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An analysis of soil fractal dimension in a sloping hedgerow agroforestry system in the Three Gorges Reservoir Area, China

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Abstract Hedgerow intercropping provides an efficient method of controlling soil erosion and improving soil fertility on sloping agricultural land. Topsoil (0–20 cm soil layer) of 32 plots established in the Three Gorges Reservoir Area of the Yangtze River was sampled from the steep land between hedgerows (P1) and within hedgerows uphill (P2), under (P3) and downhill (P4) from the hedgerow were analyzed and the soil volumetric fractal dimension (DV) was calculated and the relationships between DV and soil physicochemical properties were tested. Results show that hedgerows effectively intercept clay particles in soil; the soil clay concentration within hedgerows was significantly higher ($P < 0.05$) than that of the soil between hedgerows at P1, respectively. The soil DV varied significantly among different positions in hedgerow systems, the DV of soil within hedgerows at P2, P3 and P4 were significantly higher ($P < 0.05$) than that of the soil between hedgerows at P1. DV was correlated positively and very significantly ($P < 0.01$) with the soil clay concentration ($R^2 = 0.93$) and silt content ($R^2 = 0.74$), and the DV was significantly ($P < 0.01$) and negatively correlated with soil sand content ($R^2 = 0.78$). The DV was significantly correlated with various soil physical properties and concentrations of soil nutrients. Therefore, the DV can be considered as a potential and accurate evaluating indicator for soil quality and nutrient conservation as they relate to the hedgerow intercropping on steep land.

Keywords Hedgerow agroforestry system · Soil nutrients · Soil physical properties · Three Gorges Reservoir Area · Volumetric fractal dimension

Introduction

Soil particle-size distribution (PSD), typically presented as the percentage of the total mass of clay, silt and sand, is one of the most fundamental soil physical properties and is related to soil erosion and other hydrological process (Giménez et al. 1997; Huang and Zhang 2005). In addition, PSD serves as an important index for the evaluation of soil and its relationship with other soil functions. During the last few decades, the concept of fractal dimension has been introduced to soil science and is used to quantitatively describe PSD as a single value (Tyler and Wheatcraft 1992;

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Yang et al. 1993). The application of fractal dimension to the concept of PSD provides a novel method that can be used to describe soil structure; this method has been used as a relatively accurate tool in studies related to physical properties of soil, soil erosion and other hydrological processes. Moreover, the PSD is often used to estimate several properties in soils, such as texture and moisture characteristics (Wang et al. 2006). Previous studies had replaced the volumetric distribution of soil particles by the mass distribution of soil particles when evaluating the soil fractal dimension (Tyler and Wheatcraft 1992; Yang et al. 1993) based on the hypothesis that soil particles with different radii have the same density. However, the evidence that the density of soil particles with different radii vary had been proved (Martin and Montero 2002; Eshel et al. 2004). Therefore, it is reasonable and accurate to use the soil particle volumetric distribution to calculate the soil volume fractal dimension directly. Among various convenient and time-saving techniques, laser diffraction (LD) has been applied to soil science and to measures of soil DV, and has proved to be a reliable method for the estimation of PSD. The soil volume fractal dimension provides a new approach to describe the distribution of soil particles (Ci et al. 2009).

Population growth, economic development, and the loss of farmland caused by the construction of the Three Gorges Dam construction have all applied additional pressure on farmers to use steep farmland. A growing need has been created to improve the sustainability of farming techniques that are typically used on steep farmland. Hedgerow intercropping, an agroforestry technique, involves the cultivation of annual crops that are planted between the contours of hedgerows consisting of perennial shrubs or tree species; in this setting, legumes (Ssekabembe 1985) as well as grass species have been cultivated. This type of intercropping is believed to be an efficient technique for controlling soil erosion and improving soil fertility on sloping agricultural land. Runoff easily erodes fine soil particles with their associated nutrients (Basic et al. 2004). Hedgerows constructed in steep farmland may effectively control erosion by intercepting fine soil particles and slowing water flow thereby decreasing erosion. Therefore, the PSD of soil, including the redistribution of clay held by such hedgerows, can be considered to be a reflection of the effects of hedgerows on soil interception and nutrient conservation. Different positions within different types of hedgerow systems will have distinctive types of effects on distribution of soil nutrients and particles and the variations in their concentrations in steep land hedgerow systems.

Studies of steep farmland have focused most of their attention on the use of hedgerows and the effects of hedgerows on soil erosion and soil properties (Young 1997; McDonald et al. 2002). Very few studies have analyzed the redistribution of soil particles and nutrients from the uphill to lower elevations in hedgerow systems and fewer studies have attempted to evaluate the benefits of hedgerows on the conservation of soil and nutrients in steep land using an analysis of the soil volume fractal dimension (DV). The objective of this study was to evaluate the effects of hedgerows on the redistribution of soil particles and variations in DV among different hedgerow systems. The correlations between DV and both soil physical properties and soil nutrients were also tested to determine the potential for using DV as a parameter to evaluate soil conditions and nutrients loss as well as to analyze the effects of hedgerows on soil and nutrient conservation in steep land.

Materials and methods

Description of the study site

The Jiangjin District of Chongqing City was selected as the study area because of its representative hedgerows and topographical position. Jiangjin stands along the middle and upper reaches of the Yangtze River and in the Gorges Reservoir Area (28°28′–29°28′N, 105°49′–106°38′E) and is characterized topographically by steep slopes. The landscape of the area is dominated by the uplands with elevations between 180 and 1710 m. The subtropical monsoon climate zone of the study area has an annual average temperature of 18.4 °C and rainfall of 1030 mm; the relative humidity averages 81 %. The major agricultural crops in the area are maize (*Zea mays* L.) and sweet potatoes (*Ipomoea batatas* (L.) Lam.). The typical purple and paddy soils (FAO/USDA) developed from purple sandy shale. Purple soil is the most common soil type in the Three Gorges Area, and dominates over 79 % of the area (Shi et al. 2008).

Hedgerow systems

The hedgerows described below had been established for 5 years, with the slope gradient ranging from 15° to 25° (Fig. 1). The alleys, the space between hedgerows, averaged 5 m wide. Alleys were planted with annual crops, mainly maize and sweet potatoes. The intra-hedgerow width, that is, the width of each hedgerow itself without considering the alleys, ranged from 1 to 2 m varying for different species. Tree hedgerows were planted in one row of canopy cover 2 m wide, with pure or mixed species plantations, including mulberry (*Morus alba* L.), orange trees (*Citrus reticulata* Banco), Chinese Prickly-ash (*Zanthoxylum simulans*), pear trees (*Pyrus serotina* Rehd.) and plum trees (*Prunus cerasifera* Ehrh.). Shrub hedgerows afforested with 2 or 3 rows of shrub species included sites with mixed plantings of *Vitex negundo* L., *Ailanthus altissima* (Mill.) Swingle and *Alangium chinense* (Lour.) Rehd. Grass hedgerows were 1 m wide and planted with pure stands of *Gynura bicolor* DC., Herba Rorippae (*Rorippa montana* (Wall.) Small), and *Alternanthera philoxeroides* Griseb. Canopy cover exceeded 90 % in all hedgerows and pruned biomass was simply applied to the soil in alley farmland or used for feeding livestock or fuel wood.

Soil sampling and analysis

Prior to the initiation of cultivation in 2006, hedgerow plots (5 m wide by 20 m long) were arranged randomly within the hedgerow system on the middle slope. In each plot, topsoil (0–20 cm soil layer) was sampled from the steep land between hedgerows (P1) and within hedgerows at three locations, uphill (P2), under (P3) and downhill (P4) from the hedgerow (Fig. 1). Soil from each plot of the four locations (P1, P2, P3 and P4) described above were collected in triplicate and the soil particle distribution and soil physicochemical properties were tested.

Saturated volumetric water content (SVWC) was tested with a Field Scout TDR 100 Soil Moisture Meter

Fig. 1 Schematic of the experimental and soil sampling sites. P1 is in the center of middle slope alley between hedges, P2 is slightly uphill from hedgerows (0.5 m), P3 is under hedges, and P4 is slightly downhill from hedgerows (0.5 m)

(Spectrum Technologies, 3600 Thayer Court, Aurora, IL, USA). Saturated hydraulic conductivity (SHC) was measured using the constant water head method (Amoozegar 1989). Soil bulk (BD) density was determined by the undisturbed core method (SICAS 1978).

Soil samples were dried naturally; then, gravel and roots were carefully removed prior to sub-sampling. Next, about 200 g of soil were ground and sieved, reserving a portion for PSD and nutrients concentration analysis. Several routine methods were used to measure soil nutrient content (SICAS 1978). Soil organic matter (SOM) was determined using titration and with potassium dichromate (K_2CrO_7) oxidation in an oil bath. For total nitrogen (TN), a Kjeltec Model 1030 Auto Analyzer (Nippon General Trading Co., Tokyo, Japan) was used with sulphuric acid (H_2SO_4) digestion. Available nitrogen (AN) was determined using titration and with alkaline hydrolysis in a thermotank (40 ± 1 °C for 24 ± 0.5 h). Total and available phosphorus (TP, AP) were determined using a spectrophotometer with sulphuric acid (H_2SO_4) digestion of total phosphorus and sodium bicarbonate ($NaHCO_3$) extraction of available phosphorus. Flame photometry was used to determine total potassium (TK) and available potassium (AK). Total potassium was digested with hydrofluoric acid (HF) and perchloric acid ($HClO_4$), while available potassium was extracted using ammonium acetate (NH_4-Acetate). Cation exchange capacity (CEC) was determined by extracting the exchangeable bases using ammonium acetate (NH_4Ac).

Soil particle distribution was determined using a laser granulometer (Fritsch Particle Sizer analysette 22′, Fritsch, Idar-Oberstein, Germany) based on the volume of soil in each size class (Wang et al. 2007; Dur et al. 2004). The particles sized from 0 to 2500 μm were classified to 14 sub-intervals by default setting.

Theory for soil fractal dimension

The current PSD fractal model has been defined using Eq. (1) (Tyler and Wheatcraft 1992; Yang et al. 1993):

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

where $V(r < R)$ is the volume of soil particles with a radius smaller than R, V_T is the total volume of the soil particles, R_{max} is the upper size limit for soil particles, and D is the volume fractal dimension.

In this study, Eq. (1) was used to determine the soil PSD date. The 3-D was determined by a linear regression which was used to fit Eq. (1) on a log–log plot to the experimental data.

Statistical analysis

Statistical analysis was carried out using SPSS (version 11.5) and Microsoft Office Excel (version 2007). One-way ANOVA was used to test means among soil particle concentration and soil volumetric dimension and its coefficient of determination for linear regression. Significant differences between treatments means were evaluated according Duncan's shortest range test with $P < 0.05$. Linear regression was used to test the relationship between DV and certain diameter soil particle concentration. The correlations between soil DV and various soil properties and nutrients were tested using Pearson's correlation.

Results

Soil particle-size distribution and volumetric fractal dimension (DV) among hedgerow systems

Soil volumetric fractal dimension (DV) in all soil samples collected among hedgerow systems ranged from 2.31 to 2.47 (Table 1), with a Coefficient of Variance (CV) of 1.38 %. The coefficient of determination for regression of DV ($R^2 > 0.85$, $R_{0.01}$ (14–2) = 0.78) indicated that DV was positively correlated and the correlation was highly significant ($P < 0.01$) with the distribution of soil particle size.

The soil DV varied significantly among different hedgerows and positions in hedgerow systems (Table 2). For hedgerows with trees, grass and shrub

Table 1 Descriptive statistics of soil volumetric fractal dimension (DV) and coefficient of determination for regression of DV

Items	*N*	Minimum	Maximum	Mean	SD	Cv (%)
DV	128	2.31	2.47	2.40	0.03	1.38
R^2	128	0.85	0.96	0.90	0.02	2.44

Cv coefficient of variation, *N* number of samples, *SD* standard deviation species, the DVs of soil within hedgerows at P2, P3 and P4 were significantly higher ($P < 0.05$) than that of the soil at P1. However, these differences were not always significant ($P = 0.05$) in soil within hedgerows at P2, P3 and P4. There were no significantly differences of soil DVs within tree hedgerows at P2, P3 and P4; however, for grass and shrub hedgerows the soil DV values at P2 and P3 were significantly higher ($P < 0.05$) than that of the soil at P4.

The ANOVA results showed various amounts of spatial variation existed in the soil particle concentration among different position (P1, P2, P3 and P4) with different hedgerows (Table 2). The sand concentration of soil between hedgerows (P1) with tree and shrub species were 50.56 and 42.17 %, respectively, which were significantly higher ($P < 0.05$) than that of the soil within hedges at P2, P3 and P4. For shrub hedgerows, the soil sand concentration at P1 was significantly higher ($P < 0.05$) than that of the soil at P2, P3, but there were no significant differences between soil at P1 and P4. The mean soil clay concentration within hedgerows at P2, P3 and P4 was 7.83, 7.54 and 7.30 % respectively, which was significantly higher ($P < 0.05$) than that of the soil between hedgerows at P1.

Relationship between soil particle content volumetric fractal dimension (DV)

The DV was positively significantly ($P < 0.01$) correlated with the soil clay and silt content (Fig. 2b–c). However, the DV was significantly ($P < 0.01$) negatively correlated with the soil sand content (Fig. 2a). The DV and concentration of soil particles with specific diameters (sand, silt and clay content) followed the relationship of linear law, the formula were $y = -0.0036\ x + 2.5664$ ($R^2 = 0.79$, $n = 128$), $y = 0.0041\ x + 2.2122$ ($R^2 = 0.93$, $n = 128$), and $y = 0.024\,x + 2.2182$ ($R^2 = 0.74$, $n = 128$), respectively.

Correlation between volumetric fractal dimension (DV) and soil properties

The DV of soil in hedgerow systems was correlated with soil physical properties and concentrations of soil nutrients (Tables 3 and 4). Specifically, the DV in soil among hedgerow systems was positively and significantly ($P < 0.01$) with SVWC and SHC with Pearson's correlation coefficients of 0.460, and 0.635, respectively. Soil bulk density (BD) was negatively correlated ($P < 0.01$) with DV ($r = -0.240$). Among

Table 2 Soil particle size composition and soil volumetric fractal dimension (DV) in different positions of topsoil among hedgerow systems involving different species

Categories	Position	Particle fraction (%)			*DV*
		Sand (0.25−0.02 mm)	Silt (0.02−0.002 mm)	Clay (<0.002 mm)	
Tree species ($n = 14$)	P1	50.56 ± 8.81a	42.73 ± 7.46b	6.71 ± 1.38c	2.38 ± 0.04b
	P2	45.45 ± 8.22b	46.79 ± 7.18ab	7.76 ± 1.10ab	2.40 ± 0.03a
	P3	43.02 ± 8.11b	48.62 ± 6.89a	8.37 ± 1.36b	2.42 ± 0.03a
	P4	47.42 ± 7.15b	45.23 ± 6.14ab	7.35 ± 1.10b	2.40 ± 0.03a
Grass species ($n = 10$)	P1	55.67 ± 10.82a	38.26 ± 9.06b	6.07 ± 1.94c	2.36 ± 0.05c
	P2	44.80 ± 8.34b	47.26 ± 7.06a	7.95 ± 1.32a	2.41 ± 0.03a
	P3	47.29 ± 7.63b	44.78 ± 6.58b	7.93 ± 1.23a	2.41 ± 0.02a
	P4	52.10 ± 9.28ab	41.16 ± 7.83b	6.74 ± 1.50ab	2.38 ± 0.03b
Shrub species ($n = 8$)	P1	45.56 ± 6.78a	47.03 ± 6.52c	7.42 ± 0.26c	2.40 ± 0.04c
	P2	42.17 ± 6.57b	49.55 ± 6.49b	8.29 ± 1.08ab	2.42 ± 0.01a
	P3	39.83 ± 7.33c	51.56 ± 7.90a	8.62 ± 1.43a	2.42 ± 0.03a
	P4	42.06 ± 7.79b	49.93 ± 9.80ab	8.02 ± 1.01b	2.41 ± 0.02b

Values indicated in table are mean ± SD. Mean values followed by different letters within the same column in the same hedgerow are significantly different at $P < 0.05$ according to Duncan's shortest range test. P1 is in the center of middle slope alley between hedges, P2 is slightly uphill from hedgerows (0.5 m), P3 is under hedges, and P4 is slightly downhill from hedgerows (0.5 m)

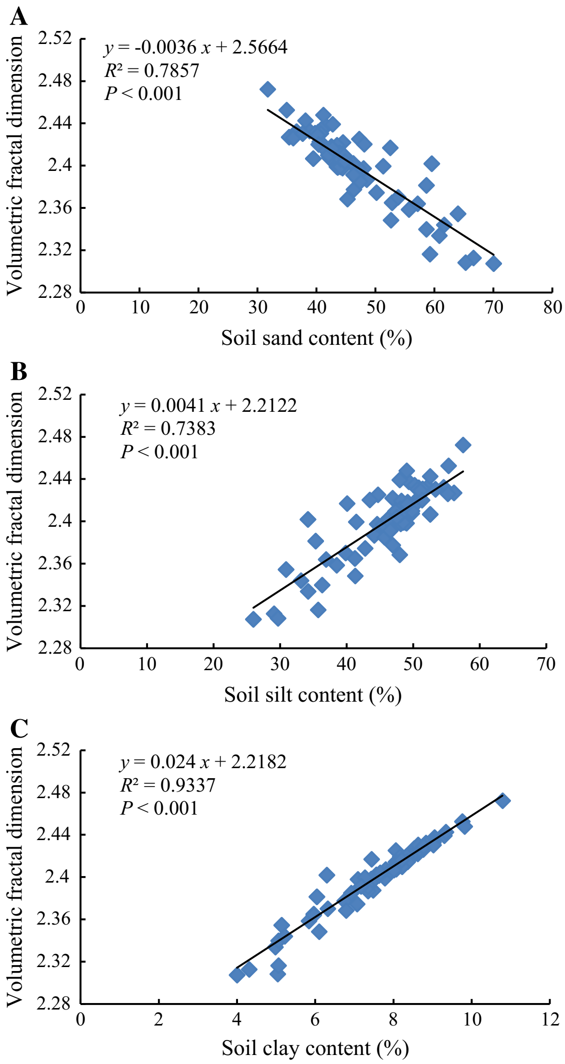

Fig. 2 The relationship between soil volumetric fractal dimension and the concentration of soil particles of specific diameters ($n = 128$). **a** sand content, **b** silt content, **c** clay content

soil nutrients, there was positive correlation ($P < 0.01$) between DV and the content of SOM, TN, AN, TK, AK and CEC, and less significantly ($P < 0.05$) with TP. No significant correlation was observed for DV and AP of soil in hedgerow systems.

Discussion

Effect of hedgerows on soil spatial particle distribution and volumetric fractal dimension (DV)

The variation in soil DV among hedgerow systems was mainly attributed to the spatial redistribution of soil particle in different positions of a hedgerow system. The clay content of soil within hedgerows at P2, P3 and P4 in study was higher than that of soil between hedgerows (P1), and the same variances observed for DV in hedgerow systems with different species. The generally high value of the coefficient of determination shows that the DV was highly correlated with the concentration of soil particles of a certain radius (clay, silt and sand concentration). Although DVs are significantly ($P < 0.01$) correlated with silt and sand content (Bittelli et al. 1999; Liu et al. 2009), the coefficient of the determination between clay concentrations had the highest value. Therefore, clay content serves as the critical factor in determining DV. Specifically, a higher clay content of is expected to be reflected in a higher DV (Tyler and Wheatcraft 1992; Dur et al. 2004; Martin and Montero 2002; Eshel et al. 2004; Wu et al. 1993; Wang et al. 2005; Pieri et al. 2006).

Table 3 Correlation coefficients between various soil physical properties and soil volumetric fractal dimension (DV; $n = 128$)

Variables	DV	BD	SVWC	SHC
Volumetric fractal dimension (DV)	1			
Soil bulk density (BD)	−0.240**	1		
Saturated volumetric water content (SVWC)	0.460**	−0.304**	1	
Saturated hydraulic conductivity (SHC)	0.635**	−0.548**	0.493**	1

** and * indicate correlation is significant at the 0.01 and 0.05 level (2-tailed), respectively

Table 4 Correlation coefficients between various soil nutrients concentration and soil volumetric fractal dimension (DV; $n = 128$)

Variables	DV	OM	TN	AN	TK	AK	TP	AP	CEC
Volumetric fractal dimension (DV)	1								
Soil organic matter (SOM)	0.420**	1							
Total N (TN)	0.501**	0.678**	1						
Available N (AN)	0.318**	0.627**	0.555**	1					
Total K (TK)	0.501**	0.291**	0.428**	0.152	1				
Available K (AK)	0.262**	0.521**	0.457**	0.399**	0.040	1			
Total P (TP)	0.226*	0.373**	0.250**	0.055	0.088	0.359**	1		
Available P (AP)	0.010	0.355**	0.124	0.247**	0.057	0.382**	0.451**	1	
Cation exchange capacity (CEC)	0.554**	0.354**	0.426**	0.240**	0.394**	0.334**	0.491**	−0.042	1

** and * indicate correlation is significant at the 0.01 and 0.05 level (2-tailed), respectively

The higher clay concentrations were observed in soils within hedgerows at P2, P3 and P4 than that of soil at P1 because clay is more easily eroded by runoff than sand, so that clay particles are selectively removed by runoff from the upper parts of the steep land and accumulate immediately uphill from and under hedgerows when hedgerows intercept soil particles (Magette et al. 1989). The hedgerows acted as a sieve-barrier to eroding soil capable of sufficiently obstructing runoff and enhancing the deposition of sediment carried by runoff (Young 1997; Mutegi et al. 2008). Advanced and effective obstruction of soil movement by sediment entrapment of sediment immediately uphill from and under hedgerows is caused by the formation of hedgerow terraces along hedgerows and the coarse belt under the hedgerow canopy formed by litter (Lal 1989; Pelleck 1992).

With respect to the ability of hedgerows to dissipate runoff and allow sediment deposition, hedgerow barriers can change the process and intensity of erosion. In addition, hedgerows change the way soil moves and is deposited causing the redistribution of soil clay. Therefore, the soil particles and DV vary within hedgerow-steep land systems.

Correlation between volumetric fractal dimension (DV) and soil properties

Soil texture classification, usually measured using percentages of clay, silt and sand within certain size ranges, is critical for understanding the transportation and storage of soil water and nutrients, and the mineralization of SOM (Bevan and German 1982; Parton et al. 1988). The presence of hedgerow litter improves the formation of soil structure by increasing the soil clay and organic matter content (Shi et al. 2008); this is beneficial to decreasing bulk density and increasing water infiltration (Young 1997). Moreover, an increase in clay concentration for soil obstructing by hedgerows leads to enhancement of the adhesive forces of soil which improves the ability of soil to absorb water and improves the cation content in soil (Tong et al. 1994). Based on the above discussion, it is easy to understand why DV is positively and significantly correlated with soil bulk density, soil porosity, SVWC and saturated hydraulic conductivity.

A positive and strong correlation ($P < 0.01$) was observed between DV and organic matter, total N, available N, total K, available K, and CEC, and less significantly ($P < 0.05$) with total P. The strong correlation between DV and these soil nutrients can be interpreted as being caused by an increase in fine soil particle and organic matter content. Soil clay particles bind nutrients in soil (Magette et al. 1989; Xu and Shen 2000), so that an increase in soil clay content is beneficial to the accumulation of soil nutrients. Furthermore, the addition of green manure provided by hedgerow litter and pruning helps to improve SOM and nitrogen content in soil (Nelson et al. 1998); that is, most soil nutrients are derived from mineralized organic matter. Therefore, the high correlation between DV and soil nutrient content can be partly attributed to the increase in soil clay particle content and partly attributed to the increase in SOM content. However, the extent to which DV can reflect changes in soil nutrient content deserve further study, although

DV are highly correlated with soil nutrient content in our study with the exception of available P.

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