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

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Abstract
Fractal scaling theory was employed to analyze the fractal dimension of soil particle-size distribution (PSD) for different plant communities with similar soil types in a watershed in the middle Dan River Valley, China. A total of 296 soil samples were collected from 78 sites. PSD and total soil nitrogen (TSN) were determined in soil from depths of 0–60 cm in four soil horizons for different plant communities. Soils in this area typically comprise silt and fine sand. The fractal dimensions of the six selected plant communities ranged from 2.73–2.89, with fractal dimension (Dn) values of grassland and forestland being lower (2.73–2.78) than those of cropland (2.81 and 2.89). There was an obvious decreasing trend in TSN content with increasing depth under the various plant communities. Spatial patterns of TSN changed significantly with land-use types. Organic nitrogen was the main component of soil nitrogen. There was a strong positive correlation between the fractal dimension and the silt and clay content (n= 78, R2 = 0.96, P<0.01), with increasing Dn values corresponding to higher silt and clay contents. The Dn value and TSN content both indicated positive correlations with silt and clay content at a depth of 20–60 cm. These results demonstrate that fractal dimension analysis offers a useful approach to quantify and assess the degree of soil degradation among similar soil types, but that anthropogenic disturbances can have a great impact on the fractal dimensions for different land-use types. Cropland was prone to soil degradation, especially on steep slopes. Consequently, improved conservation measures are needed to enhance and sustain soil and water quality, and to prevent further soil degradation in the middle Dan River.

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1. Introduction

Soil particle-size distribution (PSD) is one of the most important soil physical attributes due to its great influence on water movement, productivity, and soil erosion. In areas with high soil erosion rates induced by water such as rainfall and runoff, fine particle-size fractions (accompanied by nutrients) are selectively removed or deposited during soil erosion processes (Wang et al., 2008). A soil aggregate is made of closely packed sand, silt, clay, and organic particles. Applications of fractal geometry in soil science have shown that soil exhibits fractal characteristics, being a porous medium with different particle compositions that have irregular shapes and self-similar structures (Liu et al., 2009; Rieu and Sposito, 1991a,b; Tyler and Wheatcraft, 1992). Martínez-Mena et al. (1999) used the fractal dimension of soil aggregates (Dn) as an indicator of soil erodibility. They estimated Dn from the fractal model proposed by Rieu and Sposito (1991b) using dry-sieving of soil aggregates. The results of their study confirmed that higher Dn values were associated with lower aggregate stabilities and that the Dn can be a useful index for characterizing and describing soil erodibility. Different types of land-use and vegetation largely influence PSD by either enhancing or inhibiting soil erosion (Basic et al., 2004; Erskine et al., 2002; Fullen et al., 2006; Martínez-Casasnovas and Sánchez-Bosch, 2000; Wang et al., 2008). Wang et al. (2006b) determined the fractal characteristics of soils under different land-use patterns. The results of their study showed that land-use had considerable effects on the fractal dimension of PSD and other soil properties. Such studies support the use of fractal theory for quantifying soil structure, soil erodibility, and soil permeability (Huang and Zhan, 2002; Perfect and Kay, 1995; Rieu and Sposito, 1991a,b). In addition, fractal parameters have also become important in understanding and quantifying soil degradation and land desertification (Su et al., 2004).

Soil erosion and water loss not only affect the fractal dimension of soil particle-size distribution, but also leads to non-point source pollution (Huang and Zhan, 2002; Munodawafa, 2007; Tyler and Wheatcraft, 1992). In agricultural ecosystems, total soil nitrogen (TSN) and total soil phosphorus (TSP) are the major determinants and indicators of soil fertility and quality, which are closely related to soil productivity.

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In an agricultural context, nitrogen and phosphorus are the main non-point source pollutants of surface water and groundwater (Søvik and Aagaard, 2003; Wang et al., 2009). The reduction of TSN and TSP levels can result in decreased soil nutrient supply, fertility, porosity, penetrability, and consequently, soil productivity (Huang et al., 2007). Furthermore, the removal of excess nitrogen and phosphorus from soil by leaching or by rainfall scouring and soil erosion may lead to environmental problems, such as agricultural non-point source pollution and water quality degradation in both freshwater and marine ecosystems. Understanding the impact of land-use changes on water resources is recognized as one of the most challenging issues in environmental hydrology (e.g. Stonestrom et al., 2009).

The South to North Water Diversion Project is one of the largest projects conducted in centuries in China. The project, which is designed to solve the water shortage problem in vast areas of northern China, will divert up to 45 billion m$^3$ of water per year—an amount roughly equivalent to the annual volume of the Yellow River in a normal year—from the lower (eastern route), middle (middle route), and upper reaches (western route) of the Yangtze River in southern China by 2050 (Jiang, 2009). The middle route has a capacity of transferring a total of 13 billion m$^3$ of water annually from Danjiangkou Reservoir on the Hanjiang River, a tributary of the Yangtze River, to North China, including Henan, Hebei, Tianjin and Beijing, for irrigation, industrial and domestic usage (Dong et al., 2011). The present study focused on the Dan River, which is the water source area of the middle route of the diversion project. The Dan River originates from Shangzhou in Shaanxi province, with a drainage area of about 1.68 × 10$^4$ km$^2$ and a length of 443 km. The project seeks to promote Northern China’s economic growth by relaxing water constraints in a region now facing severe water shortage (Feng et al., 2009; Jiang, 2009; Wang et al., 2006a). However, water quality is severely degraded in the middle route. This is partly a result of serious uncontrolled agricultural non-point source pollution. Increased fertilizer application and livestock waste have contributed large amounts of nutrients to downstream water bodies (Liu and Qiu, 2007), resulting in very poor water quality in the main rivers. Accordingly, water pollution control is vital for maintaining good water quality in the middle route. Soil erosion and nutrient loss are two important aspects influencing water quality. The spatial variability of TSN levels, which may be greatly affected by land-use, plays an important role in both agriculture and the environment. This is especially so with regard to soil fertility, soil quality, and water-body eutrophication (Wang et al., 2009).

Few studies have applied fractal theory to determine the effects of different plant communities or land management on PSDs for similar soils (Liu et al., 2009; Wang et al., 2006b, 2008). Researchers have seldom studied the structure and spatial distribution of TSN or investigated the effect of slope gradient on topsoil (Ribolzi et al., 2011). Furthermore, there have been almost no studies investigating the soil fractal features associated with different plant communities in the middle line area. In this study, we employed the fractal scaling theory developed by Tyler and Wheatcraft (1992) to analyze PSD and D$_m$ for six different plant communities with similar soil types. We then evaluated the relationships between selected soil properties and the fractal dimension of PSD. The purpose of the study was to: 1) analyze the fractal dimension

![Fig. 1. Study area and soil sample sites.](image_url)
of soils involved in different land-uses and determine if the $D_m$ of the soil particle-size distribution can be used as an integrating index for quantification of soil degradation; and 2) gain more insight into the TSN structure and the relationship between PSD and TSN.

2. Materials and methods

2.1. Description of study area

The study is located in the Yingwugou Watershed (110°53′38″–110°55′18″E, 33°31′23″–33°30′35″N), 2 km southeast of Shangnan County, Shaanxi Province, China (Fig. 1). The study area is situated in the water source area of the Middle Route of the South-to-North Water Diversion Project and belongs to the Dan River Basin. The watershed has an altitude ranging between 464–600 m a.s.l., and covers an area of 1.86 km². The climate is warm and semi-humid, with an average annual temperature of 14 °C. The average annual amount of sunshine is 1974 h and the mean annual frost-free period is 216 d. The mean annual precipitation is 814 mm, 50% of which occurs between July and September.

Soil types in this area are typically yellow-brown (Haplumbrepts) and sandy (Arenosols) soils common to the mountain regions of Shaanxi. The parent rock material is granite, gneiss and limestone. The major arboreal vegetation in the area consists of pine (Pinus tabuliformis Carr.) and robur (Castanea mollissima Blume.). The dominant crops are peanut (Arachis hypogaea L.), corn (Zea mays L.) and wheat (Triticum aestivum Linn.). The land-use types investigated were mainly woodland, farmland and grassland. The studied plots have been under their present land-use for at least 10 years.

2.2. Soil sampling and analysis

Soil samples were collected from 0–60 cm in the Yingwugou Watershed during October 2010. The 0–60 cm layer was divided into four soil layers, 0–10, 10–20, 20–40 and 40–60 cm. At each plot unit, samples of each soil layer were collected from five points (equidistant length along an S-shaped sampling line) using a soil sampling auger with a diameter of 5.0 cm, after which the five replicate samples in each soil layer were homogenized by hand mixing. A total of 296 soil samples from 78 sites were collected. The numbers of soil samples (n) for the 0–10, 10–20, 20–40 and 40–60 cm soil layers were 78, 78, 74 and 66, respectively. A global positioning system (GPS) was used to determine sampling locations. Site properties, including land-use type, slope, aspect, altitude, soil type, and vegetation species and coverage were recorded for the purpose of analyzing correlations between these factors and spatial variations in soil nutrients.

Six typical plant communities within the study area were selected according to the three land-use types (Table 1). The plant communities were defined as follows: Camellia sinensis crop (CS); Zea mays crop (ZM); Quercus acutissima forest (QA); Pinus tabulaeformis forest (PT); Platycladus orientalis forest (PO); and Herbace (HB). According to land-use type, the forestlands (QA, PT and PO) were within protected

<table>
<thead>
<tr>
<th>Table 2</th>
<th>Relationships between soil fractal dimension and; A) silt-clay, B) fine sand, C) coarse sand, and D) gravel content in four soil layers.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Depth(cm)</td>
<td>Gravel content (%)</td>
</tr>
<tr>
<td></td>
<td>linear fitting ($R^2$)</td>
</tr>
<tr>
<td>0–10</td>
<td>0.30</td>
</tr>
<tr>
<td>10–20</td>
<td>0.14</td>
</tr>
<tr>
<td>20–40</td>
<td>0.20</td>
</tr>
<tr>
<td>40–60</td>
<td>0.16</td>
</tr>
</tbody>
</table>

** Correlation is significant at P<0.01 (two-tailed).
forestland preserve area (Zhang and Cui, 2007). CS is used for Chinese tea production, ZM is used for cropland production (primarily corn), and HB represents ungrazed grassland. The six plant communities in the study were located on south-facing, mid-slope areas.

Soil samples were air-dried, divided, and passed through either a 0.25-mm or 1.0-mm sieve. The samples were then analyzed for TSN using the Kjeldahl digestion procedure (Bremner and Tabatabai, 1972). For samples that were passed through the 1.0-mm sieve, soil NO3 and NH4 were analyzed with an Auto Discrete Analyzer (ADA, CleverChem200, Germany). Soil samples were air dried and machine-sieved through a 2.0-mm screen to remove roots and other debris. Soil particle-size distribution was described in terms of the percentages of silt and clay (<0.05 mm), fine sand (0.05–0.25 mm), coarse sand (0.25–1.0 mm) and gravel (1.0–2.0 mm). Soil particle composition was measured by laser diffraction using a Mastersizer2000 particle size analyzer (Malvern Instruments, Malvern, England).

2.3. Soil fractal model theory

The definition of a fractal can be given based on the relationship between number and size in a statistically self-similar system and defined by the following equation (Mandelbort, 1982; Turcotte, 1986):

\[ N(X > x_i) = kx_i^{-D} \]  

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. However, the applicability of Eq. (1) for PSD analysis is limited because complete and accurate calculations of \( N \) values are typically unavailable from conventional PSD experimental data.

In an effort to compensate for the lack of \( N \) values, Tyler and Wheatcraft (1992) estimated the fractal dimension of PSD, \( D_{fractal} \), based on the following expression:

\[ M(r < R_i)/M_f = (R_i/R_{max})^{3-D} \]  

(2)

where \( M \) is the cumulative mass of particles of the \( i \)th size, \( r \) less than \( R_i \), \( M_f \) is the total mass, \( R_i \) is the mean particle diameter (mm) of the \( i \)th size class, and \( R_{max} \) is the mean diameter of the largest particle, respectively.

The mean particle diameter is taken as the arithmetic mean of the upper and lower sieve sizes (Liu et al., 2009). Taking the logarithm of both sides in Eq. (2), we derived Eq. (3) to solve for \( D_{fractal} \):

\[ D_{fractal} = 3 - \frac{\log(M(r < R_i)/M_f)}{\log(R_i/R_{max})} \]  

(3)

### 3. Results

#### 3.1. Soil particle-size distribution and fractal features

As shown in Table 1, there are considerable differences in PSD among the six plant communities in this study. The predominant soil particle size is silt. The percentages of silt range from 45.4–66.2% with a mean value of 52.4%. Fine sand ranges between 12.9–31.0% with a mean value of 23.2% and coarse sand ranges from 10.3–22.4% with a mean value of 17.8%. The content of clay and gravel is relatively lower, with the content of clay ranging from 3.9–10.2% (mean value 6.1%), and that of gravel from 0.1–0.8% (mean value 0.5%). Soils of this nature are classified as yellow-brown soils (Haplustretes) according to the Chinese soil texture classification system (Lin, 2002; Xiong and Li, 1990).

Table 1 shows \( D_{fractal} \) values for PSD calculated using Eq. (2) for each of the six plant communities. Analysis of variance reveals significant differences in \( D_{fractal} \) between crop and forest communities (\( P<0.01 \)). The greatest differences in PSD among plant communities are in the percentages of silt. Silt content of CS (54.3%) and ZM (66.2%) are considerably higher than the mean value of 47.6% for forest communities (QA, PT and PO). Moreover, differences between crop communities and forest communities are characterized by a decrease in the fractal dimension, indicating that the soils in cropland (CS and ZM) are better. This is because sites with deep soils and good conditions were used to plant crops. Most forest communities grew in rocky and poor conditions.

#### 3.2. Relationship between fractal dimension and soil particle-size distribution

Linear regression analyses were performed to determine the strength of the relationships between \( D_{fractal} \) values and the contents of gravel, coarse sand, fine sand, and silt-clay in the 0–10 cm soil layer (Fig. 2A–D) and the other three soil layers. The statistical results obtained from the 78 sites show that the fractal dimension of PSD has a strong positive correlation with the silt-clay content (Fig. 2A, \( n = 78, R^2 = 0.96, P<0.01 \)), a negative correlation with the fine sand content (Fig. 2B, \( n = 78, R^2 = 0.39, P<0.01 \)) and coarse sand (Fig. 2C, \( n = 78, R^2 = 0.49, P<0.01 \)), and a weak negative correlation with the gravel content (Fig. 2D, \( n = 78, R^2 = 0.30, P<0.01 \)). Similar results were observed for the other three soil layers (Table 2). Thus, regression analysis indicates that soils with higher contents of silt and clay, and lower fractions of fine and coarse sand have higher \( D_{fractal} \) values. Values of \( D_{fractal} \) do not appear to be related to gravel content. Other studies have produced similar results in very different landscapes and under contrasting climate conditions (Liu et al., 2009; Su et al., 2004; Wang et al., 2006b, 2008).

#### 3.3. Slope and soil fractal features

The \( D_{fractal} \) selected from four ZM sites under different slopes in four soil layers is shown in Table 3. The \( D_{fractal} \) value in the 0–10 cm layer is bigger than those in the 10–20 cm and 40–60 cm soil layers at the slope angle of 10°. As slope increases, the \( D_{fractal} \) values in the 0–10 cm layer become smaller than those in the soil layers from 10–20 to 40–60 cm. This characteristic becomes statistically significant, especially at the slope angle of 28°. The \( D_{fractal} \) value is 2.59, which is much smaller than those of the soil layers from 10–20 to 40–60 cm.

### Table 3

Soil fractal features in different slopes for ZM.

<table>
<thead>
<tr>
<th>Slope (°)</th>
<th>Fractal dimension ( D_{fractal} )</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0–10 cm</td>
</tr>
<tr>
<td>10</td>
<td>2.84</td>
</tr>
<tr>
<td>21</td>
<td>2.88</td>
</tr>
<tr>
<td>25</td>
<td>2.89</td>
</tr>
<tr>
<td>28</td>
<td>2.59</td>
</tr>
</tbody>
</table>

Fig. 3. TSN content for each of the different plant communities in four soil layers.
3.4. Total soil nitrogen features of plant communities

The contents and vertical distribution of TSN under six different plant communities are presented in Fig. 3. There is an obvious decreasing trend in total nitrogen content from 0–10 to 40–60 cm among plant communities. The maximum TSN contents in the 0–10, 10–20, 20–40 and 40–60 cm soil layers are 1.53, 1.12, 0.674 and 0.412 g kg$^{-1}$, respectively, while the minimum TSN contents are 0.50, 0.367, 0.256 and 0.317 g kg$^{-1}$, respectively. Forestland and grassland soils maintained high TSN contents in both the 0–10 and 20–60 cm layers. The difference in TSN contents among the six plant communities decreases as soil depth increases.

3.5. Total soil nitrogen structure analysis

The mean percentages of NH$_4^+$–N, NO$_3^-$–N and other nitrogen forms range from 96.69 to 78%, respectively (Table 4) based on analysis of 296 soil samples. The percentages of NH$_4^+$–N and NO$_3^-$–N are generally less than the deeper soil layer and the NH$_4^+$–N percentage is less than that of NO$_3^-$–N in the same soil layer. The minimum and maximum values of NH$_4^+$–N and NO$_3^-$–N in each soil layer also indicate the same result. Lower percentages of NH$_4^+$–N and NO$_3^-$–N imply that nitrogen content is dominated by the other nitrogen forms. The percentages of the other forms of nitrogen decrease as depth increases and range from 96.69 to 91.51%. These findings indicate that organic nitrogen is the main type of soil nitrogen.

3.6. Relationships between soil particle-size distribution, fractal dimension and total soil nitrogen

Table 5 compares the correlation coefficients between TSN and PSD in the four soil layers based on the analysis of 78 sites. TSN has a significant positive correlation with coarse sand in the 0–10 and 10–20 cm soil layers. However, as depth increases, TSN shows a negative correlation with coarse sand, although this relationship is not statistically significant. In the 20–40 and 40–60 cm soil layers, TSN shows a significant positive correlation with silt-clay. A significant negative correlation exists between TSN and fine sand from the 10–20 to 40–60 cm soil layers. TSN is not strongly correlated with gravel in each soil layer. The TSN content is linearly correlated with SOC and the positive correlation coefficient is significant at P<0.01 (Guo, 1992; Tong et al., 2009). These findings indicate that soil organic matter decomposes into small particles as soil depth increases. This phenomenon might be related to leaching and migration of soil organic matter.

The relationship between Dm and TSN content was investigated by linear regression analyses (Fig. 4A–D). The R$^2$ values for the 0–10 and 10–20 cm soil layers are 0.01 (n=78, P>0.05) and 0.02 (n=78, P>0.05), respectively (Fig. 4A–B); therefore, no significant correlation is evident between the Dm values and TSN content in the 0–20 cm soil layer. The Dm values positively correlate with TSN content in the 20–40 (Fig. 4C, R$^2$=0.19, n=74, P<0.01) and 40–60 cm soil layers (Fig. 4D, R$^2$=0.31, n=66, P<0.01), which correspond to the correlation of PSD and TSN. The Dm value and TSN content both positively correlate with silt-clay content in the 20–60 cm soil layer.

4. Discussion

PSD is commonly used in soil classification, as well as for estimating various related soil properties (Hillel, 1980). PSD affects the movement and retention of water, solutes, heat and air in soil. In land degradation processes, a decrease in water-holding capacity, losses in soil nutrients, and the diminution of soil structure are indicative of the selective removal of fine particle-size fractions and can often be attributed to various human activities. Thus, identifying changes in PSD may provide useful indications that soils have been subjected to degradation or nutrient changes caused by certain human activities (Liu et al., 2009; Wang et al., 2008).

Fractal dimension analysis has been used to quantitatively describe soil texture, soil aggregate fragmentation, and related soil properties (Perfect, 1997). The current study demonstrates that the Dm value of PSD increases as soil becomes finer in texture (Liu et al., 2009). The Dm values of CS (2.81) and ZM (2.89) were higher than the values of forest areas (QA, PT and PO). There was also a significant difference (P<0.01) in fractal dimensions between crop and grass communities. These findings are contrary to those of Liu et al. (2009), who found that the Dm values of forestland and grassland were larger than those of cropland. This difference was primarily because the land-use types in the present study were not protected forestland or commercial forestland. These findings suggest that anthropogenic disturbances, especially in the distribution of forestland and grassland, have resulted in various levels of soil degradation in the study area. Overall, the Dm values in the Yingwugou study area varied from 2.59 to 2.93 among plant communities, indicating that the soils had high quality. The range of Dm values present in our study was relatively high, and plant communities with higher Dm values corresponded to better soil conditions. Therefore, the use of Dm values based on PSDs could provide more information than PSD or soil texture alone.

We also assessed the linear fitting for the fractal model as it applies to the different plant communities observed in this study. The results for the six plant communities are shown in the scatter diagram in Fig. 5, with linear regression analysis between the log of (R/Rmax) on the x-axis and the log of M(r<R)/M0 on the y-axis. There was a strong linear trend in the data for each of the communities and strong correlations as indicated by the R$^2$ values being >0.90 in all cases. These results are similar to those of Grout et al. (1998) and Liu et al. (2009) and indicate that using the fractal dimension of PSD as a descriptor for soils is effective.

**Table 4**

Mean percentages of NO$_3^-$–N, NH$_4^+$–N and other nitrogen forms in four soil layers.

<table>
<thead>
<tr>
<th>Depth (cm)</th>
<th>NH$_4^+$-N (mg·kg$^{-1}$)</th>
<th>NO$_3^-$-N (mg·kg$^{-1}$)</th>
<th>Other nitrogen forms</th>
<th>Number of samples (n)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Min.</td>
<td>Max.</td>
<td>Mean percentage (%)</td>
<td>Min.</td>
</tr>
<tr>
<td>0–10</td>
<td>1.73</td>
<td>12.42</td>
<td>0.99</td>
<td>1.98</td>
</tr>
<tr>
<td>10–20</td>
<td>2.07</td>
<td>30.17</td>
<td>1.68</td>
<td>2.06</td>
</tr>
<tr>
<td>20–40</td>
<td>1.38</td>
<td>11.78</td>
<td>2.82</td>
<td>2.24</td>
</tr>
<tr>
<td>40–60</td>
<td>1.56</td>
<td>14.65</td>
<td>3.94</td>
<td>1.84</td>
</tr>
</tbody>
</table>

**Table 5**

Pearson correlation coefficients between PSD and TSN in four soil layers.

<table>
<thead>
<tr>
<th>Size</th>
<th>Gravel</th>
<th>Coarse sand</th>
<th>Fine sand</th>
<th>Silt-clay</th>
</tr>
</thead>
<tbody>
<tr>
<td>Depth (cm)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0–10</td>
<td>0.077</td>
<td>0.310*</td>
<td>−0.177</td>
<td>−0.121</td>
</tr>
<tr>
<td>10–20</td>
<td>0.063</td>
<td>0.268*</td>
<td>−0.383**</td>
<td>0.098</td>
</tr>
<tr>
<td>20–40</td>
<td>−0.136</td>
<td>−0.207</td>
<td>−0.382**</td>
<td>0.406**</td>
</tr>
<tr>
<td>40–60</td>
<td>−0.178</td>
<td>−0.303*</td>
<td>−0.462**</td>
<td>0.538**</td>
</tr>
</tbody>
</table>

* Correlation is significant at P<0.05 (two-tailed).

** Correlation is significant at P<0.01 (two-tailed).
The difference in TSN contents among the six plant communities became smaller as soil depth increased. This could be explained by the very low inorganic nitrogen percentage in TSN, which is often <5% (Sainju et al., 2002). TSN levels in farmland benefit from the use of NPK fertilizers (Halvorson et al., 1999), while forestland and grassland restoration is encouraged by organic N, which primarily originates from humus and forest litter. The organic N content in humus and forest litter is much higher than the inorganic N from NPK fertilizers. This also explains why the TSN contents did not differ greatly among the four soil layers in farmland and were much higher in the 0–10 cm soil layer in forestland and grassland. The largest TSN content is present at the PO site in the 0–10 cm layer, whereas the lowest TSN content is present at the CS site in the 20–40 cm layer. This was likely due to the relatively higher soil organic matter for the PO site, while the low TSN content at the CS site is a result of farming activities, soil structure and nitrogen transport. The Dm values of forestland and grassland were smaller than those of cropland, while the TSN contents of forestland and grassland are higher than those of cropland. This could be explained by Tables 3 and 5. The fractal dimension in topsoil is related to soil erosion, which removes relatively finer soil particles and causes the content of silt-clay to decrease. However, the TSN contents are significantly positively correlated with coarse sand in the 0–10 cm and 10–20 cm soil layers. This also explains why the fractal dimension showed no significant correlation with the TSN content in the 0–10 cm and 10–20 cm soil layers. The high TSN contents and the unreasonable land-use types induced the degraded water quality together in the water source area of the South-to-North Water Diversion Project, which corresponded to the high total nitrogen content observed during water monitoring.

The Dm values in topsoil at a slope angle of less than 25° showed little difference, while the Dm value decreased greatly in topsoil at a slope angle of 28°. These findings indicate that there is a critical point between 25° and 28°. Once the angle of the cropland is greater than 25°, the topsoil is subject to serious soil erosion. Therefore, Dm values are relatively smaller on steep slopes that are prone to severe soil erosion. Accordingly, the cropland on steep slopes should be converted to woodland and grassland to strengthen soil and water conservation.

5. Conclusions

The fractal dimension of PSD is sensitive to the soil coarsening process and fractal dimension analysis of soil particle-size distribution offers a useful approach to quantify and assess the degree of soil degradation among similar soil types. There is an obvious decreasing trend in TSN content with increasing depth under the various plant communities. In addition, anthropogenic disturbances have had a great impact on the fractal dimensions of different land-use types in the study area. Most forest communities are forced to grow in rocky and poor conditions, while crops are planted in deep soils under good conditions. This resulted in various levels of soil degradation and is likely to induce greater soil erosion. These differences also led to the Dm values of forestland and grassland being smaller than those of cropland. Finally, the unreasonable land-use type and high TSN contents likely resulted in easy soil erosion and degraded water quality. Soil erosion is also found to have a critical point between 25° and 28°. Consequently, the forestland should be protected effectively and the cropland should be returned to forestland and grassland, especially on steep slopes, to enhance and sustain soil quality and water quality in the area and to avoid further soil degradation. Further research should be conducted to determine if optimizing the landscape pattern can regulate water quality.

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