Journal of Arid Environments (2000) **44**: 291–303
doi:10.1006/jare.1999.0600, available online at http://www.idealibrary.com on IDEAL®

Agricultural landscape spatial pattern analysis in the semi-arid hill area of the Loess Plateau, China

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(Received 10 June 1998, accepted 16 September 1999)

Landscape pattern analysis is a primary research tool in landscape ecology that contributes to understanding spatial ecological dynamics. This paper combines a geographic information system (GIS) and statistical analysis to examine the spatial patterns of an agricultural landscape in the semi-arid hill area of the Loess Plateau of China. Quanjiagou catchment, a typical loess hill and gully area, is the study area. A 1 : 10,000 land-use map of the study area was used for landscape pattern analysis. Ten land-use categories were identified: irrigated farmland, check-dam farmland, terrace farmland, slope farmland, orchard, grassland, shrubland, forest, reservoir and residential land. The patch size, fractal dimension of patches, patch elongation index, diversity, dominance, relative richness and fragmentation of the landscape were calculated. The results showed that the relationship between patch shape and patch size in shrubland and forest has a better correlation coefficient ($r^2 = 0{\cdot}2927$, $p < 0{\cdot}05$) than that in farmland and grassland. The diversity, relative richness and fragmentation of the gully are greater than those of the hill landscape. Thus, we suggest planting shrubland buffers in the zones between hill top and hill slope, and hill slope to gully slope to control soil erosion and to improve landscape diversity and connectivity.

Keywords: landscape pattern; land use; fractal dimension; patch; GIS; Loess Plateau of China

Introduction

Agricultural landscapes are mosaics of natural and human-managed patches that vary in size, shape and arrangement (Forman & Godron, 1986). They may be more variable than many natural environmental patterns, since agricultural landscapes reflect not only natural constraints but also financial resources and social conditions (Urban *et al.*, 1987). The spatial pattern in the landscape may influence a variety of ecological processes, such as animal movements (Henderson *et al.*, 1985; Freemark & Merriam, 1986), water runoff and erosion (Peterjohn & Correll, 1984; Burel *et al.*, 1993; Fu *et al.*, 1994), and soil nutrients (Correll *et al.*, 1992; Fu *et al.*, 1999). Nutrients such as phosphorus and nitrogen are captured and processed differently according to

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different patch types in a mosaic landscape (Risser, 1989). This depends largely on the topographical position of vegetation patches and on edaphic conditions. Nutrients and water move from one landscape unit to another according to the position of each unit. Therefore, analysis of landscape spatial patterns is an important component of understanding ecological dynamics (Turner, 1987).

The Loess Plateau, located in the middle reaches of the Yellow River basin in North China, is well known for its high erosion rate and heavy sediment load. Average and maximum erosion rates are 150 Mg ha^{-1} year^{-1} and 390 Mg ha^{-1} year^{-1}, respectively (Chen & Luk, 1989), which are equivalent to a soil surface lowering of 1·2 to 3·1 cm year^{-1}. The region's soils have been cultivated for the past 5000 years, with accelerated erosion causing problems as long as 3000 years ago (Dai, 1988). The serious soil erosion has resulted in regional ecological and land deterioration. One reason for the problematic erosion is irrational land use (Fu, 1989; Fu & Gulinck, 1994). Although some resource surveys and soil erosion studies have been undertaken in the Loess Plateau, there is still a lack of comprehensive land-use planning. Integration of landscape ecological concepts, which focus on landscape patterns and processes could support determination of an optimum pattern of land use. So far, this has not been proposed for the Chinese Loess area.

The objective of this paper is to analyse agricultural landscape patterns in a catchment of the Loess Plateau of China using a geographical information system (GIS) and statistical methods to provide a basis for ecological process study and land-use planning. Comparing the landscape patterns in the gullies and hills, two main landscapes in the Loess hill area, may help in the improvement of landscape structure and land use for soil conservation.

Methods and materials

Study area

The study area, the Quanjiagou catchment, is located near Mizhi, Shaanxi Province (37°46′N, 110°16′E) (Fig. 1). It covers about 112 ha (990 × 1130 m) with an elevation range of 150 m (Fig. 2). Landform is mainly divided into two groups, the hill and the gully (Fig. 3). The area above the gully-edge comprises 47% of the study area, and the area below the gully-edge comprises 53%. The hill top and upper hill slope is characterized by a gentle slope less than 10°, and has been cultivated by building terraces. Immediately below is the lower hill slope that is usually cultivated and is often as steep as 40°. On the gully slope with a sharp break from the slope a steeper zone is located that is not cultivated but grazed by sheep and goats. Finally, there is the gently inclined valley floor where water is concentrated. In the gully bed, a check dam was constructed and a sedimentation pond formed behind the dam.

The study area has a semi-arid continental climate, with an average annual temperature of 8·4°C (average maximum 23·5°C in July; average minimum −9·9°C in January) and an average of 2732 h of sunshine each year; there are 162 frost-free days. The average annual precipitation is 422 mm and 69·55% of rainfall occurs between July and September. The soil in the study area is mainly loess soil, which occupies >90% of the whole area. The loess soil contains 7–14% clay (<0·001 mm), 10–13% fine silt (0·001–0·01 mm), 48–56% silt (0·01–0·05 mm) and 23–30% sand (>0·05 mm). It is vulnerable to erosion and thus the erosion rate is high, up to 16,300 tons km^{-2} year^{-1} (Zhang *et al.*, 1990). The natural vegetation has been destroyed due to long-term cultivation. Crops grown on the cultivated lands include millet (*Panicum miliaceum*), sorghum (*Sorghum* spp.), beans (*Phaseolus valgaris*), maize (*Zea may* L.), wheat (*Triticum* spp.) and potatoes (*Solanum tuberosum*). On the gully slopes, shrubland and

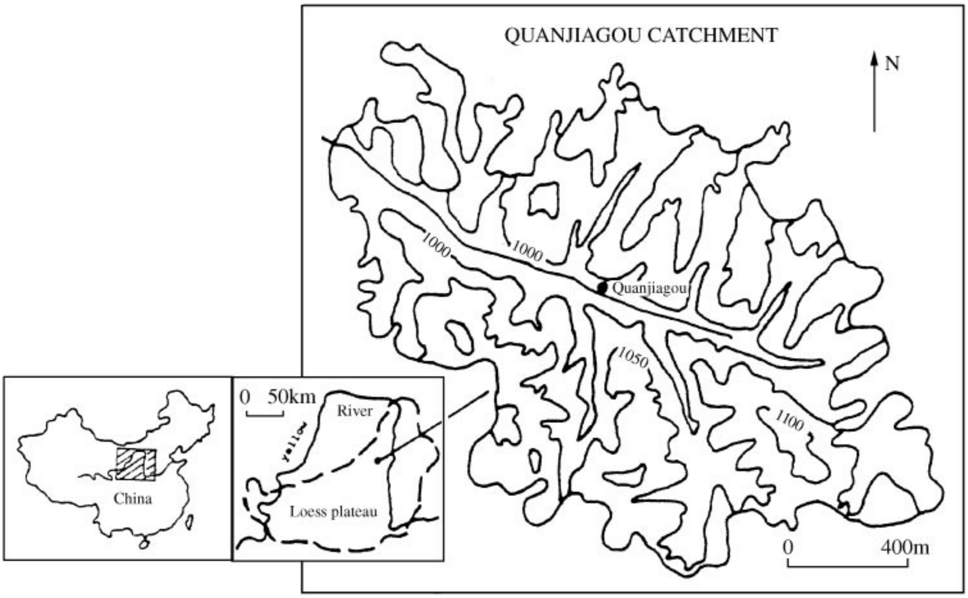

Figure 1. Location of the study area.

forest species include *Abrotanum lavandulaefolia*, *Caragana korshinskii*, *Zizyphus jujuba*, *Hippohae rhamnoides* and *Robinia pseudoacacia* L.

Techniques

A land-use map of the study area (scale 1 : 10,000; Northwest Institute of Soil and Water Conservation, 1991) was digitized using the TOSCA program of IDRISI Geographic Information System (Eastman, 1992) and was divided into 10×10 m cells when converting the map into raster format for analysis. Ten land-use types (irrigated farmland, check-dam farmland, terrace farmland, slope farmland, orchard, grassland, shrubland, forest, reservoir and residential land) were classified using the RECLASS program of IDRISI (see Table 1). Each patch in the landscape matrix was then identified by GROUP program of IDRISI. A patch was defined as contiguous, adjacent cells of the same land-use type; diagonal cells were considered to be contiguous. Each patch in the landscape matrix was located, and the following attributes measured:

(1) Patch area (A) and patch perimeter (P);
(2) Fractal dimension (D) was used as a measure of patch shape complexity (Mandelbrot, 1982). The fractal dimension was calculated using equation 1 (Lovejoy, 1982; Turner & Ruscher, 1988).

$$D = 2\ln(P/4)/\ln(A) \quad (1)$$

For regular shapes, $D = 1$, the dimension of a line, whereas for more complex shapes D approaches the value of 2 (Lovejoy, 1982).
(3) Patch elongation index (G) (Carrere, 1990) is given by:

$$G = P/A \quad (2)$$

The value of $G = 4$ represents the square patch. The larger the value of G, the more elongated the patch.

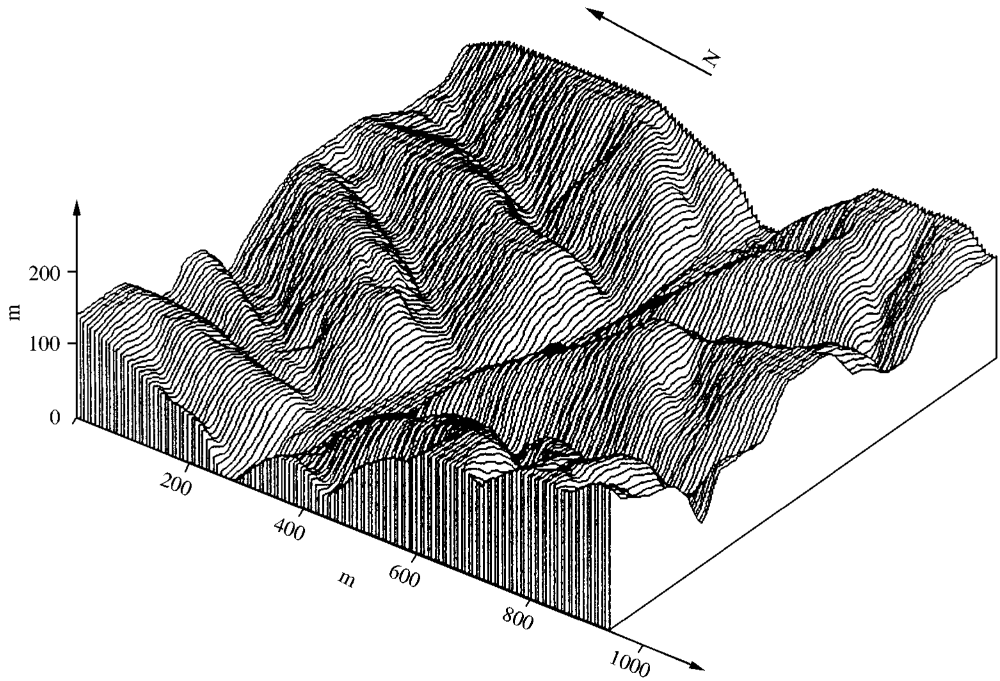

Figure 2. Digital elevation model (DEM) of the study area.

(4) Diversity; based on information theory, Shannon & Weaver (1949) developed diversity and dominance indices. O'Neill *et al.* (1988) applied them for landscape pattern analysis. H is a measure of diversity:

$$H = -\sum_{i=1}^{m} (Pi)\ln(Pi) \qquad (3)$$

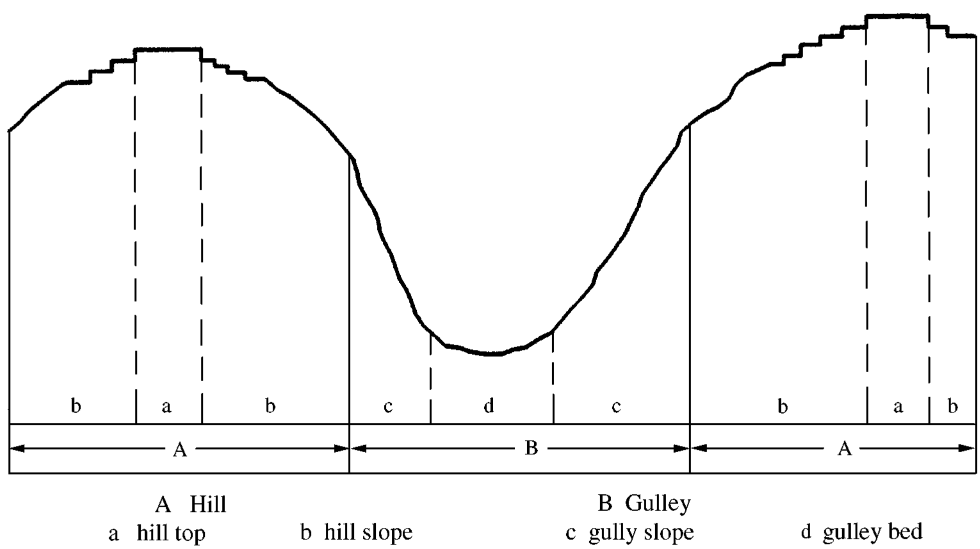

Figure 3. Cross-section of micro-landform types in the study area.

Table 1. *The area and proportion of different land-use types*

Land-use types	Area (ha)	Percent (%)
Irrigated farmland	0·51	0·46
Check-dam farmland	4·95	4·42
Terrace farmland	29·20	26·10
Slope farmland	18·44	16·49
Orchard	8·12	7·26
Grassland	10·05	8·99
Shrubland	21·36	19·09
Forest	5·14	4·59
Reservoir	0·56	0·50
Residential land	13·54	12·10

where Pi is the proportion of the landscape in cover type I, and m is the number of land-cover types observed. The larger the value of H, the more diverse the landscape.

(5) Dominance (D_0) is calculated as the deviation from the maximum possible diversity:

$$D_0 = H_{\max} + \sum_{i=1}^{m} (Pi)\ln(Pi) \tag{4}$$

where $H_{\max}$ is the maximum diversity, $H_{\max} = \ln(m)$. Large values of D_0 indicate a landscape that is dominated by one or a few land uses, and low values indicate a landscape that has many land uses represented in approximately equal proportions. However, the index is not useful in a completely homogeneous landscape ($m = 1$) because D_0 then equals zero (Turner & Ruscher, 1988).

(6) Relative richness (R) (Turner, 1989) is given by:

$$R = (M/M_{\max})*100\% \tag{5}$$

Where M is number of different land-use types present; $M_{\max}$ is maximum number of land-use types possible. The larger the value of R, the richer the landscape.

(7) Fragmentation index (F) (Monmonier, 1974) is calculated by;

$$F = [N - 1)/C]*100\% \tag{6}$$

Where N is the number of patches in the landscape matrix; C is the number of cells in the landscape matrix. The higher the value of F, the greater the fragmentation.

AREA and PERIM programs of IDRISI were used to measure the area and perimeter of each patch. In the study area, eight sample landscapes (150 × 150 m), four gullies and four hill landscapes are selected to compare the diversity, dominance, relative richness and fragmentation (see Fig. 4).

Results

Distribution and structure of land-use types

Terrace farmland is the dominant cover-type, constituting 26·1% of the study area (Table 1). Shrubland is second, followed by slope farmland. Irrigated farmland, check-dam farmland and forest are relatively rare comprising less than 5% of the study area. In

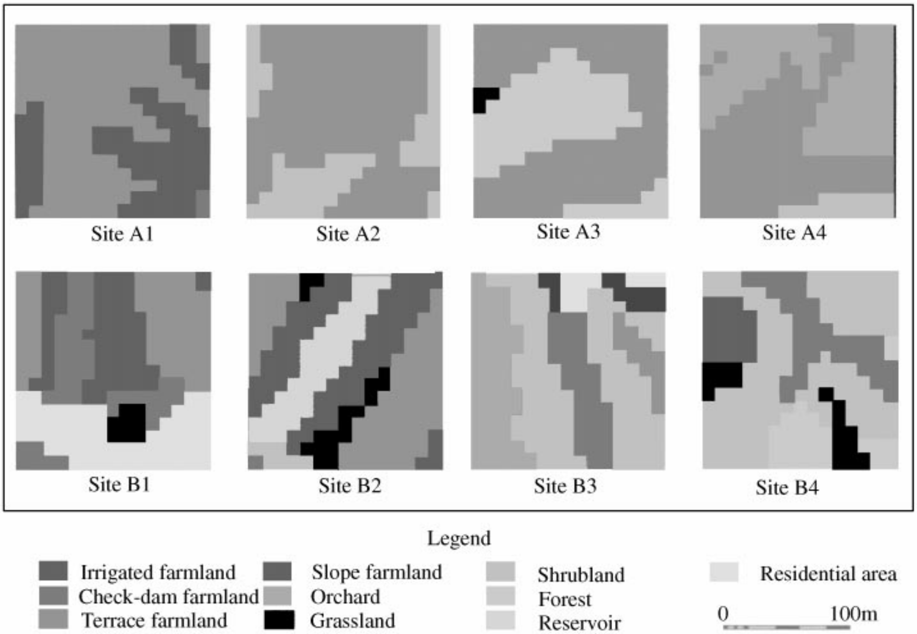

Figure 4. Sample landscapes of hill landscapes (A) and gully landscapes (B).

the study area, land use is partially controlled by micro-landform. From hill top to gully bed, micro-landform types can be divided into hill top, hill slope, gully slope and gully bed (Fig. 3). The differences of micro-landform type, slope and soil characteristics are reflected in the sequence of land use. From hill top to gully bed, the structure of land use is terrace farmland-slope, farmland-grassland (or shrubland), check-dam farmland.

The size and shape of patches

The area, perimeter and shape of patches of land-use types can be seen in Table 2. Mean patch area of irrigated farmland is the smallest at 0·17 ha in the study area, followed by grassland at 0·24 ha. Because of the complex topography and semi-arid climate, irrigated lands are few and are only distributed in the large gully bottom. Therefore, mean patch area of irrigated farmland is the smallest. Grassland in the study area is mainly natural grass on the slope. Along with the constructing terrace, planting shrubland and trees, and cultivation on slope, some grasslands were converted into terrace farmland, shrubland, forest and slope farmland. Thus, the number of grassland patches increased and patch area decreased. There are 42 grassland patches in the study area, which make up 36% of total patches in the study area. Residential land has the largest mean size of 6·67 ha, then orchard at 2·71 ha, shrubland at 1·64 ha and terrace farmland at 1·54 ha. These land-use types are man-made. The residential land is Quanjiagou village. The orchard, shrubland and terrace were planted or built up during the past 15 years. Since comprehensive land rehabilitation in the catchment from 1985, total amounts of shrubland, orchard and terrace have increased in the study area. The individual patches of shrubland, orchard and terrace lands increased in average size and shrubland and terrace lands are more connected.

Table 2. *The size, perimeter and shape of patches*

Land-use types	Patch number	Percent (%)	Mean patch area (ha)	Mean patch perimeter (m)	Mean patch fractal dimension	Mean patch elongation index
Irrigated farmland	3	2·57	0·17	2933	1·35	6·91
Check-dam farmland	7	5·98	0·71	8200	1·39	9·40
Terrace farmland	19	16·24	1·54	8137	1·24	6·64
Slope farmland	20	17·09	0·92	6740	1·20	6·67
Orchard	3	2·57	2·71	11,667	1·23	7·33
Grassland	42	35·90	0·24	2714	1·23	5·70
Shrubland	13	11·11	1·64	11,446	1·29	8·21
Forest	7	5·98	0·73	5229	1·18	6·03
Reservoir	1	0·85	0·56	6000	1·35	8·02
Residential land	2	1·71	6·77	31,600	1·30	10·93

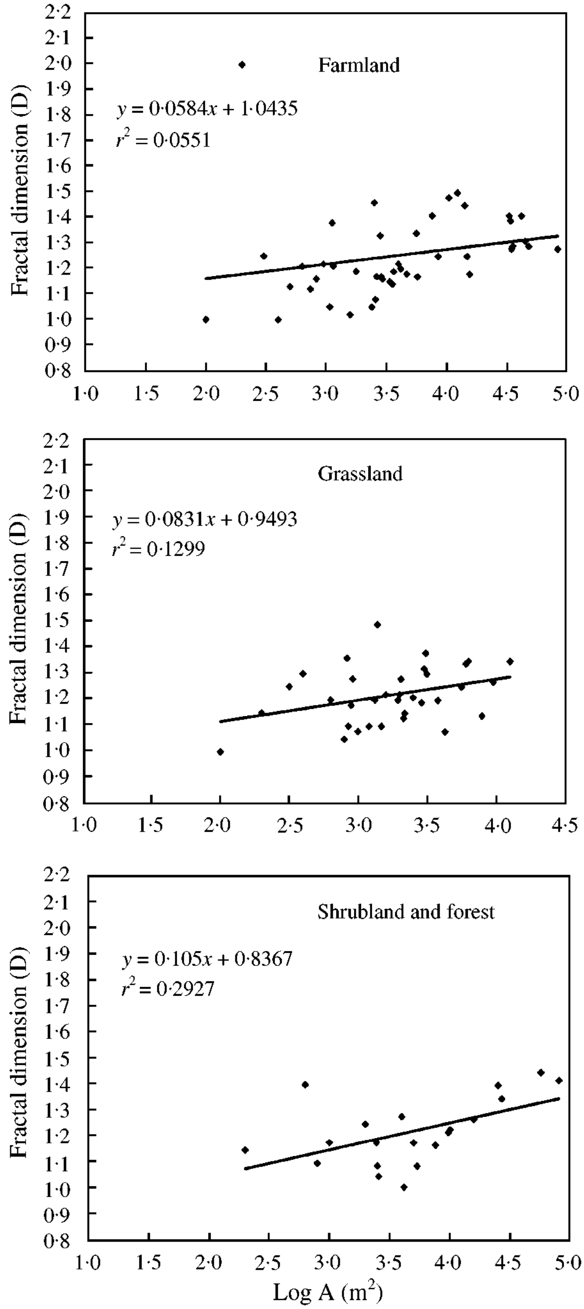

Figure 5. Relationship between fractal dimension of patches and log of patch area (m^2) for farmland, grassland, shrubland and forest.

The results of the patch shape analysis are that mean fractal dimensions of check-dam farmland, irrigated farmland, reservoir, residential land and shrubland are over 1·29, indicating relatively complex patch shapes. The mean fractal dimensions of forest, slope farmland, grassland, orchard and terrace farmland are below 1·24, indicating relatively

Table 3. *Diversity, dominance, richness and fragmentation of sample landscapes and* t-*test*★

Site	Diversity	Do	Relative richness	Patch Number	Mean patch area (m^2)	*F*
A1	0·69	1·62	0·2	5	4500	1·78
A2	0·57	1·73	0·2	5	4500	1·78
A3	0·87	1·44	0·3	3	7500	0·89
A4	0·89	1·42	0·3	5	4500	1·78
Average	0·755	1·55	0·25	4·5	5250	1·56
B1	1·16	1·14	0·5	12	1875	4·89
B2	1·38	0·92	0·4	7	3214	2·67
B3	1·29	1·01	0·6	10	2250	4
B4	1·29	1·02	0·5	11	2045	4·44
Average	1·28	1·02	0·5	10	2346	4
Σx^2	6·58	4·21	1·02	414	23093642	66·75
$(\Sigma x)^2$	6·55	4·18	1	400	22018337	64
S	0·05	0·05	0·05	1·25	346·66	0·55
T	20·08	− 20·33	10·61	8·82	− 16·80	8·83
$\alpha = 0{\cdot}05$			$\mu_0 = 2{\cdot}353$			
$\alpha = 0{\cdot}01$			$\mu_0 = 4{\cdot}541$			

★*t*-test steps:

(1) Suppose that all the values of samples within one landscape follows normal distribution.

(2) Null hypothesis (Ho) is made: $\mu = \mu_0$; opposed to null hypothesis, three alternative hypotheses are:
 (a) Ha: $\mu > \mu_0$ when μ is bigger than μ_0;
 (b) Hb: $\mu < \mu_0$, when μ is smaller than μ_0;
 (c) Hc: $\mu \neq \mu_0$, which comprises $\mu > \mu_0$ and $\mu < \mu_0$.

(3) Significance level: usually, significant differences exist when Ho is rejected at $\alpha = 0{\cdot}05$ and extremely significant differences exist when Ho is rejected at $\alpha = 0{\cdot}01$.

(4) Calculation of μ:

$$\mu = (x - \mu_0)^* n^{1/2}/\sigma$$

(5) Rejection regions of null hypothesis, i.e. the acceptance of the three alternative hypotheses are respectively:
 (a) Ha: $\mu > \mu_\alpha$;
 (b) Hb: $\mu < -\mu_\alpha$;
 (c) Hc: $|\mu| > \mu_{a/2}$ or $|\mu| > \mu_a$ (two-sides).

While carrying out the *t*-test, the values of each parameter in landscape B are used against the average value of the other one (i.e. μ_0). The value of μ for each parameter is obtained and listed in Table 3. Compared to landscape A, the values μ in landscape B are much bigger than $\mu_{0\cdot01}$ except for Do which is much lower than $\mu_{0\cdot01}$. Upon the above judgement criterion, it is concluded that the difference between Landscape B and Landscape A is extremely significant.

simple patch shapes (see Table 2). The check-dam farmland, irrigated farmland, reservoir, residential land and shrubland are located in the gullies. Their shapes depend on the shapes of the gullies. Because of serious gully erosion, gully shapes are quite complex in the study area. Therefore, the shapes of these land-use types are complex. The slope farmland, grassland, orchard and terrace farmland are distributed on the hills and ridges. Their shapes are relatively simple. The forest in the study area is man-made forest and its shape is controlled by the planner. Although the forest is mainly on the gully slope, forest patch shapes are simple.

The shapes of farmland patches (includes irrigated farmland, check-dam farmland, terrace farmland and slope farmland) show only a weak trend change (a low angular

Table 4. *Soil erosion on different types of land use in the loess hill area (after Yang & Yu, 1992)*

Land-use types	Slope degree	Vegetation cover (%)	Sediment yield ($t\ km^{-2}\ yr^{-1}$)
Slope farmland	5–10°		3364·6
Locust forest	31–33°	80	40·6
Grassland	30–31°	85	56·7

coefficient = 0·0584) with the increase of patch area (see Fig. 5). Farmland patch size between 0·27 ha and 0·58 ha (logA = 3·41 to 3·76, A in m^2) had a fractal value of about 1·20, indicating that the complexity of patch shapes is similar to simple shapes. Patch shape (fractal dimension) changes in farmland show no significant relationship ($r^2 = 0{\cdot}0551, p > 0{\cdot}05$) with patch area (Fig. 5). The size of grassland patches are mainly between 0·08 ha and 0·31 ha (logA = 2·90 to 3·49, A in m^2), which makes up 57·1% of total patches of grassland in the study area. The fractal dimensions of grassland patches vary between 1·0 and 1·5. The correlation between patch shape and patch size in grassland are significant ($r^2 = 0{\cdot}1299$, $p < 0{\cdot}05$, see Fig. 5). The shapes of shrubland and forest patch have a tendency from simple to complex with patch size increase (angular coefficient = 0·105; Fig. 5). For shrubland and forest patches of more than 0·56 ha (logA = 3·75, A in m^2), fractal dimensions increase obviously from 1·06 to 1·45. The relation existing between patch shape and patch size in shrubland and forest has a better correlation coefficient ($r^2 = 0{\cdot}2927$, $p < 0{\cdot}05$) than those in farmland and grassland (Fig. 5).

Residential land, check-dam farmland, shrubland and reservoir patches have patch elongation values over 8·0; grassland, forest, terrace and slope farmland patches have small values, below 6·7 (Table 2). The former ones are distributed within the gullies and have long and narrow shapes, the latter ones are distributed on the hills and their shapes are relatively circular.

Diversity, dominance, relative richness and fragmentation of landscapes

Eight samples of landscape (150 × 150 m), four hill landscapes (A1–A4) and four gully landscapes (B1–B4), in the study area were selected for comparison of diversity, dominance, relative richness and fragmentation in hill and gully landscapes (Fig. 4). The results are showed in Table 3.

The average values of diversity, relative richness, patch number and fragmentation of sample areas in the gully landscape are 1·28, 0·5, 10 and 4, respectively, which are larger than those of the hill landscape, while the dominance and average patch area is smaller than those of hill landscapes. The land-use types on the hill landscape are mainly terrace farmland, slope farmland, and orchard. However, the land-use types in the gully landscape include check-dam farmland, slope farmland, grassland, shrubland, forest, residential area and reservoir. Also, the results show the patch sizes in the hill landscape is bigger than those in the gully landscape. Much difference is observed between these two landscapes. To check if the difference between the two landscape types (A and B) is significant, a *t*-test was carried out (Table 4). Upon the *t*-test result, the difference between landscape A and landscape B was found to be extremely significant.

Discussion and recommendations

Landscape pattern and soil erosion

The use of landscape patterns for erosion control is well documented for humid, temperate (Morgan, 1992) and tropical (Bonell *et al.*, 1983) environments. These landscape patterns usually take the form of vegetation strips, which run parallel and adjacent to stream channels with the aim of absorbing runoff and trapping sediment from upper slope locations (Vought *et al.*, 1995). Fu *et al.* (1999) has reported the effect of land-use structure on the soil nutrients in the hilly area of the Chinese Loess Plateau. The results showed that farmland–grassland–forest and terrace–grassland–forest land-use structures from hill foot to hill top have a better capacity for soil conservation and retention of nutrients than other land-use structures. Creating a spatial mosaic pattern for potential runoff producing areas may therefore provide the most effective management strategy in runoff and erosion control for semi-arid environments. Establishing mosaic patterns may be achieved by manipulating vegetation in selected locations to create sinks for overland flow and sediment deposition (Fitzjohn *et al.*, 1998). The shape of the patch also influences how the runoff passes through the patches. The effect still lacks attention and research.

Landscape pattern analysis in this paper found the differences of landscape pattern in hill landscapes and gully landscapes (Table 3, Fig. 4). The gully landscapes were more patchy, with a mean patch area of 0·23 ha, whereas the hill landscapes have few and large patches, for example, terrace farmland, orchard and slope farmland, with a mean patch area of 0·53 ha. At the field level, risk of erosion depends on slope angle, slope length and texture of superficial soil layer, the volume of water coming into the field either by rainfall or by runoff from upper fields, nature of land use and farming practices (Burel *et al.*, 1993). Large farmland patches in the hill landscape, leading to a big slope length, enhances the erosion risk. The relationship between land use and soil erosion in the loess hill area is shown in Table 4 (Yang & Yu, 1992). The rate of erosion is greatest on farmland. At the landscape level all spatial patterns control water flow and erosion. The hill landscape currently has a lower diversity, richness, fragmentation and higher dominance than those of the gully landscape (Table 3). It is necessary to create a spatial mosaic pattern increasing spatial variation in the hill landscape for soil conservation and erosion control.

Implications for land management

Land management in the loess hill area of the Chinese Loess Plateau is primarily concerned with runoff and erosion control. The change of the current land-use structure is the main method used to control soil erosion. The results from this study have shown that spatial variation of land use in the hill landscape should be increased, particularly in ecologically sensitive and high erosion risk sites. The areas which were transformed from hill top to hill slope, and hill slope to gully slope are identified as high erosion risk sites (Fu *et al.*, 1995). The following measures should be taken so as to improve landscape patterns for soil erosion control:

(1) A shrubland buffer should be set up on the erosion sensitive zones between hill top and hill slope, and hill slope to gully slope. The structure of land use from hill top to gully bed should be: terrace farmland–shrubland buffer–slope farmland–shrubland buffer–grassland–shrubland (or forest)–check-dam farmland, which can effectively control water flow and reduce erosion by shrubland buffer;

(2) Reducing patch size is necessary and homogeneity of large tracts of land must be avoided on the hill landscape. This can decrease slope length and slope gradient of patches and reduce erosion risk;
(3) In the hill landscape, farmland should be diversified within itself. It is recommended that intercropping of different crops, grass and crop, and fruit tree and crop should be carried out, which increases diversity, and creates a more patchy landscape. Increasing the spatial diversity of land use not only protects the soils but also enhances habitat biodiversity.

This project was supported by the National Natural Science Foundation of China (No. 49725101). The authors thank professors D. A. Davidson and H. Gulink in the U.K. and Belgium for their valuable comments and suggestions on a draft of this paper.

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