homogeneous soil particles (the smaller the uniform index, the more uniform the soil particles) to some extent, and reflected the soil structure. Soil reunion, dispersion coefficient, structural factors could be used to express the soil corrosion resistance, the greater the dispersion coefficient, the worse the corrosion resistance, and

the larger the reunion and structure coefficient, the more powerful the soil resistance. That these indicators were used to characterize soil properties could reflect the nature of the soil, fertility status and conservation performance. Soil properties of different stands were shown in Table 4.

The relation of soil structure and its properties can explore the effect of soil structure on its property. Using the Eq. (3), the following nonlinear regression models was built based on the 19 soil samples in different horizons of different stands (Table 5).

It was shown in Table 5 that the soil properties had obvious dependency on the PSD, ASD and SPD of different forest and arable land in Jinyun Mountain (R is above 0.5), in particular, the characterization of soil moisture, corrosion resistance and soil uniformity (R is over 0.7).

4.3 Effects of fractal characteristics on soil properties

4.3.1 Elastic analysis

The elasticity coefficient (EP) of the fractal dimension changes was shown in Table 6. The effects of ASD on the following properties occurred negative effect ($EP < 0$), the total porosity, non-capillary porosity, capillary porosity, aggregate degree, structural factors and the field capacity. When the fractal dimension of ASD increases 1%, the above mentioned properties decrease 2.7%, 7.3%, 1.5%, 5.8%, 7.8% and 2.4%; performed positive effect on the organic matter content, diffusion coefficient, mechanical uniformity index, aggregate uniform index and natural water content of a positive effect, increase 7.5%, 16%, 10.3%, 2.8% and 30.4% respectively; exhibited degressive effects on soil bulk density and wilting coefficient ($0 < EP < 1$), that the fractal dimension of ASD increases 1%, they declined 0.05% and 0.17%. The ASD had the greatest effect on aggregate uniform

Table 4 Soil properties of different forest stands

Stand	Horizon	$e/\%$			B_d /($g \cdot cm^{-3}$)	O_c /($g \cdot kg^{-1}$)	$D_c/\%$	$C_d/\%$	$S_c/\%$	u_i	u_t	$\theta_0/\%$	$\theta_w/\%$	$\theta_c/\%$
		Total pore space	Non-capillary	Capillary tube										
Mixed <i>Pinus massoniana</i> -broadleaf forests	A	62.96	15.93	47.03	1.15	46.2	40.3	45.6	59.7	51.1	90.0	29.36	5.55	44.00
	AB	50.42	12.32	38.10	1.39	6.9	27.2	35.2	72.8	39.5	6.2	20.50	5.10	37.70
	B	49.43	12.27	37.16	1.51	3.9	24.8	14.7	75.2	87.0	8.0	20.91	5.40	28.19
	C	38.14	8.73	29.41	1.72	1.2	42.1	9.2	57.9	433.3	121.0	14.95	3.55	23.54
Evergreen broadleaved forests	A	55.92	12.40	43.52	1.18	31.8	45.8	28.9	54.2	48.2	43.0	25.82	4.68	41.55
	AB	44.60	10.26	34.34	1.49	3.0	36.2	10.0	63.8	273.3	83.0	17.57	3.07	32.54
	B	38.23	8.90	29.33	1.69	0.8	57.0	10.8	43.0	237.2	136.0	14.77	2.36	24.04
	C	42.44	9.80	32.64	1.53	1.0	52.5	10.8	47.5	214.6	135.0	15.99	2.28	23.19
<i>Phyllostachys pubescens</i> forest	A	58.5	14.48	44.02	1.14	20.8	42.1	7.7	57.9	225.7	50.5	22.20	2.97	29.75
	AB	47.11	12.70	34.41	1.46	11.0	48.9	14.7	51.1	253.4	150.0	16.55	2.69	24.47
	B	45.40	9.91	35.49	1.54	3.2	49.4	11.9	50.6	233.5	108.0	19.87	2.77	23.65
	C	43.91	9.99	33.92	1.64	2.0	47.7	8.6	52.3	269.8	162.5	20.07	5.38	23.91
Evergreen broadleaved shrub forest	A	73.33	16.94	56.39	0.73	77.9	16.8	55.6	83.2	35.4	44.6	33.31	5.94	44.12
	AB	57.85	14.21	43.64	1.17	14.1	13.7	47.2	86.3	15.9	3.5	24.21	6.79	40.10
	B	45.29	11.43	33.86	1.46	2.9	36.0	8.9	64.0	439.3	31.1	15.78	4.07	31.08
Arable land (Control)	A	72.01	10.8	61.21	0.78	69.7	32.6	51.1	67.4	38.5	31.0	33.06	6.11	36.47
	AB	40.70	5.77	34.93	1.45	9.1	39.9	39.8	60.1	20.0	14.5	27.50	7.71	31.91
	B	29.20	4.92	24.28	1.87	3.0	51.1	12.5	48.9	47.7	58.3	20.25	9.52	22.66
	C	30.60	5.06	25.54	1.63	1.4	61.9	8.4	38.1	284.1	26.7	19.79	5.99	21.47

Table 5 Relationships between soil properties and fractal dimension of soil

Soil properties	Relation to fractal	R
Organic content /(g · kg ⁻¹)	$\gamma = 8.78E - 16D_t^{7.452} D_j^{16.735} D_k^{12.382}$	0.569
Total porosity /%	$\gamma = 5.14D_t^{-2.661} D_j^{3.073} D_k^{1.697}$	0.546
Non-capillary porosity /%	$\gamma = 5.73E + 3D_t^{-7.345} D_j^{0.110} D_k^{0.797}$	0.572
Capillary porosity /%	$\gamma = 4.46E - 1D_t^{-1.505} D_j^{3.891} D_k^{1.917}$	0.601
Volume weight of soil /(g · cm ⁻³)	$\gamma = 1.42E + 2D_t^{-0.053} D_j^{-2.413} D_k^{-2.185}$	0.561
Dispersion coefficient /%	$\gamma = 2.34E + 2D_t^{15.982} D_j^{-16.413} D_k^{-0.510}$	0.937
Aggregate degree /%	$\gamma = 8.46E - 12D_t^{-5.784} D_j^{29.725} D_k^{3.385}$	0.795
Structural coefficient /%	$\gamma = 1.44E + 1D_t^{-7.789} D_j^{8.571} D_k^{0.166}$	0.855
Mechanical uniform index	$\gamma = 5.88E + 21D_t^{10.352} D_j^{-49.1391} D_k^{-4.900}$	0.853
Aggregate uniform index	$\gamma = 5.03E + 7D_t^{30.424} D_j^{-38.121} D_k^{-4.473}$	0.794
Wilting coefficient /%	$\gamma = 3.16E - 8D_t^{-0.173} D_j^{16.841} D_k^{1.559}$	0.753
Nature moisture content /%	$\gamma = 1.86E - 4D_t^{2.774} D_j^{6.877} D_k^{1.891}$	0.747
Field capacity /%	$\gamma = 3.47E - 1D_t^{-2.435} D_j^{4.524} D_k^{2.248}$	0.722

index, due to the larger fractal dimension of ASD led to the relative uniform granular, perform poor structure.

Fractal dimensions of PSD and SPD have negative effects on soil bulk density, dispersion coefficient, mechanical uniformity index and aggregate uniform index, in the condition of fractal dimension of PSD increased by 1%, they reduced 2.4%, 16.4%, 49.1% and 38.1%; fractal dimension of SPD by 1%, they reduced 2.1%, 0.5%, 4.9% and 4.5%; whereas, organic matter content, porosity, capillary porosity, reunion, the natural water content, wilting coefficient and field capacity, fractal dimension of PSD increased by 1%, they increased 16.75%, 3.1%, 3.9%, 29.7%, 6.9%, 16.8% and 4.5%, fractal dimension of SPD by 1%, they increased 12.4%, 1.7%, 1.9%, 3.4%, 1.9%, 1.6% and 2.2%, for non-capillary pores diminishing effects were 0.1% and 0.8%; and fractal dimension of SPD performed diminishing effects on structural coefficient of 0.2%. Fractal dimension of PSD had the greatest impact on mechanical uniformity index, the fine soil texture led to more coarse particles and reduced its uniformity index, but it is beneficial for aggregate formation. Soil aggregate uniform index was also influenced greatly by

Table 6 EP (Elasticity coefficient) and MPP (Marginal yield) of soil properties

Soil Properties	EP			MPP		
	ASD	PSD	SPD	ASD	PSD	SPD
Organic content /(g · kg ⁻¹)	7.452	16.735	12.382	45.615	96.904	77.302
Total porosity /%	-2.661	3.073	1.697	-47.944	52.390	31.189
Non-capillary porosity /%	-7.345	0.110	0.797	-30.006	0.425	3.320
Capillary porosity /%	-1.505	3.891	1.917	-20.976	51.290	27.240
Volume weight of soil /(g · cm ⁻³)	-0.053	-2.413	-2.185	-0.028	-1.196	-1.167
Dispersion coefficient /%	15.982	-16.413	-0.510	241.793	-234.898	-7.873
Aggregate degree /%	-5.784	29.725	3.385	-49.307	239.726	29.431
Structural coefficient /%	-7.789	8.571	0.166	-174.457	181.615	3.802
Mechanical uniform index	10.352	-49.139	-4.900	663.986	-2,981.539	-320.571
Aggregate uniform index	30.424	-38.121	-4.473	782.906	-927.979	-117.411
Wilting coefficient /%	2.774	6.877	1.891	22.924	53.767	15.945
Nature moisture content /%	-0.173	16.841	1.559	-0.314	28.928	2.887
Field capacity /%	-2.435	4.524	2.248	-28.101	49.399	26.463

PSD, the mechanical composition determined the soil texture, the fine texture benefits a good soil structure, making an increase in soil particles reunion and increasing the capability of scattered resistance. The effects of fractal dimension of SPD compared with ASD and PSD is lower, and had the greatest impact on the distribution of organic matter content.

In typical arable land and forest soils of Jinyun Mountain, fractal dimension of PSD had greater effects on soil properties than those of ASD and SPD. The change in the soil structure means that the mechanical components, micro-aggregates, the composition of pore changed together. Therefore, the soil properties change is a comprehensive result, especially for PSD.

4.3.2 Marginal analysis

One unit value of fractal dimension of ASD brought about the changes in organic matter content, total porosity, non-capillary porosity, capillary porosity, soil bulk density, dispersion coefficient, aggregate degree, structural factor, mechanical uniformity index, aggregate uniformity index, natural water content, wilting coefficient, and field capacity of 45.6%, -48%, -30%, 7.9%, -0.03%, 241.8%, -49.3%, -174.5%, 664%, 783%, 22.9%, -0.3% and -28.1%. For PSD, the value changes are 96.9%, 52.4%, 0.4%, 51.3%, -1.2%, -234.9%, 239.7%, 181.6%, -298.1%, -928%, 53.8%, 28.9% and 49.4%. For SPD, the value changes are 77.3%, 31.2%, 3.3%, 27.2%, -1.2%, -7.9%, 29.4%, 3.8%, -320.6%, -117.4%, 15.9%, 2.9% and 26.5%. It can be seen from the marginal analysis that in Jinyun Mountain, PSD had greater effects than ASD and SPD. Moreover, both PSD and ASD had the greatest effects on uniformity index, and SPD had the greatest effects on soil fertility and water-holding properties.

5 Conclusions and discussion

1) Fractal dimension of ASD, PSD and SPD can be used as indicators of soil structure. Fractal dimension of PSD in

different stands are between 2.7 and 2.9, followed the order: *Phyllostachys pubescens* forest (2.770) < evergreen broadleaved forest (2.802) < evergreen broadleaved shrub forests (2.818) < mixed *Pinus massoniana*-broadleaf forest (2.84.3) < arable land (2.852). The *Phyllostachys pubescens* forest had the coarsest texture and had the worst ability to form good soil structure.

The fractal dimension of ASD is 2.5–2.8, and is obviously lower than that of PSD. This shows that both woodland and farmland activity have a positive impacts on good soil structure formation. The fractal dimension in each horizon is the smallest (2.582), and the largest in the arable land (2.718). The soil structural and stability of evergreen broadleaved shrub forests is the best and the arable land is the worst.

The fractal dimension of SPD in evergreen broadleaved shrub forests is the largest (2.786), followed by arable land (2.660), the worst in *Phyllostachys pubescens* forest (2.466). The soil in the *Phyllostachys pubescens* forests is the most uneven and its permeability is poor.

The soil structure of evergreen broadleaved shrub forest is all the best in PSD, ASD and SPD, and the soil of *Phyllostachys pubescens* forest is the worst. Therefore, the fractal dimension of PSD, ASD and SPD can be taken as the indices of soil structures evaluation.

2) There also were the certain relationships among the PSD, ASD, SPD and some soil properties in the different forests and arable land (R is over 0.5), especially for soil retentiveness, corrosion resistance and evenness degree (R over 0.7). For this paper, some preliminary studies just were conducted on the relationship between fractal dimension and soil properties, and the soil properties scope was relatively small. However, according to the model of fractal dimension of soil structure and soil properties, the effect of soil structure change on the basic physical properties, fertility status and properties and water conservation of forestland can be discovered. Therefore, this paper provided a new research method for studying different properties of forestry soil and water conservation function of different vegetation types, and this approach can be further proved by more and more studies on vegetation types and soil properties.

3) By the elastic effect (EP) and marginal effect analysis (MPP) of the fractal dimension on the soil properties, it can be seen that, for ASD, when fractal dimension of ASD increased by 1%, the EP of soil properties changes is -7.3% – 30.4% , and increased one unit value, MPP change scope is -48% – 783% ; and for PSD, the EP change among -49.1% – 29.7% , and MPP of $2,982\%$ – 240% ; for SPD, EP change of -4.9% – 12.4% , and MPP of -321% – 77% . Based on the elasticity analysis and marginal yield analysis, the effect of PSD was more than those of ASD and SPD. Therefore, the soil texture was the basic factor, because good soil texture was the fundamental condition to form good soil structure. Obviously, the further research on the fractal theory application in soil structure and soil properties has important significance.

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