

Research on Optimal Spatial Settlement Patterns in the Hilly-Gully Region of the Loess Plateau in Northern Shaanxi: A Case Study of Donggou, Mizhi County (Postprint)

Authors: Tian Darui

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Abstract

The hilly-gully region of the Loess Plateau constitutes a critical challenge for new urbanization practices in western China. In the absence of clarified regional characteristics, the intervention of modern urban-rural planning and design has generated substantial impacts on the local environment and culture. Taking Donggou in Mizhi County, Northern Shaanxi as a case study, this research utilizes satellite remote sensing imagery, Digital Elevation Model (DEM) data, and grid-based methods to reveal the spatial distribution characteristics of topographic variation and settlement scale in Donggou. Through four-quadrant scatter plot analysis and a three-dimensional grid fractal dimension model, the study measures and evaluates the coupling coordination relationship between topographic complexity and settlement agglomeration, as well as settlement spatial distribution efficiency, thereby summarizing settlement spatial construction patterns appropriate for gully regions. The results demonstrate: (1) Distinct spatial differentiation characteristics exist in Donggou settlements from the gully mouth to the interior: settlements progressively deviate from riverbanks, while building density and floor area ratio exhibit a pattern of decreasing from high to low, followed by a subsequent increase and decrease. (2) Based on overlay analysis of topographic complexity and settlement agglomeration degree, agglomerated settlements in gentle terrain and dispersed settlements in complex terrain represent human-land coordinated settlement types, comprising approximately 70.5% of total settlement scale. (3) The three-dimensional grid fractal dimension of Donggou settlements displays pronounced segmentation features, with terraced row-type and free row-type settlements achieving the highest fractal dimension values of 2.35–2.55. (4) Among five typical human settlement spatial patterns in Donggou, terraced row-type, free row-type, and dense patch-type settlements exhibit dual characteristics of human-land coordination and

efficient spatial utilization, which can serve as references for settlement spatial construction in hilly-gully regions.

Full Text

Suitable Spatial Patterns for Settlements in the Hilly-Gully Region of the Loess Plateau in Northern Shaanxi: A Case Study of Donggou, Mizhi County

TIAN Darui¹, TANG Hao², TAN Jingbin³

¹School of Architecture, Xi'an University of Architecture and Technology, State Key Laboratory of Green Building in Western China, Xi'an 710055, Shaanxi, China

²LAY-OUT Planning Consultants Co., Ltd., Shenzhen 518049, Guangdong, China

³School of Architecture, Chang'an University, Xi'an 710061, Shaanxi, China

Abstract

The hilly-gully region of the Loess Plateau represents a critical challenge for new urbanization initiatives in western China. Without a clear understanding of regional characteristics, conventional urban planning and design practices have significantly impacted local environments and cultural heritage. Taking Donggou in Mizhi County, northern Shaanxi as a case study, this research employs grid-based analysis of satellite remote sensing imagery and digital elevation model (DEM) data to reveal the spatial distribution characteristics of topographic variation and settlement scale. Using four-quadrant scatter plot analysis and a three-dimensional grid fractal dimension model, the study measures and evaluates the coupling coordination between topographic complexity and settlement agglomeration, as well as the spatial distribution efficiency of settlements, to summarize appropriate settlement construction patterns for gully regions. The results indicate: (1) Settlements exhibit distinct spatial differentiation from the gully mouth inward, with building density and floor area ratio showing a pattern of decreasing, then increasing, then decreasing again, while settlements gradually deviate from riverbanks. (2) Based on overlay analysis of terrain complexity and settlement agglomeration, concentrated settlements in gentle terrain and dispersed settlements in complex terrain represent coordinated human-land relationships, accounting for approximately 70.5% of total settlement area. (3) The three-dimensional grid fractal dimension values of Donggou settlements show clear segmentation, with terrace parallel and free parallel patterns achieving the highest values of 2.55. (4) Among five typical settlement patterns in Donggou, terrace parallel, free parallel, and dense patch patterns demonstrate both human-land coordination and high spatial efficiency, serving as valuable references for settlement construction in hilly-gully regions.

Keywords: Loess Plateau hilly-gully region; settlement spatial pattern; human-

land coordination; three-dimensional grid fractal dimension; Mizhi County

Introduction

The Loess Plateau is both a crucial cradle of Chinese civilization and an ecologically fragile region. Its unique natural and cultural resources establish its significant position in China's urbanization development. The hilly-gully region constitutes an important component of the Loess Plateau, where the development of traditional urban and rural settlements represents a spontaneous, self-organizing dynamic process. This process embodies and perpetuates the profound wisdom of local residents, shaping distinctive spatial orders and logics with regional characteristics, and gradually forming a complex system containing intricate elements and relationships. However, due to the lack of scientific and effective planning guidance, rapid and extensive outward expansion of valley towns in recent years has led to the emergence of high-rise residential areas constructed through massive excavation, high cutting, and large-scale earthwork on shallow hillside slopes within gully watersheds. This rigid and disordered architectural layout has destroyed the original settlement spatial fabric and scale of the gully region, pushing traditional settlements toward aging and abandonment, while the diverse and rich spatial characteristics and aesthetic qualities of Loess Plateau human settlements are gradually disappearing. Consequently, the human-land contradiction in urban and rural construction is intensifying.

Therefore, human settlement development in the Loess Plateau hilly-gully region cannot directly apply urban-rural planning techniques and experiences from plain areas. Its urbanization urgently needs to draw upon local human settlement wisdom, prioritize human-land coordination, explore and effectively utilize spatial potential within gully regions, and thereby develop settlement spatial organization modes suitable for hilly-gully areas.

To address human settlement challenges in the Loess Plateau, scholars have accumulated rich research findings and proposed valuable experiences. First, studies on spatial distribution characteristics and evolution mechanisms of urban-rural spaces in the Loess Plateau hilly-gully region are relatively abundant. Scholars have analyzed spatiotemporal differentiation characteristics of human settlements from various perspectives, including population shrinkage patterns and their driving forces. In recent years, research employing computer technology and related models to explore urban-rural evolution dynamics has gradually increased. For instance, Duan Xiaowei et al. used factor analysis and geographic detectors to analyze settlement evolution characteristics and influencing factors, while Zhu Jingjing employed grey system correlation models to reveal spatial autocorrelation patterns of land use in loess hilly and mountainous areas.

Second, research on human settlement spatial morphology and appropriate development modes based on the complex topography and fragile ecological environment of the Loess Plateau has been a focus. At the macro level, existing studies have frequently examined appropriate spatial patterns and urban-rural inte-

grated development models for valley towns from perspectives such as regional balanced coordination, organic growth, and fractal theory, and have constructed planning and evaluation methods. For example, Yu Hanxue et al. proposed the basic pattern of “large dispersion, large aggregation” and dendritic multi-center clusters for urban spatial systems in the Loess Plateau gully region. At the micro level, scholars have primarily focused on water resources, ecological units, and gully landscape to derive settlement spatial development models. Liu Binyi et al. constructed an ecological water-green win-win human settlement spatial model for semi-arid areas of the Loess Plateau to address water scarcity issues.

In summary, current planning research on human settlements in the Loess Plateau hilly-gully region has concentrated mainly on overall spatial morphology and development patterns from an ecological perspective. However, studies exploring settlement construction patterns based on three-dimensional space and the spatial coupling relationship between urban-rural settlements and topography remain scarce, making it difficult to meet current demands for territorial spatial planning, design, and control in the complex geomorphic regions of the Loess Plateau. This article takes the Donggou watershed in Mizhi County, northern Shaanxi as its object of study, analyzing the coordination relationship between human settlements and topography in complex hilly-gully terrain from a three-dimensional spatial perspective, as well as their spatial efficiency, to explore efficient and appropriate settlement spatial layout patterns.

1. Study Area Overview

Mizhi County is located in northern Shaanxi, east of Yulin City. The Wuding River basin where it is situated features crisscrossing gullies, deeply incised river channels, and interlocking ridges and hills, presenting typical loess hilly-gully landforms. The county center lies in the flat Wuding River valley, but the Wuding River tributaries near the old city exhibit the most concentrated and diverse settlement patterns, with typical human-land relationships in the loess hilly-gully region. Within Mizhi County, there are over 20 Wuding River tributaries, among which “Donggou” near the old city contains the largest and most diverse settlements. To ensure sample diversity, this study defines its research scope along the gully, extending west to Songjiayan at the intersection of Donggou and the main valley channel, east to Qilimiao, and covering the hilly slopes on both sides of the gully with a width of approximately 600 m north-south. The total area is 4.7 km², with valley area comprising only 24 km², indicating extremely limited construction land resources.

2. Methodology

2.1 Research Framework This study follows the logical framework of “characteristic cognition → pattern extraction” for gully terrain and local settlements. First, grid analysis is employed to draw 100 m × 100 m grids covering the entire study area, dividing the research object into manageable units. Sample grid squares (hereinafter referred to as “samples”) are used to quantitatively

describe and reveal spatial distribution characteristics of topographic variation and settlement scale within the study area. Building upon this, settlements are evaluated from two dimensions: human-land coupling coordination and three-dimensional spatial utilization efficiency. Four-quadrant scatter plot analysis is used to overlay and classify terrain complexity and settlement agglomeration, identifying settlement samples with coordinated human-land relationships. A three-dimensional grid fractal dimension model analyzes the spatial distribution efficiency of settlement samples, and high-dimension samples are selected from coordinated types as optimal spatial paradigms to extract and summarize appropriate settlement spatial patterns for hilly-gully regions (Figure 2).

2.2 Data Sources Basic data include two categories: topography and settlement buildings. First, digital elevation model (DEM) data were downloaded from the Geospatial Data Cloud platform, and ArcGIS spatial analysis tools were used to generate slope and aspect vector maps (Figure 3). Second, based on field surveys and combined with satellite remote sensing imagery and current land use maps, settlement building CAD plans were obtained. Sketch Up shadow simulation and solar altitude angle calculation methods were used for mutual verification and correction to acquire building height data for the study area. Finally, a three-dimensional spatial morphology map of Donggou was generated through fitting topographic and building elevation data (Figure 4).

2.3 Measurement Methods

2.3.1 Calculation of Gully Terrain Complexity Terrain complexity is a key factor affecting human settlement construction in the Loess Plateau hilly-gully region. Previous analyses based on single elevation or slope cannot comprehensively reflect the complex effects of terrain factors on settlement distribution. Recently, geography and geomorphology have introduced relief amplitude and terrain niche index to describe regional landform morphology and classify terrain levels, thereby more profoundly reflecting how complex changes in natural factors affect human settlement spatial patterns.

Relief amplitude, also called relative height, refers to the difference between maximum and minimum elevation among all grids within a specific area, intuitively reflecting regional terrain undulation characteristics. To accurately and completely present terrain features, sliding windows are commonly used to calculate relief amplitude at different window sizes, determining the optimal statistical window area for average relief amplitude. This study uses manual change point detection to determine the optimal statistical analysis window for the study area as an 11×11 matrix, corresponding to an optimal statistical range area of 0.0189 km^2 .

The terrain niche index comprehensively describes terrain features through the combination of slope and elevation variables. Points with higher elevation and

steeper slope have larger terrain niche indices, indicating more complex terrain changes less suitable for urban-rural development. The calculation formula is:

$$T = \log \left[\left(\frac{E}{E_0} + 1 \right) \times \left(\frac{S}{S_0} + 1 \right) \right]$$

where T represents the terrain niche index; E represents the elevation value of any point; E_0 represents the average elevation value within the calculation unit; S represents the slope value at any point; and S_0 represents the average slope within the calculation unit.

2.3.2 Calculation of Settlement Agglomeration Scale Settlement agglomeration scale reflects the distribution quantity of settlement building clusters within unit space, characterized in this study by building density and floor area ratio. Building density refers to the ratio of total building footprint area to land area within a certain range, reflecting building intensity and open space ratio. Floor area ratio refers to the ratio of total above-ground building floor area to land area within a certain range, measuring construction land use intensity.

2.3.3 Comprehensive Indices for Terrain Complexity and Settlement Agglomeration To analyze the coupling coordination between terrain complexity and settlement agglomeration in Donggou, this study employs comprehensive index methods to synthesize relief amplitude and terrain niche index into a terrain complexity index, and building density and floor area ratio into a settlement agglomeration index. First, the range standardization method is used for dimensionless standardization of terrain niche index, relief amplitude, building density, and floor area ratio. The coefficient of variation method determines weights for individual indicators, which are then used to calculate comprehensive indices for each sample. The calculation formula is:

$$C = \sum_{i=1}^n W_i \times X'_{ij}$$

where C represents the comprehensive index of several indicators; i represents a specific indicator ($i = 1, 2, \dots, n$); W_i represents the weight of indicator i ; and X'_{ij} represents the standardized value of indicator i for sample j .

2.3.4 Three-Dimensional Grid Fractal Model for Settlement Space As a frontier theory for studying complex systems, fractal theory provides new perspectives and methods for urban-rural spatial morphology research. Fractal dimension is a core indicator reflecting spatial characteristics and fractal states of fractal bodies. Among these, grid dimension is a widely applied fractal model across disciplines, revealing a system's space-filling capacity and serving as a comprehensive quantitative indicator for evaluating and comparing spatial benefits. Settlements influenced by hilly-gully landforms exhibit complex vertical

variation characteristics. Therefore, this study extends planar grid dimension measurement principles to three-dimensional space, using a three-dimensional grid fractal model to evaluate spatial utilization efficiency of settlements in gully regions.

The model is defined as follows: Cover the three-dimensional space of a settlement with cubes of length L , width L , and height H , measuring the number of cubes $N(L)$ required to contain settlement buildings. Then divide each side of the cube in half, partitioning it into smaller cubes of side length $L/2$, and count the number of non-empty cubes as $N(L/2)$. Repeating this operation, when dividing to step n , the number of non-empty cubes is recorded as $N(r)$. If the settlement is fractal in three-dimensional space, according to general fractal laws $N(r) = kr^{-\alpha}$ (where k is a constant and α is the scaling exponent, i.e., fractal dimension), then three-dimensional scale r and its corresponding number of non-empty cubes should satisfy:

$$\ln N(r) = -\alpha \ln r + \ln k$$

Transforming the $(\ln r, \ln N(r))$ point series to a double logarithmic coordinate diagram, these points distribute along a straight line whose slope represents the three-dimensional fractal dimension of the research object. Combining the spatial connotation of planar grid fractal dimension, the three-dimensional grid fractal model reflects the change rate of the relationship between cube scale and corresponding element quantity, revealing the three-dimensional space-filling degree and spatial distribution efficiency of the research object. Larger values indicate more efficient and compact settlement distribution. Due to computational complexity from decreasing cube scale resolution and exponential quantity increase, this study selects 7 groups of cube scales with sequentially halved side lengths to measure settlement samples, counting corresponding non-empty cube numbers for each sample at different scales, then uses least squares method for linear fitting of points within the scale-free region.

3. Results

3.1 Spatial Characteristics of Terrain Complexity in Donggou

Through grid-based analysis of terrain index data, the spatial characteristics of terrain complexity variation in Donggou are clearly revealed.

First, terrain undulation varies richly within the study area, with relatively balanced proportions of high, medium, and low relief amplitude. According to classification standards in Chinese digital geomorphology mapping specifications, the study area's relief amplitude is divided into five levels using natural breaks and reclassification tools: flat (0-30 m), slight undulation (31-40 m), small undulation (41-50 m), medium undulation (51-60 m), and high undulation (61-90 m). Approximately 43.6% of samples show small terrain undulation (40 m), 26.2% 51 m (Figure 5).

Second, the spatial distribution of terrain niche index exhibits overall gully characteristics of “low near water, high far water; high and low alternating north-south.” Terrain niche index gradually increases from riverbanks to both sides. Low-index areas (0.85–1.28) account for 36.9% of total samples, distributed continuously along the river forming gentle riparian zones. In the western section (0–2.0 km) and eastern section (3.4–4.7 km), low-index samples are relatively concentrated, forming two gentle zones along the river. In the middle section (2.0–3.4 km), low-index areas gradually narrow, and terrain complexity increases (Figure 5).

3.2 Spatial Characteristics of Settlement Distribution

3.2.1 Interval Characteristics Approximately 42.6% of samples in the study area contain buildings and artificial construction, indicating relatively dispersed land occupation by human settlements in Donggou. Using natural breaks to classify indicator data for built-up samples reveals that building density samples can be divided into three intervals, with 58.3% showing very low density (≤ 10), 21.7% showing low ratio (0.11–0.30). Thus, low-rise, low-intensity settlements are common in Donggou, though a few settlements exhibit high building density and floor area ratio (Figure 6).

3.2.2 Distribution Characteristics First, building density and floor area ratio of samples show an overall pattern of “high-low-high-low” from west to east. Specifically, obvious building agglomeration exists near the gully mouth (0.0–1.2 km) where Donggou intersects with the main valley channel. Building density and floor area ratio then decrease, with almost no human construction in the middle section (1.8–2.4 km). In the 2.8–4.0 km section, building density and floor area ratio gradually increase again, forming the second agglomeration zone along Donggou, before decreasing once more (Figure 6).

Second, human construction generally distributes near river channels but gradually deviates from riverbanks as Donggou extends inward. Grid data analysis shows that 92.9% of high building density samples and 86.7% of medium-high floor area ratio samples are within 100 m buffer zones. In the western section near the gully mouth, high-value samples for both density and floor area ratio cling to the river, while in the middle and eastern sections, high-value samples gradually deviate from the river by about 100 m.

Finally, settlements exhibit an overall pattern of “generally dispersed, point-like agglomeration” at the watershed scale. Spatial distribution of building density and floor area ratio forms several riverine building clusters centered on peak-value samples that decrease outward in concentric circles (Figure 6).

4. Analysis of Human-Land Relationship Types

4.1 Four Human-Land Relationship Types from Spatial Overlay Using the mean and median of each sample’s terrain complexity comprehensive

index as references, terrain complexity across all samples is classified into high and low levels, with high-value and low-value samples each accounting for approximately 50.0%. Similarly, the 446 built-up samples are divided into high and low levels by settlement agglomeration comprehensive index, with highly agglomerated samples accounting for 34.2% and low agglomeration samples for 65.8%. Through spatial overlay of terrain complexity and settlement agglomeration indices, samples are categorized into four types using four-quadrant scatter plot analysis based on “high/low terrain complexity” and “high/low settlement agglomeration” data distribution, representing four human-land relationships: agglomerated settlements in complex terrain, dispersed settlements in complex terrain, agglomerated settlements in gentle terrain, and dispersed settlements in gentle terrain (Figure 8).

4.2 Distribution Characteristics of Human-Land Overlay Types First, according to statistical proportions of the four sample types, the ranking by quantity is low-high type (37.5%), low-low type (28.3%), high-low type (15.2%), and high-high type (11.0%). This indicates a relatively high proportion of dispersed settlement units distributed across both complex and gentle terrain (Figure 8).

Second, according to statistics on settlement building footprint area, the ranking by proportion is low-high type (59.5%), low-low type (24.2%), high-low type (14.3%), and high-high type (11.0%). Low-high type samples occupy 59.5% of total settlement area within only 37.5% of samples, indicating large-scale agglomerated construction in gentle terrain. The other three types show relatively balanced proportions (approximately 11–15% each), suggesting that agglomerated settlements in gentle terrain constitute the primary form of human construction in the study area, while most agglomerated settlements avoid areas with particularly complex terrain (Figure 8).

Third, samples of the same type show certain continuity and clustering in spatial distribution. For example, low-high type samples mostly distribute in “field” or “group” patterns, forming several settlement clusters in gentle terrain areas. High-high type samples are relatively dispersed, forming transitional zones from concentrated to dispersed distribution. A few high-low type samples are adjacent to these, surrounding low-high type samples, while high-low type samples distribute in peripheral areas (Figure 9).

4.3 Typical Settlement Samples with Coordinated Human-Land Relationships From the perspective of human-land coupling coordination, gentle terrain areas are suitable for higher-scale agglomerated construction, while complex terrain areas should adopt dispersed layouts. Large-scale artificial construction in complex terrain and dispersed layouts in gentle terrain are both unsuited to the regionally specific characteristics of fragile ecological environments and scarce construction land resources in gully areas. Therefore, high-low type samples are eliminated from the four human-land overlay relationships, retaining

low-high and high-high type samples as “human-land coordinated settlement samples.” To ensure completeness of settlement building clusters, adjacent samples of the same type are merged and some sample edges appropriately expanded to form “human-land coordinated settlement samples” composed of irregular samples, including 10 low-high type and 5 high-high type settlement samples (Figure 9).

5. Evaluation of Settlement Spatial Patterns

5.1 Three-Dimensional Fractal Dimension Calculation Results for Coordinated Samples The three-dimensional grid fractal dimension model is applied to measure the fractal dimension and goodness-of-fit (R^2) of the 15 “human-land coordinated settlement samples” (Figure 10). The results show: First, among the 15 samples, 11 have $R^2 \geq 0.995$, indicating that the three-dimensional morphology of most samples satisfies fractal distribution patterns, while many high-high type samples have $R^2 < 0.995$, suggesting their three-dimensional morphology does not meet fractal distribution requirements. Second, the three-dimensional fractal dimension values of samples passing the goodness-of-fit test range between 2.05–2.55, indicating significant differences in three-dimensional spatial efficiency among samples in Donggou (Figure 11).

5.2 Sample Selection Based on Three-Dimensional Spatial Distribution Efficiency Using natural breaks, the three-dimensional fractal dimension values of samples passing the goodness-of-fit test are divided into three intervals: high fractal dimension (2.35–2.55) accounting for 27.25% of samples, medium fractal dimension (2.15–2.34) accounting for 45.50%, and low fractal dimension (2.05–2.14) accounting for 27.25%.

First, in the high fractal dimension interval, low-high sample No. 1 exhibits similar three-dimensional spatial morphology to sample No. 8, with layouts that can be summarized as terrace parallel settlements. Building clusters are arranged closely and parallel to hill contours on sloping land, elevating progressively with terrain, such as the typical stepped cave dwelling cluster at Sanlilu Village (Figure 12). These samples demonstrate high fractal dimension effects, indicating that while terrace parallel buildings expand horizontally along terrain, they achieve compact and efficient layout effects through vertical staggering and overlapping techniques.

Additionally, free parallel settlements represented by low-high sample No. 5 also exhibit relatively high three-dimensional fractal dimension values. Building clusters in these samples curve along terrain changes in plan view, forming multi-directional parallel groups with larger building spacing and richer height variations. Their spatial layout is more flexible than single-direction terrace parallel patterns, though slightly less three-dimensionally aggregated (Figure 12).

Second, in the medium fractal dimension interval, low-high sample No. 7 is repre-

sentative, characterized by small building unit scales, dense distribution within limited gentle terrain, and small vertical drop, such as at Songjiayan in Donggou (Figure 12). This can be summarized as dense patch settlements, whose three-dimensional spatial distribution efficiency is lower than parallel types (Table 1).

Finally, in the low fractal dimension interval, some samples such as low-low type No. 1 disperse 11 individual buildings across 2-3 km², which can be summarized as scattered point settlements. Others such as high-high type No. 2 align linearly along rivers or roads with local staggered distribution, summarized as linear extension settlements. These two settlement types show the lowest three-dimensional spatial distribution efficiency.

5.3 Summary of Appropriate Spatial Patterns for Donggou Settlements

The fragmentation of hilly-gully landforms causes water and soil resource dispersion and low carrying capacity, making it easy for human settlements in Donggou to form scattered layout types such as scattered point and linear extension patterns during long-term evolution. While these adapt to local natural environments and traditional agricultural production methods to some extent, excessively dispersed and isolated construction modes result in extremely low spatial land use efficiency, inconvenient communication and cooperation between villages and towns in small watersheds, and difficulties in infrastructure and public service facility allocation.

Through mutual adaptation between people and the gully environment, some settlements in Donggou have moderately aggregated and grown in three-dimensional space relying on hilly slopes, forming terrace parallel, free parallel, and dense patch settlement types. First, terrace parallel settlements excel at building along mountains, with buildings and alleys arranged parallel to hill contours forming layered stacked composite multi-story building clusters that achieve high spatial occupation efficiency due to compact arrangement. Second, to adapt to complex and variable terrain, free parallel settlements feature more flexible spatial layouts, with buildings distributed in non-regular stepped patterns following terrain elevation changes, achieving better spatial integration with terrain and unique settlement landscape aesthetics. Finally, dense patch settlements often develop in aggregation at micro-hill gentle slopes, featuring richer diversity in spatial organization. High-density building groups combined with streets, courtyards, squares, and other elements form human-scale, richly varied landscape environments containing complex spatial orders and logics. However, this type's spatial utilization efficiency is slightly lower than the former two, and it is more constrained by natural environments such as terrain, with high-low variations and winding twists limiting its spatial expansion.

Overall, these three settlement types exhibit relatively high spatial utilization efficiency, can alleviate construction land shortage pressure in hilly-gully regions, and help form a “large dispersion, small aggregation” belt-cluster spatial pattern at the watershed scale. They represent settlement spatial layout modes

that both respect natural conditions and ensure agglomeration benefits in gully watersheds. Due to their different characteristics, planning and design should select appropriate spatial patterns according to specific micro-topographic environments and local development needs.

6. Discussion

As conflicts intensify between human settlement development and natural environment destruction in the Loess Plateau of northern Shaanxi, and as modern towns impact traditional settlements, rationally utilizing hilly-gully region spatial potential and exploring gully settlement spatial patterns integrating urban-rural development and human-land symbiosis have become urgent tasks. Although scholars have explored this issue—for example, Hui Yian proposed moderately utilizing slopes, hills, and gully land as urban-rural construction land to form unique spatial expansion modes for Loess Plateau hilly-gully regions; Liu Binyi et al. constructed ecological water-green win-win human settlement spatial models for semi-arid Loess Plateau areas; and Liu Hui proposed human settlement ecological unit models comprising construction, support, and natural support systems at the small watershed scale—these spatial models focus more on respecting ecological foundations than on settlement layout spatial efficiency.

In complex topographic regions such as the Loess Plateau hilly-gully area, human settlements exhibit increasingly strong three-dimensional spatial characteristics through long-term evolution. To improve urban-rural spatial utilization and allocation efficiency in such areas, three-dimensional organic growth and fractal analysis of settlements have become important contents of urban morphological research. This study employs grid analysis and three-dimensional fractal models to evaluate human-land coordination relationships and three-dimensional spatial utilization efficiency of settlements in gully regions, summarizing three efficient and appropriate settlement construction patterns from local traditional human settlement environments. The research proposes that “three-dimensional high-fractal-dimension settlement spatial expansion based on human-land coupling” is an important breakthrough for addressing urban-rural spatial development bottlenecks and human-land contradictions in Loess Plateau hilly-gully regions.

It should be noted that settlement spatial types formed over millennia in thousands of gullies across the Loess Plateau are not limited to those listed in this article. This study only takes Donggou in Mizhi as an example for methodological exploration and case pattern summarization. Subsequent research should collect more settlement samples from numerous gully watersheds to further explore their spatial organization logic and generation mechanisms, summarizing local experiences and wisdom in Loess Plateau human settlement construction.

7. Conclusions

Through research on human-land relationships in Donggou, Mizhi County, the main conclusions are:

- (1) In the distinctly gullied Donggou study area, settlement scale exhibits obvious spatial differentiation characteristics along the axis from gully mouth to interior. Building density and floor area ratio show a pattern of decreasing, then increasing, then decreasing again from west to east. The gully mouth section (0–1.2 km range) and middle section (2.8–4.0 km range) form settlement agglomeration zones. Additionally, settlements in the gully mouth section mostly cluster near water systems, but gradually deviate from riverbanks by about 50–100 m in the middle and eastern sections. Finally, settlements exhibit an overall pattern of “generally dispersed, point-like agglomeration” at the watershed scale.
- (2) Based on overlay analysis of terrain complexity comprehensive index and settlement agglomeration comprehensive index, four human-land relationship types are identified: agglomerated settlements in gentle terrain, dispersed settlements in complex terrain, agglomerated settlements in complex terrain, and dispersed settlements in gentle terrain. The first two represent coordinated human-land relationship types, with agglomerated settlements in gentle terrain accounting for the highest proportion of total settlement area at approximately 59.5%. The other three types show relatively balanced proportions of 15.2%, 14.3%, and 11.0% respectively.
- (3) According to three-dimensional grid fractal model measurement results, three-dimensional spatial distribution efficiency varies significantly among Donggou settlements. Terrace parallel and free parallel settlements exhibit high three-dimensional fractal characteristics, with sample fractal dimensions ranging from 2.35–2.55. Dense patch settlements have medium fractal dimensions in the 2.15–2.34 range. Scattered point and linear extension settlements have the lowest fractal dimensions. Overall, among typical human settlement spatial patterns in Donggou, terrace parallel, free parallel, and dense patch settlements possess dual characteristics of human-land coordination and high spatial efficiency, serving as references for settlement construction in hilly-gully regions, though they differ in spatial organization and terrain adaptability, requiring context-appropriate pattern selection.

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Figures

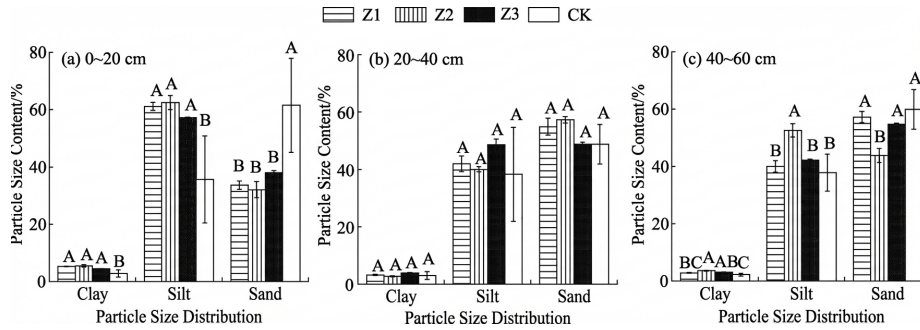


Figure 1: Figure 1

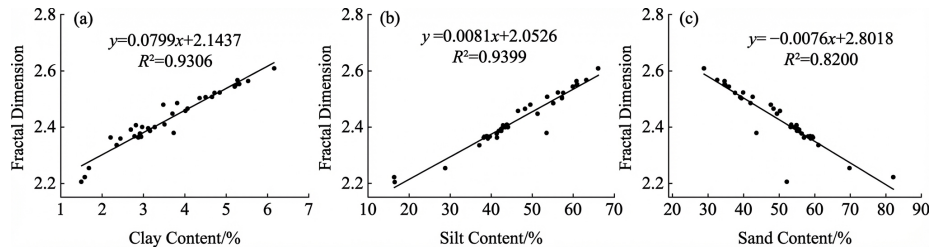


Figure 2: Figure 2

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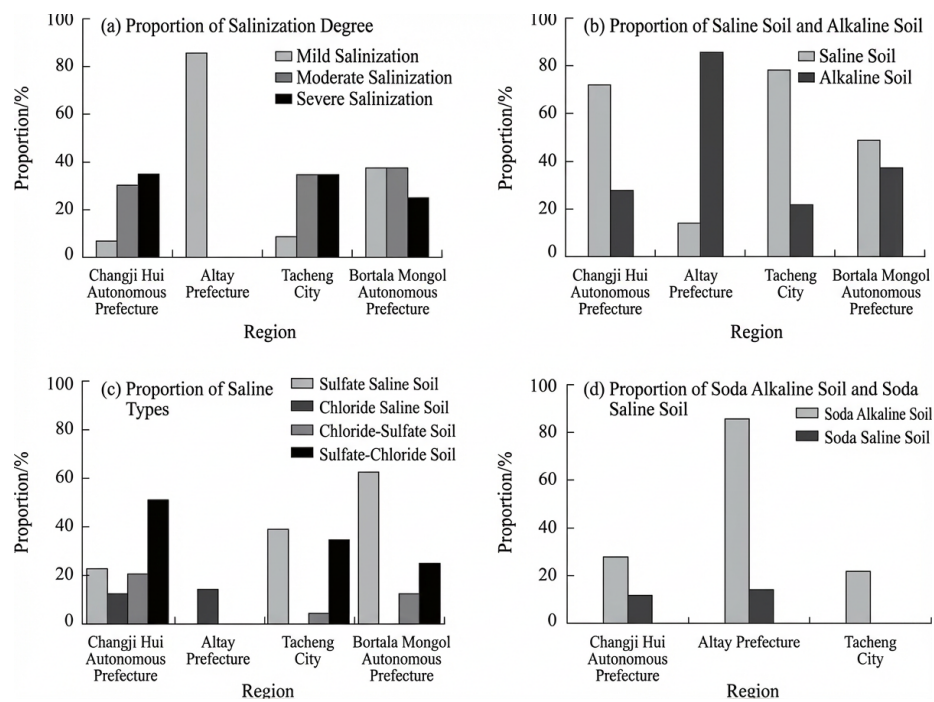


Figure 3: Figure 3

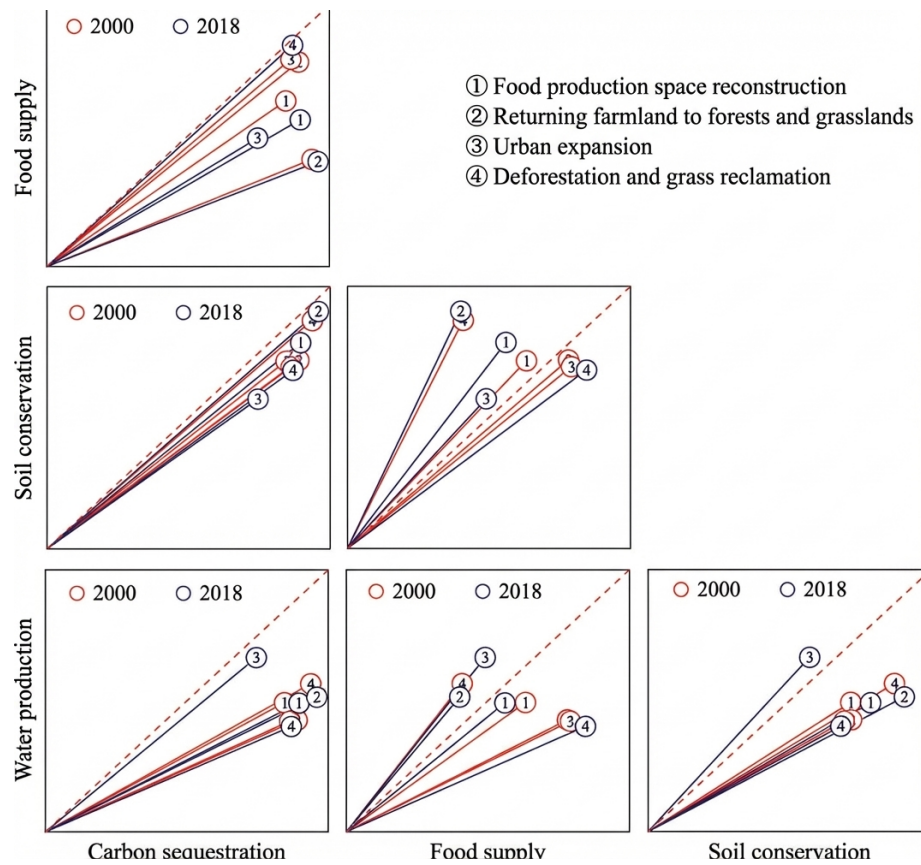


Figure 4: Figure 5

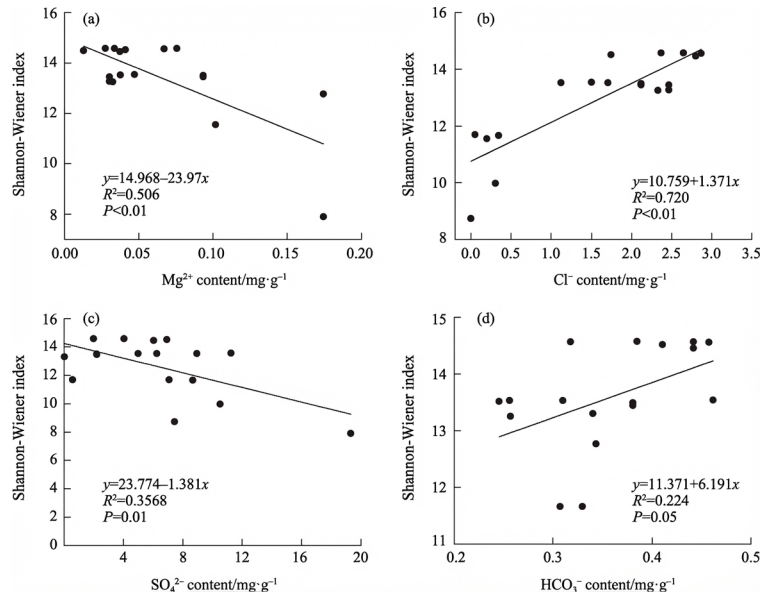


Figure 5: Figure 6

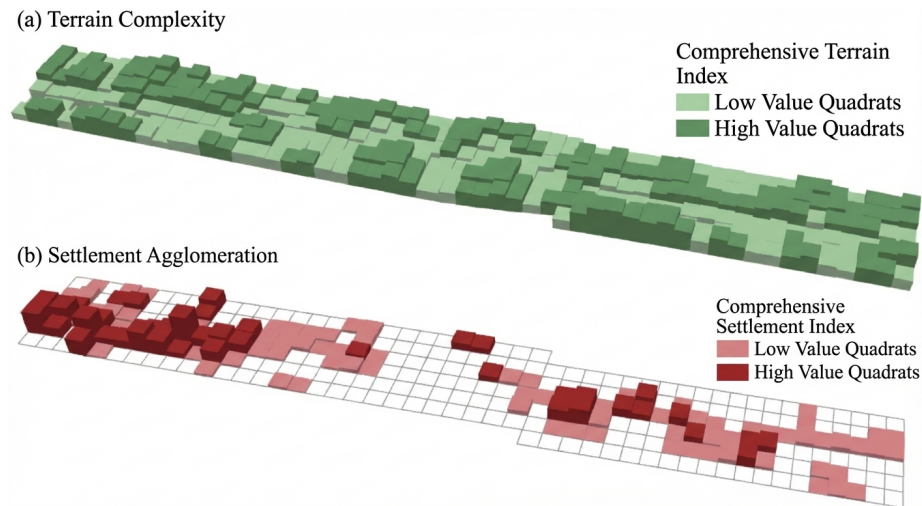


Figure 6: Figure 7

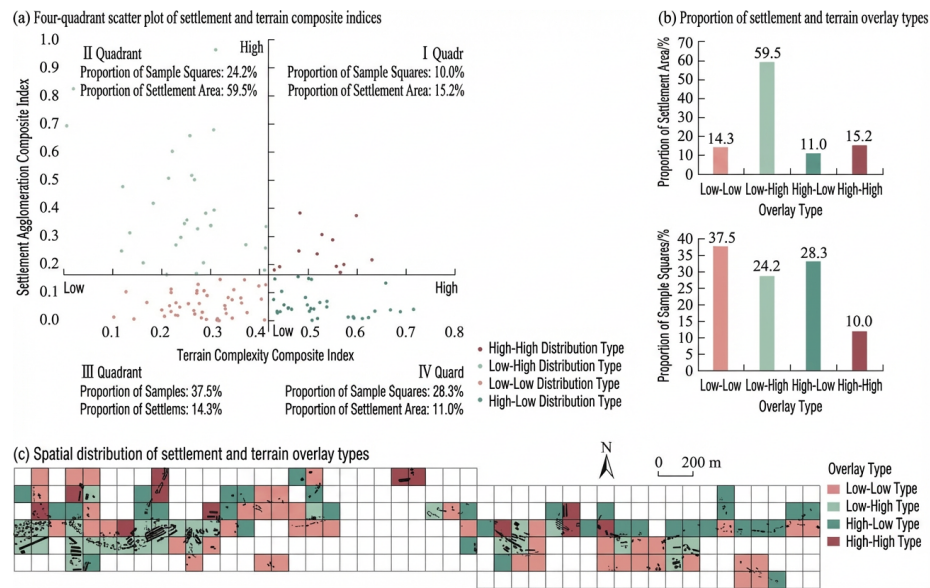


Figure 7: Figure 8

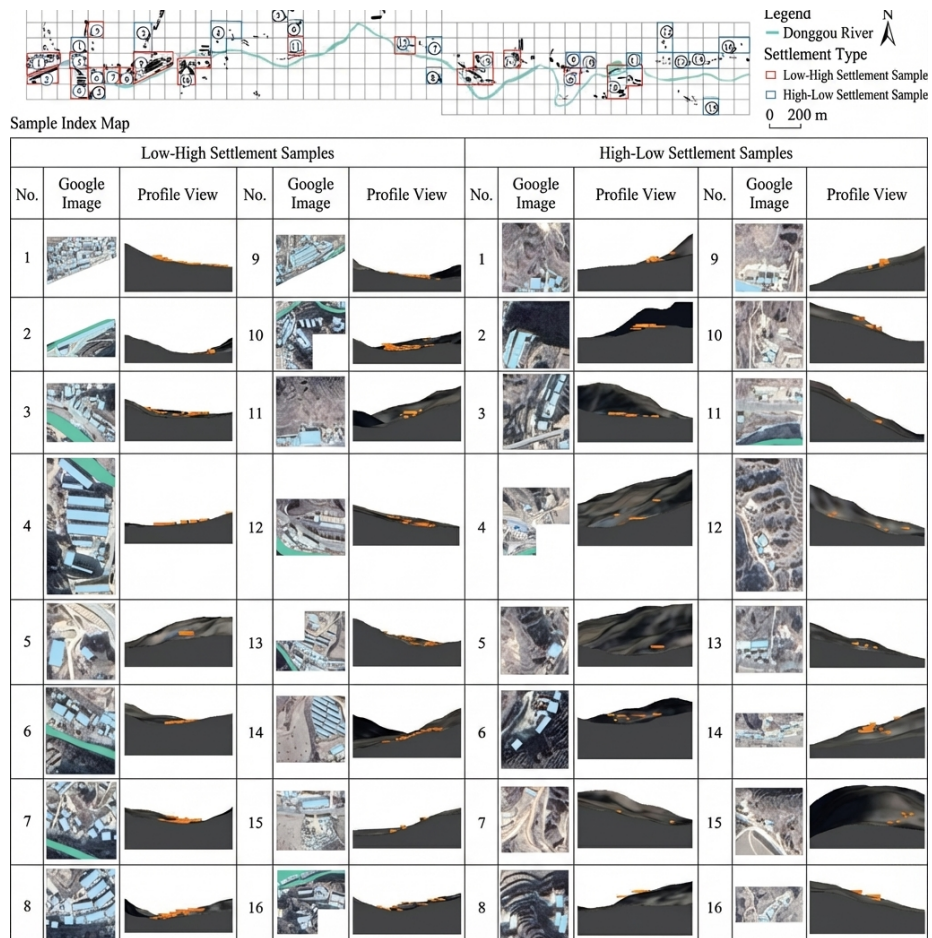


Figure 8: Figure 9

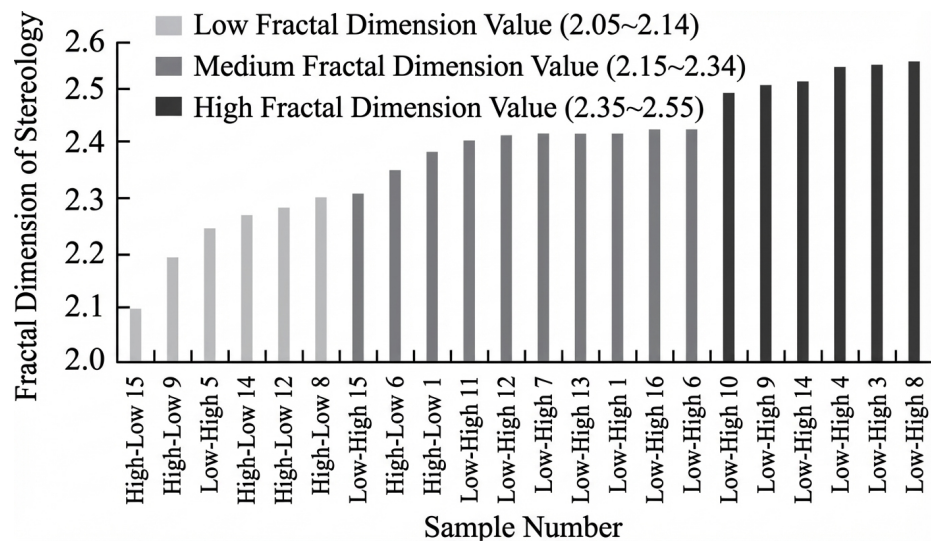


Figure 9: Figure 11



Figure 10: Figure 12