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Fractal Characters of Soil Erosion Spatial Pattern in the Watershed on Loess Plateau, China

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ABSTRACT

In order to study quantitative indexes and characteristics of soil erosion on the Loess Plateau, degree of complexity and stability of erosion patterns are discussed. The fractal characteristics of soil erosion spatial patterns in the Dalihe River basin were evaluated by combining them with measurements extracted from the soil erosion database of the Loess Plateau, illustrated using GIS. Results demonstrate that fractal characteristics of spatial patterns of soil erosion intensity are obvious in the Dalihe River basin. Indeed, the results show that fractal dimension reflects the degree of soil erosion complexity at certain scales of observation, is indirectly related to soil erosion degree of complexity at certain scales of observation, which indirectly corresponds to the level of difficulty to implement soil-water erosion management. In addition, the fractal characteristics of soil erosion spatial patterns in the Dalihe River basin show that patch shapes correspond with size. In other words, when the patch size is about 0.2 km^2, scale conversion is observed in spatial patterns of soil erosion intensity and complexity of patch shape also changes. However, at patch sizes greater than 0.2 km^2, the two dimensional feature was gradually enhanced for a single patch, while with the patch size less than 0.2 km^2, the point feature was gradually enhanced. Thus, the order of complexity in spatial patterns of soil erosion intensities in the Dalihe River basin is drastic erosion > extreme erosion > serious erosion > moderate erosion, and thus the order of priorities for the implementation of management controls on soil erosion should be moderate erosion > serious erosion > extreme erosion > drastic erosion.

INTRODUCTION

As a significant reflection of surface morphology and the ecological landscape characteristics of watershed landforms, patterns of soil erosion have been one focus of research in the fields of erosion and soil-water conservation. A watershed is the basic unit of soil-water conservation management, and as such is a relatively complete and ordered ecological system (Leng 1986). Indeed, soil-water erosion is an important constituent of the hydrological and ecological processes in the complex earth surface system (Bartley 2010, Chen 2007). Thus, in terms of soil erosion, patches of different intensity can be treated as elements of the landscape (Wang 2003), allowing the study of different grades of soil erosion using landscape ecological theory. Indeed, a great deal of work in this area has been published; for example, Cola (1989) and Lam (1990) evaluated regional landscape complexity and the intensity of human disturbances using the fractal dimension index, while Zhang (2001) discussed the intensity of soil erosion in the Yichang area using GIS. This latter study utilized an area comparison of the landscape, as well as the diversity, dominance, and abundance indexes. Applying the landscape pattern analysis software FRAGSTATS. Wang (2003) calculated indexes for more than ten landscape types, and quantitatively analysed the distribution and patterns of variation in soil erosion across Xingguo County, China. However, although remote sensing images, or large scale maps were used as the basis for analysis at the county level in most previous studies, research on spatial patterns of soil erosion across large watershed areas, especially the Loess Plateau, remains absent. This is surprising because research on the spatial patterns of soil erosion, especially in this basin, has both important theoretical value and practical significance in revealing the characteristics of large-scale changes, and effects on the ecological environment of regional landscape patterns (Imeson 2004, Xia 2012, Renard 1997).

Soil-water erosion is one of the most significant environmental problems in China. Indeed, the Loess Plateau is amongst the most seriously affected regions nationally because of its particular natural conditions (Liu 2008, Sun 2013). Thus, research on the spatial patterns of soil erosion on the Loess Plateau watershed is critical for soil-water loss management as well as the monitoring and evaluation of regional soil erosion (Fu 2006). In this study, fractal theory and spatial analysis are combined with the remote sensing survey database of soil erosion in the Dalihe River basin on the Loess Plateau to evaluate fractal characteristics in spatial patterns of soil erosion, as well as the relative complexity and stability of these patterns.

MATERIALS AND METHODS

Summary of the research area: The Dalihe River basin in the hilly and gully region of the Loess Plateau was selected as the research area for this study; a geographic location map is shown in Fig. 1. This river basin is located in northern Shanxi Province at eastern longitude 109°14' ~110°13', and northern latitude 37°30'~37°56'. The total length of the major river section is 170 km, while the drainage area is approximately 3,908 km^2. The overall topography of the basin is high in the west and low in the east, with a western elevation of 1,600~1,700 m, and an eastern elevation of 900~1,000 m. Terrain fragmentation, sparse vegetation, and serious soil erosion are all characteristics of this watershed region; indeed, after a long period of geological erosion, this watershed is characterized by the loess hilly gully landforms of projected ridges, gullies, and inlaid valley floors, the regions of most intensive soil erosion in the entire Loess Plateau.

Data sources: For this study, the remote sensing soil erosion database established in 2010 by the Ministry of Water Resources of the People's Republic of China was used as the basic source of watershed soil erosion spatial patterns. This database comprises the national and provincial 1:100,000 TM image library, the 1:100,000 soil erosion intensity map, a soil erosion intensity atlas in unified format, a database of soil erosion for sub-provinces/counties, and a typical plot album. A binary class system was used to categorize the type and intensity of soil erosion in the database, with the primary class determined on the basis of the type and nature of dominant erosion, including hydraulic and wind power, freeze-thaw, gravity, and construction. Erosion intensity was then classified using the secondary class index given in Table 1.

The vector boundaries in the Dalihe River basin were generated using GIS on the basis of the 1:100,000 DEM. Subsequent to the unified projection process, these bounda-

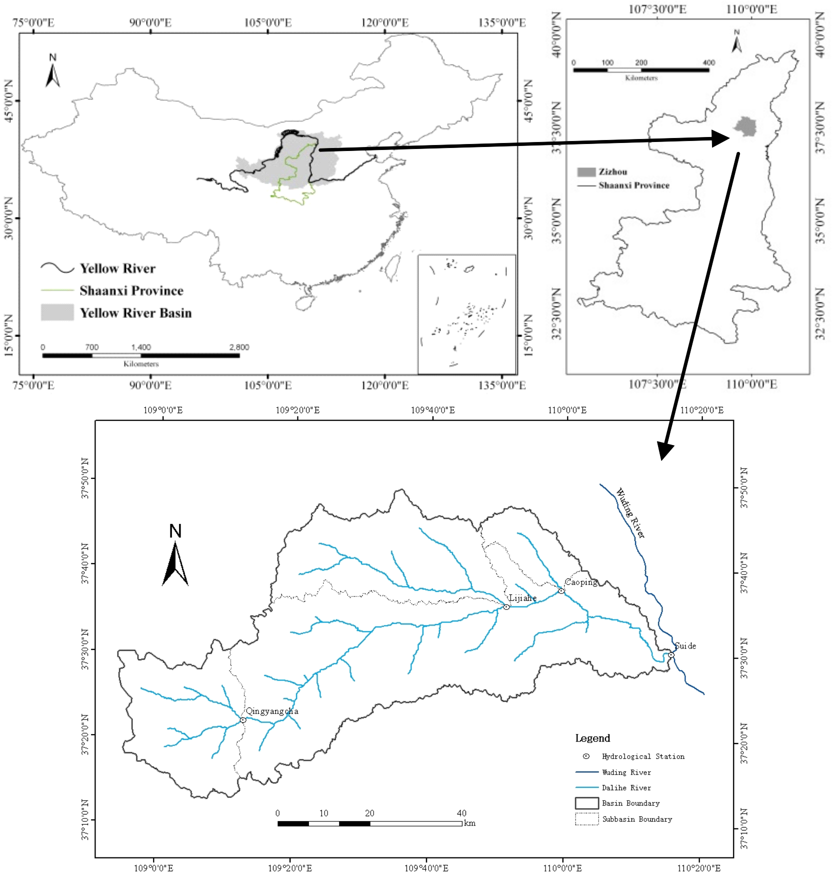


Fig. 1: Location map of the Dalihe River basin.

Table 1: Classification system for soil erosion in China.

Primary class of erosion	Erosion intensity (secondary class)
1 Hydraulic	11 inapparent, 12 slight, 13 moderate, 14 serious, 15 extreme, 16 drastic
2 Wind	21 inapparent, 22 slight, 23 moderate, 24 serious, 25 extreme, 26 drastic
3 Freeze-thaw	31 inapparent, 32 slight, 33 moderate, 34 serious, 35 extreme, 36 drastic
4 Gravitation	40
5 Construction	50

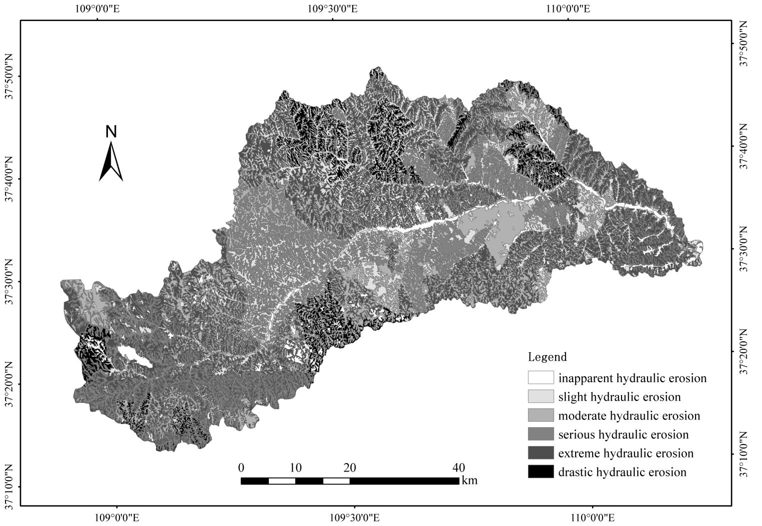


Fig. 2: Spatial pattern of soil erosion in the Dalihe River basin.

ries were then superimposed onto the soil erosion database for the watershed, and the spatial patterns of soil erosion in the Dalihe River basin were extracted. Fractal dimensions of soil erosion type spatial patterns and intensity were calculated and analysed using GIS attribute query and spatial analysis functions. The resultant spatial pattern of soil erosion in the Dalihe River basin is shown in Fig. 2.

Fractal dimension calculation: Fractal theory has facilitated the rapid development of a number of disciplines concerned with the study of non-regulatory aspects (Riitters 1995, Kepner 1995, Shen 2008), and the fractal dimension has been widely applied to the study of landscapes (Qin 2003). However, because a unified formula for the calculation of fractal dimension has not yet been derived, specific fractal features of a given research object are combined to obtain an appropriate numerical representation. For example, Mandelbrot proposed that the fractal relationship between surface and volume could usefully be applied to study the structure of animal brain folds (Mandelbrot 1977), as follows:

$$S(r)^{1/D} \sim V(r)^{1/3} \qquad ...(1)$$

Subsequently, building on this formula and by deduction using the method of physical dimension analysis, Dong (1991) obtained the fractal formula applicable to n-dimensional Euclidean space. Thus, the formula to express the relationship between the area of two-dimensional Euclidean space and the perimeter is as follows:

$$P(r)^{1/D} = k \cdot r^{(1-D)/D} \cdot A(r)^{1/2} \qquad ...(2)$$

In this expression, $A(r)$ denotes the spot area, r is the measurement scale, and $P(r)$ is the perimeter for the same spot. In this approach, the area and perimeter of a series of patches are measured, plotted on a double logarithmic coordinate chart, and the $LnP(r)$ and $LnA(r)$ series are then fitted linearly to obtain the formula for calculating the area perimeter dimension of patches, as follows:

$$LnP\,(r) = \frac{D}{2} LnA\,(r) + C \qquad ...(3)$$

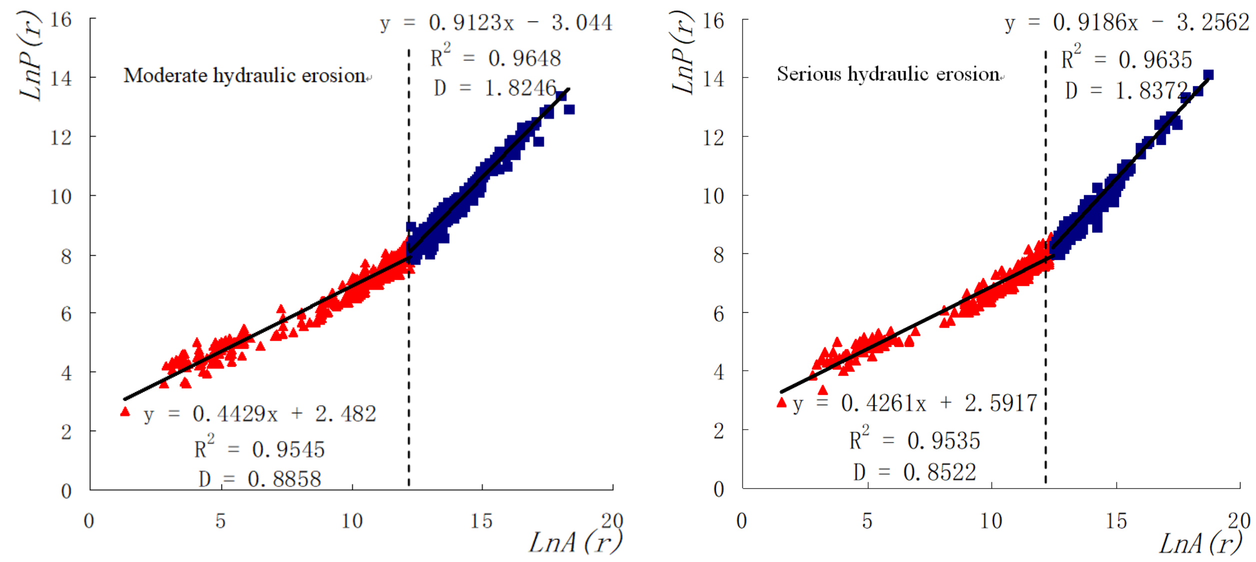
In this expression, the value for the fractal dimension D is twice that of the linear slope; its value should be smaller than the topological dimension of two-dimensional Euclidean space 2.

RESULTS AND DISCUSSION

Basic characteristics of watershed soil erosion intensity: Using GIS attribute query and spatial analysis functions, data describing the spatial distribution of soil erosion in the

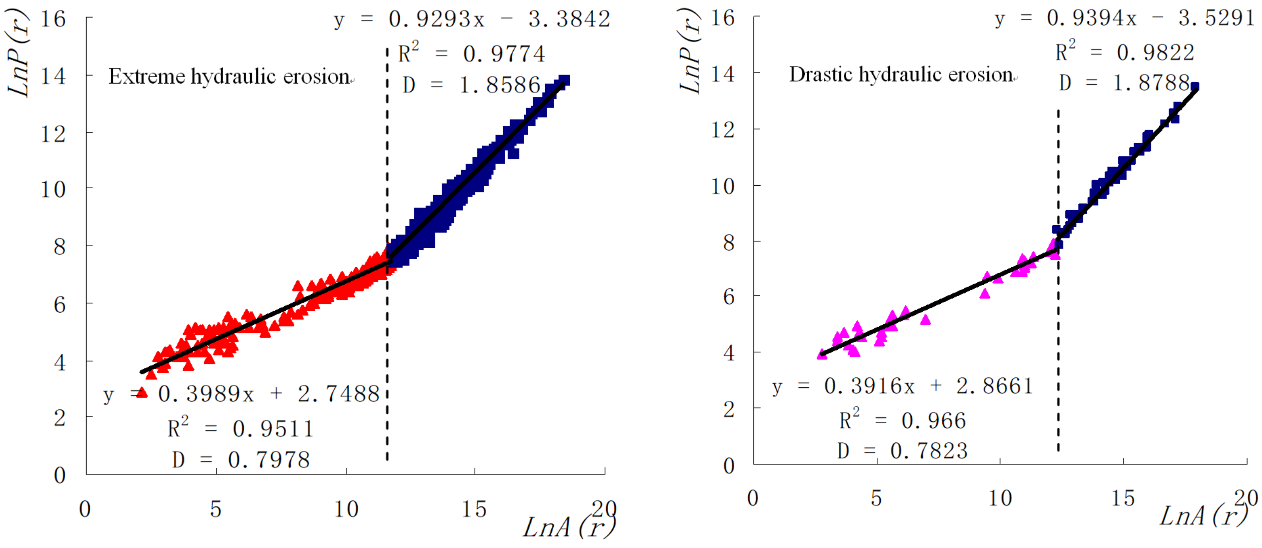
Dalihe River basin were processed and analysed to obtain basic statistical indicators of the spatial pattern of erosion intensities across the watershed. Results show that hydraulic erosion is the main form of soil erosion acting in the Dalihe River basin (Table 2); for this mechanism, the area of soil erosion occurring at highest intensity was 53.98%, while the eroded area occurring at severe intensity encompassed 28.68%. The eroded soil area intensity lower than mild accounted for just 22.09%, indicating that high intensity areas and wild areas characterized by erosion and severe soil-water loss make up the bulk of the Dalihe River basin at present.

Significance of the fractal dimension of soil erosion patterns in the watershed: The pattern of soil erosion in any watershed is the result of the dual action of nature and humans, characterized by being both irregular and relatively unstable. Indeed, different types and intensities of eroded patches have different spatial characteristics, and the spatial



a: Moderate erosion.

b: Serious erosion.



c: Extreme erosion.

d: Drastic erosion.

Fig. 3: Calculation of fractal dimension of soil erosion spatial patterns.

Table 2: Basic characteristics of soil erosion in the Dalihe River basin.

Erosion intensity	Code	Area proportion (%)	Number of patches
Inapparent	11	4.78	348
Slight	12	17.31	548
Moderate	13	23.93	764
Serious	14	17.30	388
Extreme	15	28.68	529
Drastic	16	8.00	102
Total		100	2679

Table 3: Calculated results for the fractal dimension of soil erosion spatial patterns.

			Before the knee point			After the knee point		
Code	Erosion intensity	Knee point (m^2)	Fractal dimension D	R^2	Sample number	Fractal dimension D	R^2	Sample number
11	Slight	282675	0.9534	0.9014	238	1.6912	0.9145	110
12	Mild	129239	0.8002	0.9582	191	1.7934	0.9387	357
13	Moderate,	202886	0.8858	0.9545	391	1.8246	0.9648	373
14	Intense	268184	0.8522	0.9535	242	1.8372	0.9635	146
15	Serious	132072	0.7978	0.9511	246	1.8586	0.9774	283
16	Extreme	201106	0.7823	0.9660	40	1.8788	0.9822	62

pattern for any given eroded area will be different as it evolves. Thus, the use of area-perimeter dimension to describe the characteristics of a patch may improve the study of soil erosion in the watershed, indeed presents a new angle for the analysis of the underlying mechanisms of soil erosion.

In this formulation, the size of the area-perimeter dimension reflects the complexity in the form of soil erosion patches at a given scale of observation. Thus, as expressed by the formula, for a given area, the bigger the perimeter, the greater the fractal dimension value D, indicating a more complicated shape of patches. In contrast, the smaller the fractal dimension value D, the simpler the shape of the patches (Yu 2005). Thus, for a given region experiencing soil erosion, the degree of difficulty in implementing soil-water conservation measures will be closely related to the edge complexity. Generally, the simpler the patch shape, the easier it will be to implement soil-water conservation measures more effectively, and therefore the size of the area perimeter dimension for the soil eroded patch directly reflects the difficulty of soil-water loss and management. The area and perimeter of each patch were extracted from Fig. 3, and the regression equation established in the double logarithmic coordinate system to calculate the area-perimeter dimension of soil patches under different erosion intensities. Results show that linear fits for patches at six soil erosion intensities do not conform to a straight line, but instead exhibit two different linear regions with a knee point. Fractal dimension values were calculated before, and after, the knee point, as presented in Table 3.

The significance of fractal theory for the scale of the knee point: Morphological characteristics of patches are scale dependent; however, at a certain scale, these characteristics conform to a power-law relationship, the fractal feature of patch shape. Thus, the relationships and rules controlling the spatial characteristics of patches at different scales can be extracted, indicating the scale of complexity change in patch shape. Indeed, the knee point shown in Fig. 3 demonstrates that patches eroded at various intensities exhibit different spatial similarities and, indeed, comprise different fractal characteristics at two different scales, before and after the knee point.

In the first place, the rationality of the area-perimeter dimension is determined based on classic fractal theory, and, therefore, the fractal dimension should be less than the topological dimension of the space (Liu 2003). In other words, because the research object in this study is to determine spatial patterns of two-dimensional soil erosion, the fractal dimension should be less than two. Indeed, and as shown in Fig. 4, the area-perimeter dimension was less than two within the two scale domains before, and after, the knee point, and in addition, the correlations of fit for the linear equations in both the scale domains were greater than 0.9, corroborating the presence of two no scale intervals. In other words, the area-perimeter dimension in both the scale domains is a reasonable expression of the spatial pattern of two-dimensional soil erosion.

Further analysis shows that within the whole watershed, the area of individual patches is relatively large, and that

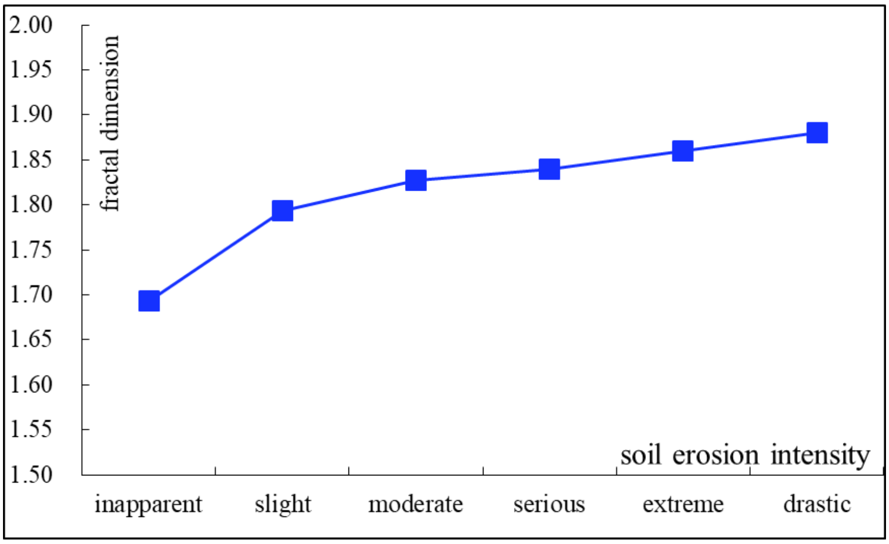


Fig. 4: Fractal dimensions of different soil erosion intensities.

the two-dimensional features of single patches were evident in the scale domain after the knee point when the area-perimeter dimension was between one and two. Under these conditions, the fractal dimension is able to adequately reflect the shape complexity of soil erosion patches in two-dimensional space. However, because the area of individual patches was relatively small, the two-dimensional features of a single patch were gradually eliminated as the point feature increased, at area-perimeter dimensions between zero and one. Under these conditions, fractal dimension can reflect the diversification degree of patches with different soil erosion intensities; in other words, the closer to zero the fractal dimension is, the stronger the point feature of a patch will be, and the simpler the corresponding shape. Thus, the appearance of the knee point indicates that the fractal characteristics of soil erosion patch shapes in the Dalihe River basin hierarchically correspond with size (Li 2006). The area-perimeter dimension in both the scale domains before, and after, the knee point is thus the rational representation index for the complexity of soil erosion spatial patterns in the watershed.

Analysis of the fractal characteristics of soil erosion spatial patterns: As given in Table 3, the fractal dimension before the knee point was significantly smaller than it was after the knee point in the case of various soil erosion intensities. Indeed, when patch size was over 0.2 km^2, nested phenomena occurred in large-scale patches, and staggered segmentation among patches was enhanced, reflected by an increase in fractal dimension and shape complexity of patches. In contrast, when patch size was smaller than 0.2 km^2, patch distribution became dispersed, and individual shapes were simpler, corresponding with the point distribution trend and resulting in a reduction in the overall complexity of patch shape. Therefore, in terms of soil-water loss in the Dalihe River basin, eroded patches with areas less than 0.2 km^2 should be priorities for management. On the one hand, a smaller size of eroded patches and a simpler spatial pattern would allow for the easier implementation and layout of soil-water conservation measures; more effective management for less cost. On the other hand, prioritizing management would prevent the gradual expansion of eroded areas and avoid an increase in management problems pass the knee point.

Indeed, within the scale domain above the knee point, the order for the area-perimeter dimension of soil erosion at various intensities is drastic erosion > extreme erosion > serious erosion > moderate erosion > light erosion > inapparent erosion. Thus, fractal dimension reflects the complexity of the soil erosion pattern at various intensities. Generally, the spatial pattern of extreme erosion is most complicated, while the simplest patterns are seen with just slight erosion. The order of fractal dimensions is the same as the order of soil erosion intensity; the more intensive the soil erosion, the larger is the fractal dimension, and hence the corresponding spatial pattern is also more complicated. Thus, from the point-of-view of soil-water loss management, a more irregular patch shape will give rise to a more complicated spatial pattern, resulting in differences in the level of difficulty to implement soil-water loss management and conservation. Results show that the order of difficulty for implementing soil-water loss control at various erosion intensities in the Dalihe River basin is drastic erosion >

extreme erosion > serious erosion > moderate erosion > light erosion > inapparent erosion. Thus, for implementation of soil-water loss management, the 'easy first and difficult afterwards' principle should be followed. In particular, soil erosion with the lowest fractal dimension spatial pattern should be the priority for management, as this will lead to integration of large, scattered patches and change the disordered state of patch structure across the whole basin, reducing dimensions and entropy. Indeed, if eroded areas with high fractal dimension spatial patterns are managed, this will reduce the difficulty of soil-water conservation across the whole watershed and consequently improve control effects. Therefore, from the point-of-view of the fractal characteristics of soil erosion spatial patterns across the watershed, the conservation and management priority order (to the exclusion of areas of slight and mild soil erosion) in the Dalihe River basin should be moderate erosion > serious erosion > extreme erosion > drastic erosion (Fig. 4).

CONCLUSION

Taking the Loess Plateau Dalihe River basin as a typical example, this study draws three main conclusions regarding the spatial characteristics of soil erosion patterns across the watershed.

First, the spatial patterns of soil erosion in the Dalihe River basin have clear fractal characteristics, and indeed, the size of the fractal dimension reflects the degree of morphological complexity of an eroded soil patch. This, in turn, reflects the degree of difficulty in implementing soil-water loss management.

Second, the fractal characteristics of soil erosion spatial patterns in the Dalihe River basin exhibit hierarchical features corresponding to patch size. In other words, when patch size is approximately 0.2 km^2, the complexity of patch shape changes; the two dimensional feature of a single patch is gradually enhanced as size increases to over 0.2 km^2, while the point feature is gradually enhanced at patch sizes less than 0.2 km^2.

Third, the order of complexity in spatial patterns at different soil erosion intensities in the Dalihe River basin is drastic erosion > extreme erosion > serious erosion > moderate erosion. Therefore, in conclusion, priority order for the implementation of soil-water management should be moderate erosion > serious erosion > extreme erosion > drastic erosion.

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