Landscape Pattern Evolution and Ecosystem Service Value Response in Small Watersheds of the Loess Hilly and Gully Region: Postprint

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Abstract

Taking Nihegou watershed, a typical small watershed in the loess gully region, as the study area, and based on interpretation results of 1986 color-infrared aerial photographs, 2002 SPOT imagery, and 2016 GF-1 satellite imagery, together with socio-economic statistical data, this study analyzed the evolution of landscape patterns in the watershed over the past 30 years using methods including landscape metrics, land use degree, and information entropy, and quantitatively examined the variation characteristics of ecosystem service value by drawing upon the ecosystem service value equivalent estimation method. The results indicate that: Over the past 30 years, the land use landscape pattern in the study area has undergone significant changes: except for increases in forest land and construction land areas, cultivated land, orchard land, and unused land have all decreased by varying proportions. The overall landscape fragmentation within the watershed has decreased, while the connectivity of dominant patches shows an increasing trend. The overall land use degree shows an upward trend and is higher than the national average level 231; land use information entropy first decreased and then increased, indicating that the watershed landscape has undergone a transformation of "disorder-order-disorder". During the study period, the total ecosystem service value of the watershed exhibited a continuous upward trend, with individual ecosystem service functions dominated by soil formation and protection, waste treatment, water conservation, and biodiversity protection. High-resolution satellite imagery provided relatively detailed data support for analyzing watershed landscape pattern evolution and ecosystem service value.

Full Text

Preamble

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Landscape Pattern Changes and Evaluation of Ecological Service Values in a Small Watershed of the Loess Gully Region

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Abstract

This study examines the Nihegou watershed, a typical small watershed in the Loess Gully region. Using color-infrared aerial photographs from 1986, SPOT satellite imagery from 2002, GF-1 (Gaofen-1) satellite imagery interpretations from 2016, and socio-economic statistical data, we analyzed the evolution of landscape patterns over the past three decades using landscape metrics, land use degree indices, and information entropy theory. The characteristics of ecosystem service value changes were quantitatively assessed using an equivalence estimation method adapted for ecological service valuations.

The results show that over the past 30 years, land use and land cover in the study area have undergone significant changes, with arable land, orchards, and unused land decreasing in area while woodland and developed land increased. Landscape fragmentation decreased overall, and the connectivity of dominant patches tended to increase. The land use level continued to rise and exceeded the national average level of 231. Land use information entropy first decreased and then increased, indicating that landscape patterns changed from an originally disordered state to a more ordered state and then returned to a more disordered state. The total ecosystem service value of the watershed showed a continuous upward trend during the study period, with the major individual functions being soil formation and protection, water conservation, and biodiversity conservation. High-resolution satellite imagery provided detailed data support for analyzing watershed landscape pattern evolution and ecosystem service values.

Keywords: land use; landscape pattern; landscape index; ecological service value; equivalence method; Nihegou watershed

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1. Study Area Overview

The Nihegou watershed is located in Chunhua County, Xianyang City, Shaanxi Province, in the southern Loess Plateau, and represents a typical Loess Gully region. The watershed includes seven administrative villages with a permanent population of approximately 6,000. The terrain slopes from north to south with elevations ranging from 699–1,163 m. The upper reaches of the gullies have steep slopes and narrow channels, while downstream erosion moderates. The region has a warm temperate semi-humid climate with an average annual temperature of 9.8°C and annual precipitation of 600.6 mm, with more than 50% occurring during July–September, mostly as heavy rain. The frost-free period is 183 days and annual solar radiation totals 504.35 kJ/cm². Natural vegetation consists primarily of herbs and shrubs. The main landscape types are cultivated land, orchards, woodland, grassland, water bodies, construction land, and unused land.

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2. Data Sources and Preprocessing

The remote sensing data sources include: 1986 color-infrared aerial photographs (1:10,000 scale), 2002 SPOT-5 images (with 2.5 m panchromatic and 10 m multispectral resolution), and 2016 GF-1 images. All data underwent radiometric calibration, atmospheric correction using FLAASH, image fusion, and registration with the 1986 land use map interpreted from aerial photographs. Registration errors were controlled within one pixel.

An object-oriented classification method was used for interactive interpretation of the two high-resolution images. Based on the National Agricultural Land Use Classification System and considering watershed characteristics, land use types were classified as: arable land (dry farmland and rotational fallow), orchard, woodland (sparse forest and planted forest), grassland (natural and artificial), water body, construction land (rural settlements, independent enterprise land, and roads), and unused land (steep slope grassland, abandoned gully land, etc.). Interpretation accuracy was evaluated using confusion matrices and field validation, with all images achieving accuracy greater than 85%, meeting analysis requirements. Additional data included the Chunhua Statistical Yearbook and field survey data.

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3. Methods

3.1 Landscape Pattern Evolution Analysis

Landscape Metrics Selection
Landscape metrics are simple quantitative indicators that condense landscape pattern information to reflect structural composition and spatial configuration

characteristics. At the class level, we selected: Class Area (CA), Percentage of Landscape (PLAND), Landscape Shape Index (LSI), Largest Patch Index (LPI), Clumpiness Index (CLUMPY), and Mean Patch Area (AREA_MN). At the landscape level, we selected: Number of Patches (NP), Patch Density (PD), Shannon' s Diversity Index (SHDI), Shannon' s Evenness Index (SHEI), Contagion Index (CONTAG), Patch Richness (PR), Largest Patch Index (LPI), and Mean Patch Area (AREA_MN). These metrics reflect area, shape complexity, and aggregation of landscape types. Calculation methods and meanings are detailed in reference [19].

Land Use Dynamic Degree
Single land use dynamic degree refers to the annual change rate of a particular land use type within a certain time period [20]:

$$D = \frac{L_n - L_m}{L_m} \times \frac{1}{n} \times 100\%$$

where D is the single dynamic degree of a land use type during the study period, L_m and L_n are the areas of a landscape type at the start and end years respectively, and n is the number of years.

Land Use Degree
Land use degree analyzes the breadth and depth of regional land use, quantitatively reflecting natural attributes and the combined effects of human-environment interactions [20-21]:

$$L_u = \sum_{i=1}^{n} (P_i \times Q_i)$$

where L_u is the comprehensive land use degree index, P_i is the grading index of land use degree level i, and Q_i is the percentage area of level i.

Land Use Information Entropy
Land use information entropy comprehensively reflects dynamic changes in various land use types and guides regional land use structure adjustment. Lower entropy indicates higher system order; when the system reaches complete equilibrium, information entropy reaches its maximum value [22-23]:

$$H = -\sum_{i=1}^{n} P_i \log P_i$$

where P_i is the percentage of each landscape type area relative to the total watershed area, and n is the number of landscape types.

Ecosystem Service Value Assessment
The assessment primarily uses the equivalence factor method based on Costanza et al. [24] and Xie et al. [25-26]. The value of an equivalence factor is calculated

as:

$$VC = \frac{P \times Q}{n}$$

where VC is the value of an equivalence factor, P is the average grain price (¥/kg), Q is the average grain yield (kg/km²), and n is the number of years.

In this study, cultivated land and orchard were combined to correspond to farmland in the ecological asset classification. Using the study area' s average grain yield of 2,819,300 kg/km² as the baseline and combining it with the average grain price, we determined that the economic value of natural grain production from farmland in Nihegou is ¥67,663.2 per km². Multiplying this by the ecosystem service value equivalents yields the per-unit ecological value for Nihegou landscape types.

The ecosystem service value (ESV) is calculated as:

$$ESV = \sum (A_k \times VC_k)$$

$$ESV_f = \sum (A_k \times VC_{fk})$$

where ESV is the total ecosystem service value of the study area, ESV_f is the value of ecosystem service function f, A_k is the area of landscape type k, VC_{fk} is the value coefficient of function f for landscape type k, and VC_k is the ecosystem service value coefficient for landscape type k.

3.2 Sensitivity Verification

To verify whether the selected VC values are suitable for this study area, we used the sensitivity index (CS). Sensitivity analysis examines how much parameters can change in a model while maintaining the original optimal solution conditions [27]. CS indicates the dependence of ESV on VC over time. The formula is:

$$CS = \left| \frac{(ESV_j - ESV_i)/ESV_i}{(VC_{jk} - VC_{ik})/VC_{ik}} \right|$$

where CS is the sensitivity coefficient, VC_{ik} and VC_{jk} are the initial and adjusted value coefficients respectively, and ESV_i and ESV_j are the corresponding ecosystem service values. If CS is too high or too low, it affects the accuracy of ESV changes over time. Conversely, if ESV lacks elasticity to VC changes, the results are more reliable. In this study, we adjusted the ecosystem service value coefficients by ±50% to test sensitivity.

4. Results

4.1 Landscape Type-Level Change Characteristics

At the landscape type level, the shape index (LSI) of arable land in Nihegou watershed first decreased then increased, while patch density continued to increase. Orchard patch area increased significantly by 24.04% from 1986–2002 and 27.73% from 2002–2016, indicating reduced landscape fragmentation. Woodland patch area showed a continuous increasing trend, with its clumpiness index reaching the highest among all types, indicating increased patch connectivity. As living standards improved, construction land (roads and factories) gradually increased. Grassland patch number and shape index showed continuous decreasing trends, while unused land was effectively utilized. Water bodies remained relatively stable during the study period.

4.2 Landscape-Level Change Characteristics

At the landscape level, the Landscape Shape Index (LSI) showed a significant decreasing trend from 1986–2016, indicating that human activities transformed landscape shapes toward greater concentration. The Contagion Index (CONTAG) increased, suggesting slightly reduced overall landscape fragmentation. Shannon' s Diversity Index (SHDI) and Shannon' s Evenness Index (SHEI) both first decreased then slightly increased. The decrease in SHEI indicates that landscape dominance increased, with dominant categories exerting stronger control over the entire landscape—primarily due to increased woodland patch area.

4.3 Landscape Type Area Changes and Conversion Relationships

All landscape types in the study area experienced area changes. Arable land decreased continuously, orchards first increased then decreased, woodland changed significantly, and construction land proportion increased from 5.14% to 7.84%. Unused land decreased from 12.07% to 3.34%. Arable land and orchards dominated the landscape, with their combined area exceeding 50% of the total watershed area throughout the study period. Woodland and unused land showed the most obvious change rates, with woodland reaching 18.80%.

The most significant conversion relationships were between woodland and orchards/arable land, accounting for the majority of change area in the study region. This conversion was partly policy-driven: some sloping arable land and orchards on steep slopes prone to soil erosion were systematically converted to woodland to restore forest and grass vegetation. Meanwhile, some old orchards with outdated varieties were replaced by new varieties with better economic returns or converted back to arable land, changing the quantity and structure of orchards. As Nihegou management deepened, coupled with agricultural technology contracts, farmland improvement, and market economy influences, the landscape layout—especially the proportions of arable land, orchards, and woodland—was adjusted and optimized.

4.4 Land Use Degree Analysis

The comprehensive land use degree index of Nihegou watershed showed an overall upward trend, exceeding the national average level of 231. The slight decline in 2016 was due to accelerated economic development and urbanization, which increased migrant workers and reduced land management, leading to ineffective land utilization. Construction land expansion somewhat damaged landscape integrity and connectivity, causing some decline in landscape function.

4.5 Land Use Information Entropy Evaluation

The land use information entropy values for the three periods were 0.7248, 0.7148, and 0.7219 respectively. The highest entropy in 1986 indicated lower land use system order, while the lowest in 2002 indicated higher order and reduced disorder. The changes show that Nihegou' s land use system experienced a gradual adjustment process from disorder to order and back to disorder. Through concentrated management during the key project period, the land use structure became more stable and orderly compared to pre-management conditions.

4.6 Total Ecosystem Service Value Changes

The total ecosystem service value (ESV) of Nihegou watershed showed a continuous upward trend, increasing from 548.69×10 yuan to 673.11×10 yuan. In terms of landscape type contributions, only woodland and orchard ESVs showed increasing trends. Woodland ESV increased by 119.16×10 yuan (53.49%) from 1986-2002 and by 47.22×10 yuan (13.81%) from 2002-2016. The increase in woodland ESV played a crucial role in the total ESV increase.

4.7 Individual Ecosystem Service Value Changes

Individual ecosystem service values in Nihegou watershed changed significantly. Except for food production value, which showed a decreasing trend, all other functions increased to varying degrees. Raw material and entertainment/leisure values changed more dramatically than other functions, with change rates of 46.06% and 39.09% respectively.

From 1986-2002 and 2002-2016, the ranking of individual function values was: soil formation and protection > water conservation > biodiversity conservation > waste treatment > climate regulation > gas exchange > raw material > entertainment and leisure > food production. Soil formation and protection function value was most prominent, followed by water conservation and biodiversity protection, which together accounted for 70.42% of total function value. Entertainment and leisure accounted for the smallest proportion. In 2015, a modern agricultural demonstration park was established in Zuitou Village, Nihegou, featuring leisure agriculture tourism, greenhouse grape picking (new varieties like Red Balado), and modern agricultural technology experiences, which gradually enhanced the watershed' s entertainment and leisure function.

4.8 Sensitivity Analysis

Sensitivity analysis showed that the CS index was highest for woodland but remained below 0.58 in all years, indicating that when woodland' s ecological value coefficient increases by 1%, the total ecosystem service value increases by only 0.58%. The low sensitivity coefficients for all landscape types demonstrate that the ecosystem service value is inelastic to changes in value coefficients, confirming that the ecological value coefficients are reliable and the research results are credible for providing references for watershed ecological construction.

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5. Conclusions and Discussion

Ecosystem service value estimation methods fall into two categories: unit service price-based methods and unit area equivalence factor methods [24, 26]. Different models and parameters yield different results, and no universally accepted standard currently exists. The former involves complex parameter input and calculation processes with difficult-to-standardize parameters for each service value, while the latter is more intuitive and suitable for regional assessments [29]. Therefore, this study adopted the equivalence estimation method based on Xie et al. [25-26] to analyze Nihegou watershed' s ESV changes from 1986–2016, combined with landscape metrics, land use dynamic degree, and information entropy to quantitatively analyze landscape pattern evolution.

The results show that over the past 30 years, Nihegou' s land use landscape patterns changed significantly. Except for woodland and construction land, all other land types decreased in area. Landscape fragmentation decreased overall, while dominant patch connectivity increased. The conversion between orchards and woodland was the main transformation pattern. Except for construction land showing positive dynamic change, all other land types showed negative dynamic changes. National management programs optimized the land use structure, significantly improving land use degree above the national average. The land use system became stable and orderly.

From the ESV perspective, total value showed a continuous upward trend, consistent with studies on the Loess Plateau by Li and Ren [30] and Li et al. [31]. Woodland and orchard ESVs increased while other landscape types decreased from 1986–2002; only woodland ESV increased from 2002–2016. Individual service values showed that soil formation and protection, water conservation, and biodiversity conservation were dominant, accounting for 70.42% of total function value. The changes primarily resulted from landscape pattern-induced changes in natural ecosystem areas.

Sensitivity analysis confirmed that ESV is inelastic to value coefficient changes, indicating that uncertainty in ecological value coefficients has minimal impact on total ESV estimation stability. The results are reliable and can provide references for understanding scientific research achievements and subsequent resource allocation. However, accurately obtaining ecosystem service values for specific regions requires using specific units for that region' s ecosystem services [32-33], which warrants further research.

References

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Note: Figure translations are in progress. See original paper for figures.