

Post-disaster reconstruction and spatial reconstruction of traditional villages : measurement and mechanism analysis of Qiang settlements in Northwest Sichuan based on fractal theory

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Article

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Posted Date: October 20th, 2026

DOI: <https://doi.org/10.21203/rs.3.rs-10795472/v1>

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Additional Declarations: No competing interests reported.

Post-disaster reconstruction and spatial reconstruction of traditional villages : measurement and mechanism analysis of Qiang settlements in Northwest Sichuan based on fractal theory

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Abstract:

The 2008 Wenchuan earthquake and subsequent reconstruction created a rare pre- and post-disaster natural experiment for Qiang traditional villages, whereas systematic quantitative evidence regarding the multi-dimensional impacts of reconstruction on settlement spatial structure remains insufficient. Taking Xiuxi Village, a typical Qiang settlement in northwest Sichuan, as the research case, this study explores the long-term spatial evolution characteristics and driving mechanisms of ethnic traditional villages, providing scientific support for their conservation and post-disaster spatial assessment. Integrating fractal theory and landscape ecological methods with historical documents, remote sensing data and field measurements, this study divides the village's evolution into four stages: the Ming and Qing Dynasties, the early to mid-20th century, the mid-20th century to 2008, and 2008-2025. Four fractal dimensions were quantitatively measured: boundary dimension via the perimeter-area method, road radius dimension via the concentric circle method, public space box-counting dimension via grid coverage, and building correlation dimension via correlation integral calculation, together with the aspect ratio and landscape shape index for comprehensive morphological analysis. Taking 2008 as the critical temporal breakpoint, comparative analysis reveals that the village generally transformed from linear terrain extension to compact clustered development. Post-disaster reconstruction significantly raised the road radius dimension from 0.6871 to 1.0862, improving road network balance. The public space box-counting dimension increased from 1.295 to 1.338, indicating growing spatial complexity, while the building correlation dimension rose from 1.482 to 1.651, reflecting more balanced architectural distribution. By contrast, the boundary dimension gradually declined. These evident indicator changes demonstrate that post-disaster intervention substantially restructured the village's spatial system. In essence, Xiuxi Village's spatial evolution is co-determined by mountainous terrain constraints, long-term Qiang cultural shaping and post-disaster planning intervention, with reconstruction acting as a pivotal turning point for structural transformation. The established multi-dimensional fractal framework provides verifiable morphological evidence for post-disaster spatial reconstruction effects, and enriches empirical understanding of spatial evolution in mountainous ethnic traditional villages.

Keywords: Qiang traditional villages ; the evolution of spatial form ; post-disaster reconstruction ; fractal theory ; evolution mechanism

Traditional villages carry regional cultural heritage and long-term human – land relationships, whose spatial morphology adapts to natural conditions and evolves with social, productive and cultural changes. Rapid

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urbanization has reshaped village spatial patterns and eroded cultural landscapes, making the quantitative exploration of village morphological evolution critical for rural heritage conservation (Zhou et al., 2020). Qiang traditional villages are primarily distributed in the alpine gorge regions of northwest Sichuan. Shaped by mountainous terrain and ethnic cultures, they feature terrain-adaptive settlement layouts and unique localized human – land systems. The 2008 Wenchuan earthquake severely damaged numerous Qiang villages, and post-disaster reconstruction greatly improved local infrastructure while profoundly restructuring traditional settlement spaces. Accordingly, Qiang villages provide valuable samples for exploring the coupled effects of natural constraints, cultural inheritance and external planning intervention. Fractal theory is widely adopted to quantify the scale features and self-similarity of complex village spatial systems. Existing studies predominantly focus on cross-sectional comparisons of plain settlements (Feng et al., 2025). Mountain settlement research remains limited, with insufficient longitudinal exploration of long-term morphological evolution, leaving room for further fractal-based empirical investigation of ethnic mountain villages. Some studies used fractal dimension to analyze the influence of topography on the spatial form of mountain settlements, and revealed the positive correlation between the fractal dimension of buildings and the fractal dimension of suitable construction land (Wang et al., 2025). Others applied the fractal method to the landscape morphology analysis of Heijing ancient town in Yunnan province. However, most of the above studies focus on horizontal comparison, and pay insufficient attention to the vertical evolution of single settlement spatial form in the long-term historical process. At the same time, the change trend of fractal dimension has not been effectively corresponding to the specific driving factors (such as cultural customs, post-disaster reconstruction) in the time dimension. In the field of Qiang settlement research, landscape gene theory and cultural geography method have achieved fruitful results. Some studies constructed the landscape gene information chain of 39 Qiang settlements in the Zagunao River Basin (Fan et al., 2026). Others explored the formation and cultural essence of Qiang architectural features from the perspective of cultural geography (Gan et al., 2016). These studies have laid an important foundation for understanding the cultural spatial logic of Qiang settlements, but their analysis methods mainly focus on the identification and spatial positioning of cultural elements, and there is still room for expansion in the quantitative description of the scale characteristics and evolution process of settlement spatial form.

Recent village-morphology research has moved from qualitative description to quantitative fractal analysis. However, most studies focus on Han villages and general landscapes, with few systematic quantitative analyses of mountain-ethnic settlements, especially the combined effects of natural conditions, local culture and post-disaster reconstruction on Qiang-village evolution (Liu et al., 2026). Taking well-documented alpine-valley Xiuxi Village as the case, this paper establishes a four-stage, four-dimensional framework for boundaries, road networks, public spaces and building layouts. Combining multi-source data with fractal-landscape metrics, it quantifies morphological evolution driven by natural constraints, cultural inheritance and external intervention.

This study makes three contributions. First, it extends fractal-based village research with a multi-dimensional longitudinal framework identifying stage-specific spatial features. Second, it provides quantitative evidence for Qiang settlements' post-disaster restructuring, revealing reconstruction-induced changes in road-network balance, public-space complexity and building distribution. Third, it builds a “measurement-evolution-mechanism” chain linking fractal changes to driving factors and proposes a testable evolutionary mechanism for ethnic settlements (Lin et al., 2018).

1 Research object and data source

1.1 Research object

Xiuxi Village is a traditional Qiang village in Li County's upper Minjiang alpine gorge, covering 7.8 km² at 2600 m altitude with 282 residents. Listed as a Chinese Traditional Village in 2012, its terrain-constrained spatial

pattern is shaped by indigenous Qiang customs. The 2008 earthquake and subsequent reconstruction created an integrated traditional and planned landscape, making it a typical case for settlement evolution and post-disaster spatial research (Gao, 2025).

Free from intensive tourism commercialization, the village retains authentic settlement features and fully records the complete evolutionary process of mountain Qiang settlements, including natural growth, modern expansion and post-earthquake renewal (Zheng et al., 2019). The juxtaposition of original spatial textures and reconstructed layouts facilitates the exploration of external intervention-led spatial reorganization.

Located in the core distribution area of Qiang settlements in the upper Minjiang River valley, the village possesses typical regional terrain, production modes and settlement formation characteristics. Accordingly, this case study can reveal both individual village morphological rules and universal evolutionary features of mountain Qiang settlements, providing practical references for the conservation and renewal of ethnic traditional villages (Lai et al., 2019; Zhang et al., 2023).

1.2 Data source and preprocessing

Multi-source historical documents, remote sensing imagery, CAD topographic data, field mapping and interview data were integrated to construct four-phase spatial datasets.

1.3 Research ideas

As a typical Qiang traditional village in northwest Sichuan, the spatial form evolution of Xiuxi Village is not only constrained by the long-term mountain natural environment, but also affected by multiple factors such as social and cultural development and post-disaster reconstruction. In order to systematically reveal the evolution law and formation mechanism of its spatial form, this paper takes the plane form of villages in historical periods as the research object(Mang et al, 2016) , and constructs the research framework of morphological identification-feature measurement-process analysis-mechanism induction (Figure 1).

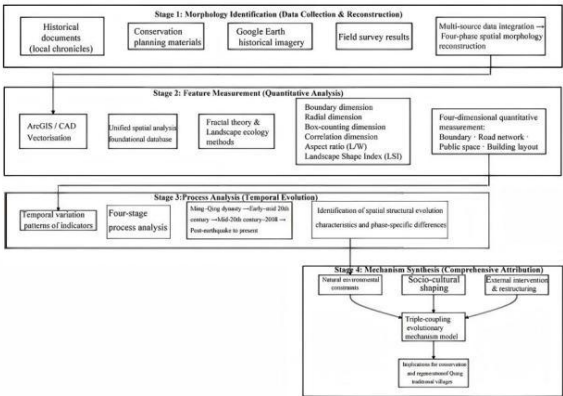


Figure 1 | Research framework of this study.

This study adopts four-phase technical workflow. First is historical-space reconstruction: historical documents, remote-sensing interpretation and field surveys are applied to restore Xiuxi Village’ s multi-period spatial forms following the procedure of time-section definition, multi-source data registration, spatial feature extraction and cross-validation. Four temporal phases are defined: Ming-Qing dynasties, early-to-mid-20th century, mid-20th century-2008, and 2008-2025.

Second, three rounds of fieldwork (Mar 2025, Oct 2025, Apr 2026) collect GPS-laser surveyed coordinates, building chronology-function records and street-feature datasets, cross-validating remote-sensing vector outputs to guarantee database accuracy.

Third, a quantitative indicator system covering village boundary, street network, public space and building layout is built. Metrics include length-width ratio, LSI, boundary, radius, box-counting and correlation dimensions. Fractal calculations are implemented on ArcGIS and MATLAB, with scale-free intervals identified from double-logarithmic scatter plots.

Finally, multi-dimensional evolutionary traits are summarized according to indicator variations and planar maps. A driving-mechanism model is further established from natural constraints, local culture and post-disaster intervention to interpret factor pathways and interactions (Wu et al., 2023).

2 Research methods and process

2.1 Quantitative indicators of landscape morphology in Xiuxi Village

2.1.1 Quantitative comparison of length-width ratio (L/W)

In order to further analyze the spatial morphological characteristics of Xiuxi Village, this study introduced two quantitative indicators : length-width ratio (L/W) and landscape shape index (LSI). The length-width ratio refers to the ratio of the length of the long axis to the short axis of the minimum circumscribed rectangle of the village. The calculation formula is :

$$L/W = \frac{\max(\ell_1, \ell_2)}{\min(\ell_1, \ell_2)} \quad (1)$$

Where ℓ_1 and ℓ_2 represent the lengths of the major and minor axes of the minimum bounding rectangle, respectively. This value intuitively reflects the overall morphological characteristics of the settlement: when $L/W \leq 1.5$, the settlement tends to exhibit a “compact-cluster” distribution; when $1.5 < L/W \leq 2.0$, the settlement displays a transitional morphology between “cluster” and “strip”; and when $L/W > 2.0$, the settlement presents a distinctly "strip" distribution. The delineation of these threshold values draws upon existing research findings and has been validated against the actual topographical conditions of Xiuxi Village (Tables 1 – 2).

Based on the compilation and calculation of relevant indicators across the four periods, the results are as follows.

Table 1 | Historical evolution of the boundary morphology of Xiuxi Village

Period	Ming-Qing period	early-to-mid 20th century	mid-20th century to 2008	2008 – 2025
Boundary				
(L/W)				

Table 2 | Evolution of the length-to-width ratio of boundary morphology of Xiuxi Village

Period	Ming-Qing period	early-to-mid 20th century	mid-20th century to 2008	2008 – 2025
Major axis (m)	705.16	737.63	741.32	763.65
Minor axis (m)	158.25	247.26	363.57	385.29
Length-to-width ratio (L/W)	4.46	2.98	2.04	1.98
Boundary morphology	Distinctly strip-shaped (>2.0)	Distinctly strip-shaped (>2.0)	Distinctly strip-shaped (>2.0)	Transitional between strip and cluster (1.5<L/W≤2.0)

2.1.3 Quantitative comparison of landscape shape index

The landscape shape index is used to measure the complexity of the village patch shape. Its calculation formula is :

$$LSI = \frac{E}{2\sqrt{\pi A}} \quad (2)$$

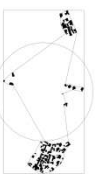
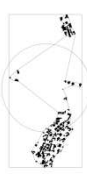
P represents the perimeter of the village patch, and A represents its area ; the larger the value of LSI is, the more irregular the shape of the village is, and its spatial expansion will also show obvious directional characteristics (Table 3-5).

Table 3 | Criteria for judging landscape shape index of Xiuxi Village

Circle index LSI		LSI>2			LSI<2	
aspect ratio (L/W)	L/W<1.5	1.5<L/W<2	L/W>2	L/W<1.5	1.5<L/W<2	L/W>2
The judgment results of village spatial morphological characteristics	Finger shape of cluster tendency	Finger shape without clear tendency	Finger shape with banded tendency	Group shape	Group shape without clear tendency	A banded tendency of the cluster shape

After summarizing and calculating the relevant indicators of the four periods, the results are as follows.

Table 4 | Measurement results of landscape shape index in Xiuxi Village

Stage	Village landscape morphological index	Patch perimeterP (m)	Patch area A (m ²)	Area of the minimum bounding rectangle (m ²)	Length-to-width ratio (L/W)	LSI	Morphological classification
Ming-Qing period		1726.52	41722.78	111485.87	4.46	2.3844	Finger-shaped with strip tendency
early-to-mid 20th century		1969.74	79442.48	182382.75	2.98	1.9714	Clustered form with strip tendency
mid-20th century to 2008		2202.35	155922.91	268169.52	2.04	1.5734	Clustered form with strip tendency
2008–2025		2297.88	159305.67	294226.71	1.98	1.6241	Clustered form without clear tendency

2.2 Analysis of fractal characteristics of spatial morphology of Xiuxi Village

Focusing on multi-temporal planar patterns of Xiuxi Village, this paper conducts feature induction and causal analysis. Natural environment and folk beliefs constitute external conditions shaping village spatial morphology. Adopting fractal measurement and landscape-morphology analysis as quantitative tools, this study quantifies spatial traits from four dimensions: boundary contour, public space, street texture, and building correlation (Gao et al., 2020). Based on fractal-dimension outputs, it identifies planar-pattern arrangement rules and interprets formative causes. Synthesizing quantitative results, it summarizes spatial-morphology evolutionary features and extracts corresponding evolutionary logic and driving factors. These drivers in turn affect periodic planar-pattern changes, forming a closed-loop quantitative research framework (Zeng et al., 2023).

2.2.1 Spatial morphology extraction and preprocessing

Through the Google satellite map to obtain the historical images of different periods, combined with the measured CAD drawings of the village, it is imported into the ArcGIS platform for vectorization, and a high-precision village space base map is built. In the CAD, the building monomer, street network and public space are depicted as the main elements, and a two-dimensional plan (Fig.2) is drawn to ensure the accuracy of the information.

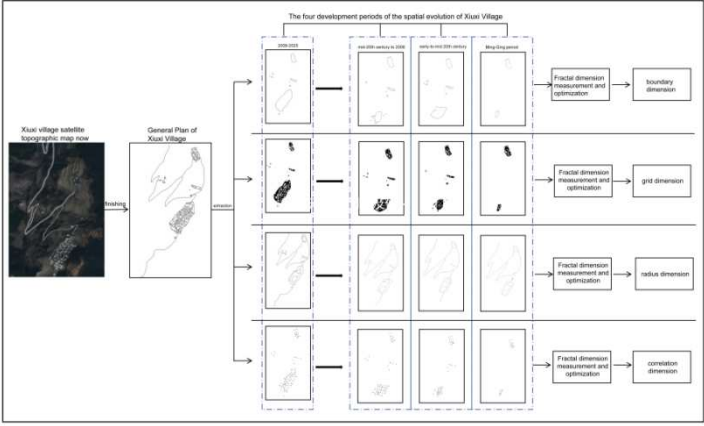


Fig.2 | The plane shape of Xiuxi Village in each period

2.2.2 Analysis of boundary fractal characteristics

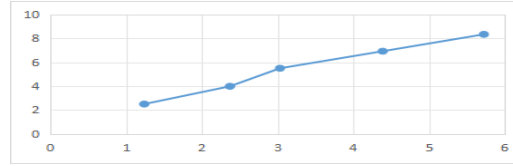
(1) Research method of fractal characteristics of boundary morphology

The fractal dimension can directly determine the complexity of the outer contour of the village, and it is also a very important quantitative reference standard in the study of village morphology. The value is obtained by the calculation method of perimeter combined with area. The core logic of the calculation method is to determine the complexity of the spatial form itself by relying on the non-linear correlation between the perimeter of the body and the occupied area. In this study, the external contours of Xiuxi Village in four development periods are sorted out in turn, including the Ming and Qing Dynasties, the beginning of the 20 th century to the middle of the 20 th century, the middle of the 20 th century to 2008 and 2008 to 2025. The calculation method of area perimeter combination is used to calculate the fractal dimension corresponding to the village boundary in each period one by one. The whole process of the study adopts the calculation method of area perimeter combination, and calculates the fractal dimension corresponding to the village boundary in each period one by one. The grid size is $\delta_i = 2i$, where ($i = 0, 1, 2, 3, 4, 5$) fits the village boundary shape. According to the double logarithmic coordinates of $[\ln(\frac{A(\delta_i)^{\frac{2}{D}}}{\delta_i^2}), \ln(P(\delta_i)/\delta_i)]$, the scatter plot is drawn and the linear regression analysis is carried out to obtain the slope of the straight line at different stages, that is, the boundary dimension D value (table 5).

Table 5 | Calculation of the boundary fractal dimension using the perimeter-area method

Calculation process of the boundary fractal dimension for Xiuxi Village	D	Regression equation	Correlation coefficient	Scale-free interval	
during the 2008–2025 period	1.1468	$y=1.1468x+2.1927$	0.9998	0-4	
I	0	1	2	3	4
Y_i	1	2	4	8	16
$N_p(\delta_i)$	4251	2064	987	435	196
$N_A(\delta_i)$	93572	25846	6852	1365	238
$N_A(\delta_i)+N_p(\delta_i)$	97823	27910	7839	1800	434
$\left(\frac{A(\delta_i)^{\frac{2}{D}}}{\delta_i^2}\right)\ln$	5.7232	4.3865	3.0297	2.3681	1.2363
$\ln(P(\delta_i)/\delta_i)$	8.3549	6.9396	5.5084	3.9959	2.5055

Double logarithmic scatter plot



(2) Boundary shape boundary dimension data statistics

The boundary morphological characteristics of Xiuxi Village can be quantified by the ' area-perimeter ' measurement method, which can fully cover the four development stages of the Ming and Qing Dynasties, the early 20 th century to the middle 20 th century, the middle 20 th century to 2008, and 2008 to 2025. The results of the measured boundary shape dimension correspond to the plane layout of the village and different development periods (Table 6).

Table 6 | Statistical table of boundary dimension of Xiuxi Village

Stage	Number of data points n	Scale-free interval (i-value range)	regression equation	R ²	boundary dimension D	Boundary shape diagram
Ming-Qing period	5	i=0~4	y = 1.1623x + 2.0378	0.9992	1.1623	
early-to-mid 20th century	5	i=0~4	y = 1.2056x + 2.1184	0.9995	1.2056	
mid-20th century to 2008	5	i=0~4	y = 1.1815x + 2.1562	0.9997	1.1815	
2008~2025	5	i=0~4	y = 1.1468x + 2.1927	0.9998	1.1468	

Village-boundary fractal dimension quantifies interactions between settlement constructions and natural surroundings. Boundary fractal properties reveal how well a settlement adapts to local terrain, reflecting self-similarity and geomorphology-driven spatial rules. Statistically, the concave-convex undulations of segmented contours form the scattered overall boundary and determine how closely internal layouts integrate with nature.

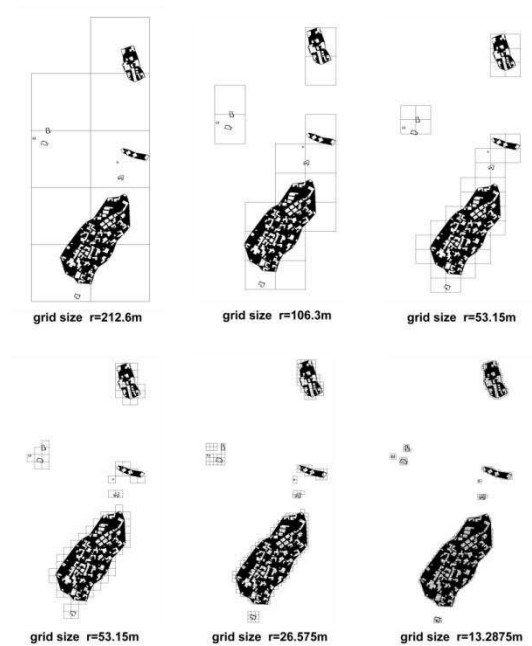
Mathematically, a low D value indicates straighter, less fluctuating boundaries; a high D value signifies highly tortuous, complex outlines. Dimension variations mirror the dynamic interplay between village growth and terrain adaptation. Spontaneous building activities reshape boundaries under diverse topographic conditions. A high D value means strong terrain constraints, intricate boundary structures and efficient edge-space utilization. A low D value points to regular building layouts dominated by human-cultural order, with limited integration with nature and weak capacity for terrain-adapted outward expansion.

2.2.3 Analysis of fractal characteristics of public space

(1) Calculation method of common space grid dimension

The study can use a grid with a side length equal to r to cover the complete graphic area of the public space. When the side length of the grid r changes, the total amount of grids c (r_i) with public space patterns inside the grid will also change synchronously. Logr_i is used as the horizontal axis and logc (r_i) is used as the vertical axis to draw the point distribution map, and then linear regression operations are performed on all points in the figure. The

calculated linear tilt value will be used as the box-counting dimension D corresponding to the shape of the public space.



The measurement method will select the initial grid side length r for each village. The grid can completely cover all the public activity space within the development boundary of the village. The grid side length selected in each subsequent round will be adjusted to $1/2$ of the side length value of the previous round, and the side length size r of the grid will be continuously narrowed (Figure 3). At the same time, the number of squares containing public space patterns inside each type of side length specification $c(r_i)$ (Table 7).

Fig.3 | Common space box-counting dimension grid scale calculation steps

Table 7 | 2008-2025 Xiuxi village public space box-counting dimension grid calculation example table

grid size r	212.6	106.3	53.15	26.575	13.2875	6.6438
Non-empty grid $C(r_i)$	9	16	45	106	348	1125
$\log r_i$	2.328	2.027	1.726	1.425	1.124	0.823
$\log c(r_i)$	0.954	1.204	1.653	2.026	2.542	3.051
The fractal dimension value of each level $D(212.6-106.3)=0.830$ $D(106.3-53.15)=1.492$ $D(53.15-26.575)=1.236$ $D(26.575-13.2875)=1.715$ $D(13.2875-6.6438)=1.693$ goodness-of-fit $R^2=9893$ $D=1.338$						

(2) Box-counting dimension data statistics of public space in different periods

Based on the above-mentioned box-counting dimension calculation rules, the dimension results corresponding to the stage of Xiuxi Village can be calculated, and the values are corresponding to the village public space form one by one (Table 8).

Table 8 | Box-counting dimension statistical table of public space in Xiuxi Village

Stage	Number of data points n	Scale-free interval (i-value range)	regression equation	R^2	boundary dimension D	Public space form diagram
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Stage	Number of data points n	Scale-free interval (i-value range)	regression equation	R ²	boundary dimension D	Public space form diagram
Ming-Qing period	4	$r \in [26.575, 3.32]$	$y = 1.279x + 0.856$	0.971	1.279	
early-to-mid 20th century	4	$r \in [26.575, 3.32]$	$y = 1.247x + 0.923$	0.968	1.247	
mid-20th century to 2008	5	$r \in [53.15, 3.32]$	$y = 1.295x + 0.789$	0.979	1.295	
2008–2025	5	$r \in [53.15, 3.32]$	$y = 1.338x + 0.712$	0.982	1.338	

The box-counting dimension quantifies the aggregation and fragmentation of settlement space, which is jointly determined by patch aspect ratio, internal void fragmentation, spatial density, building coverage scale, boundary morphology, and the dispersion or concentration of architectural layouts. Specifically, building density fundamentally shapes the structural complexity of village public space. A higher box-counting dimension indicates a richer, multi-scale public space system with well-connected spatial hierarchies, whereas a lower value corresponds to loose public space distribution, weak inter-building spatial correlation, and insufficient structural integrity. Due to the complex terrain and mixed land components such as farmland and woodland within mountain villages, their public space morphology presents more diversified spatial compositions and requires comprehensive site-specific interpretation.

2.2.4 Analysis of road street classification characteristics

(1) Research method of road street classification characteristics

The radius dimension effectively characterizes road network fractal features, multi-scale connectivity, density distribution, hierarchical continuity and spatial accessibility. Based on the power-law relationship between radius and cumulative road length, this index reflects the central-peripheral radiation characteristics and self-organizing growth rules of village road networks during spatial expansion (Li et al., 2025).

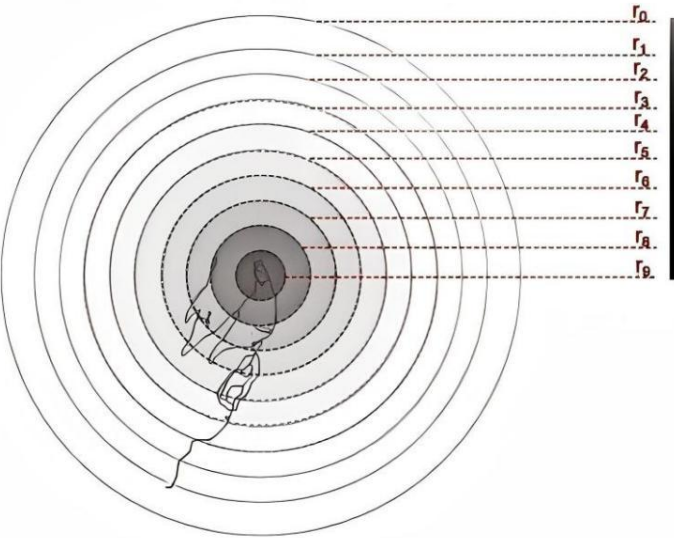
In a regional space, the concentric circle method is used to determine the radius r_i of different sizes according to the change of arithmetic sequence ($i = 1, 2, 3, \dots, n$). The roads in the region change in circles of different radii according to certain rules, and the ring k ($k = 1, 2, 3, \dots, I$) Corresponding to the radius r , $L (r_i)$ is used to represent the length of the road network in the ring of radius r , that is, $L (r_i) \propto r_i^{-D}$. The $\log (r_i)$ and $\log [L (r_i)]$ are used to construct the double logarithmic coordinates and carry out linear regression. If the data are linearly distributed, the slope of the regression line is the radius dimension D .

The setting of radius sequence. After the reference center is determined, the radius of the concentric circle is set by the arithmetic sequence (step size 100m), and the maximum radius is set to be able to fully cover the

distance of the 200m buffer zone of the village built-up area to ensure the integrity of the road network data and eliminate the boundary truncation effect. The maximum radius of each period is about 400m in the Ming and Qing Dynasties, 550m in the early 20 th century to the middle of the 20 th century, 750 m in the middle of the 20 th century to 2008, and 850 m in 2008 to 2025.

With the help of ArcGIS software, this study takes the reference center determined in each period as the center of the circle, and sets 100m, 200m, 300m in turn... The gradient radius of R_{max} , the full coverage is used to measure the road length within each radius range, and finally the fractal dimension of the road network in each period of Xiuxi Village is obtained (Figure 4).

In a regional space, the concentric-circle method adopts an arithmetic-sequence rule to generate radii $r_i(i=1,2,3...n)$. For ring k corresponding to radius r_i , road-network length $L(r_i)$ follows $L(r_i) \propto r_i^{-D}$. Double-logarithmic coordinates of $\log(r_i)$ and $\log[L(r_i)]$ are constructed for linear regression; the regression slope yields the radius-based fractal dimension D when points show linear distribution.



For radius-sequence configuration, concentric-circle radii are generated with a 100 m step after fixing the reference centre. The maximum radius R_{max} fully covers the 200 m buffer of village built-up areas to guarantee complete road-network data and avoid boundary truncation, set as ~400 m (Ming-Qing), 550 m (early-mid-20th century), 750 m (mid-20th century-2008), and 850 m (2008-2025). Using ArcGIS, concentric buffers of 100 m, 200 m ... R_{max} are created centred on each period’ s reference point. Road-segment lengths within each buffer are measured to compute the road-network fractal dimensions for Xiuxi Village across different periods (Figure 4).

4).Fig.4 |The schematic diagram of radius dimension calculation

(2) Xiuxi Village Road Radius Dimension Data Statistics

According to the above calculation method of ' radius dimension ', the radius dimension of the four periods of Xiuxi Village is measured, and the dimension value is one-to-one correspondence with the shape of the village roads and lanes (table 9).

Table 9 |Statistical table of radius dimension of Xiuxi Village

Stage	Concentric circle number n	maximum radius R_{max} (m)	scale-free interval (r , m)	regression equation	R^2	radius dimension D	Road shape diagram
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Stage	Concentric circle number n	maximum radius R_{max} (m)	scale-free interval (r , m)	regression equation	R^2	radius dimension D	Road shape diagram
Ming-Qing period	6	400	$r \in [100, 400]$	$y = 0.9138x + 0.452$	0.952	0.9138	
early-to-mid 20th century	7	550	$r \in [150, 550]$	$y = 0.6925x + 0.687$	0.941	0.6925	
mid-20th century to 2008	8	750	$r \in [200, 750]$	$y = 0.6871x + 0.723$	0.938	0.6871	
2008–2025	9	850	$r \in [200, 850]$	$y = 1.0862x + 0.315$	0.956	1.0862	

The radius-based fractal dimension characterizes density changes of village street-road networks extending outward from the settlement core. Mathematically, $D < 2$ denotes road-network density declining from the centre toward peripheries; $D = 2$ indicates uniform density across space; $D > 2$ means progressively denser peripheral roads. Spatially, this dimension reflects road-network aggregation and distribution. A low- D value implies strong road clustering in the core, rapid density decay outwards, sparse peripheral roads and limited spatial coverage. Higher D produces complex cross-shaped road structures, more symmetrical centre-to-periphery street layouts, improved connectivity and alternative routes, forming stable self-adaptive road patterns (Yang et al., 2020).

2.2.5 Analysis of fractal characteristics of architectural form

(1) Calculation method of architectural form correlation dimension

The correlation dimension is used to describe the correlation degree and distribution characteristics of the building point set in space. The calculation principle is as follows : for the point set composed of N building center points, the Euclidean distance between all point pairs is counted. Given a distance threshold r , the proportion of the number of point pairs whose distance is less than r to the total number of point pairs is calculated, that is, the correlation integral $C(r)$. If the point set has fractal characteristics, then in the scale-free interval $C(r)$ and r satisfy the power function relationship $C(r) \propto r^{-D}$, D is the correlation dimension.

The specific estimation procedure is as follows :

Building center point extraction. In ArcGIS, the ' element turning point ' tool is used to convert the vectorized building surface elements of each period into geometric center points. For buildings with irregular shapes or inner courtyards, the center point takes the centroid position of the outer contour of the building base. The number of building points in each period is : 32 in the Ming and Qing Dynasties, 87 in the early 20 th century to the middle of the 20 th century, 186 in the middle of the 20 th century to 2008, and 203 in 2008-2025 (including new and

renovated buildings after the earthquake).Distance matrix calculation. The plane coordinates (projection coordinate system) of all building center points are derived, and the calculation script is written in Python (pdist function of SciPy library is called). The Euclidean distance between any two building points is calculated, and the distance matrix $D = [d_{ij}]$ of $N \times N$ is formed. In order to avoid repeated counting, only the upper triangular matrix is calculated, with a total of $\frac{N(N-1)}{2}$ distance values.

Correlation integral calculation. Set the distance threshold sequence r_k ($k = 0, 1, 2, \dots, m$), and the threshold range is determined by arithmetic or geometric sequence. In this study, the threshold was set by the equal sequence : $r_k = r_{\min} \times 2^k$ ($k = 0, 1, 2, \dots, m$) is set as the average value of the minimum distance between adjacent buildings in the village, and the maximum threshold $r_{\max}$ is set as 1.2 times the distance between the farthest two buildings in the village built-up area. The maximum distance thresholds of each period are : 210m in the Ming and Qing Dynasties, 320m in the early-20th century-mid-20th century, 450 m in the mid-20 th century-2008, and 510 m in 2008-2025. The threshold level series k of each period is controlled between 15 and 20 to ensure that enough scale intervals are covered.

For each threshold r_k , the correlation integral is calculated :

$$C(r_k) = \frac{2}{N(N-1)} \sum_{i=1}^N \sum_{j=i+1}^N I(d_{ij} \leq r_k) \quad (3)$$

In the formula, I is the indicator function, and the value is 1 when $d_{ij} \leq r_k$, otherwise 0.

Scale-free interval determination and dimension estimation. The scatter diagram is drawn with $\log(r_k)$ as abscissa and $\log(C(r_k))$ as ordinate. In the double logarithmic coordinates, if there is a linear interval (i.e.scale-free interval), the data points in this interval satisfy the power-law distribution. The scale-free interval is determined by the following methods : first, the possible linear interval is identified by observing the scatter plot, and then the data points in the interval are linearly regressed to calculate the goodness of fit R^2 ; the continuous interval with the highest R^2 and the widest interval width is selected as the scale-free interval. The slope of the regression line is the estimated value of the correlation dimension D .

(2) Correlation dimension data statistics of architectural form in different periods

With the help of the calculation rules of correlation dimension, the dimension data corresponding to the four development stages of Xiuxi Village are calculated, and the spatial appearance of the architectural point arrangement and the overall plane of each village are synchronously sorted out (Table 10).

Table 10 | Statistical table of architectural form and correlation dimension of Xiuxi Village

Stage	Number of building points N	correlation dimension D	scale-free interval	regression equation	R^2	Architectural lattice form
Ming-Qing period	32	0.587	$\log r \in [1.20, 2.10]$	$y = 0.587x + 0.124$	0.978	
early-to-mid 20th century	87	1.146	$\log r \in [1.35, 2.35]$	$y = 1.146x - 0.032$	0.985	
mid-20th century to 2008	186	1.482	$\log r \in [1.50, 2.55]$	$y = 1.482x - 0.187$	0.991	

Stage	Number of building points N	correlation dimension D	scale-free interval	regression equation	R ²	Architectural lattice form
2008– 2025	203	1.651	$\log r \in [1.55, 2.65]$	$y = 1.651x - 0.312$	0.993	

The correlation dimension reflects building spatial regularity, with higher values indicating more uniform dispersion. To avoid sample-size bias, this study adopted random subsampling robustness verification. Based on 100 repeated calculations with 32 building samples, the average dimension was 1.438 (SD=0.087). The significant increase from the historical 0.587 ($p < 0.001$) confirms that the shift toward balanced, dispersed building distribution results from actual spatial restructuring rather than sampling interference.

2.2.6 Summary of fractal analysis parameters

In order to facilitate the reproduction and comparison of the research results, table 11 summarizes the key parameter settings of the four fractal dimension calculation methods.

Table 11 | Summary of fractal dimension measurement parameter settings.

Type of fractal dimension	analytical object	calculating method	Reference Center/Benchmark	Scale sequence/step size	Scale-free interval determination method
boundary dimension	Village boundary outline	Perimeter-area method	mesh side length $\delta = 2^i$ ($i=0-5$)	Determined by the linear region of the double logarithmic scatter plot	One group in each of the four periods
radius dimension	Street road network	concentric circle method	The weighted geometric center of buildings in each period	The arithmetic step is 100m, and the R_{max} covers the built-up area of +200m.	Determined by the linear region of the scatter plot
box-counting dimension	public space	Grid cover Cover method	The initial side length $r_0=212.6m$, isometric 1/2 decreasing to the minimum space unit	Determined by the linear region of the scatter plot	4 periods, 6-8 scales in each period.
correlation dimension	Architectural dot matrix	Correlation product Division method	Distance threshold isometric sequence $r_{min} \times 2k$, $r_{min} \approx 3m$	R^z maximization and interval width comprehensive judgment	4 periods, with points ranging from 32-203

3 Analysis of the evolution of spatial form in Xiuxi Village

3.1 Division of historical evolution stages

Combining regional natural constraints and social-development contexts, this paper divides the spatial evolution of Xiuxi Village into four phases. The first is the naturally-formed initial stage before and during the Ming-Qing dynasties: restricted by mountain terrain and agricultural conditions, the village maintained a small

scale with scattered dwellings highly adapted to local landforms. The second phase covers natural expansion from the early- to mid-20th century; population growth reduced inter-building distances and drove settlement extension onto adjacent flat terraces (Lin et al., 2025). The third, stable-development phase spans from the mid-20th century to 2008. Supported by improved living infrastructure and relevant development policies, the village expanded spatially with intensified residential construction and gradually stabilized its overall spatial pattern. The fourth is the post-2008-Wenchuan-earthquake reconstruction-driven adjustment phase, after which the village presented more scattered and irregular spatial characteristics (Wang et al., 2021).

3.2 Evolution characteristics of landscape morphology

L/W and LSI characterize village morphology and boundary complexity, and both declined across Xiuxi Village's four developmental stages, marking a transition from linear expansion to clustered agglomeration. L/W decreased from 4.46 (Ming-Qing) to 1.98 (post-earthquake), falling into the band-to-cluster transition range ($1.5 < L/W \leq 2.0$); post-disaster reconstruction improved spatial balance without altering the core morphological type. A slight post-quake LSI rise (1.5734-1.6241) suggests boundary adjustments from road-related new construction, while the clustered pattern remained. Confined by valley terrain, the village initially expanded linearly along valleys and later grew onto gentle slopes to become more compact.

The overall LSI drop (2.3844-1.6241) indicates simpler, more regular boundaries. Irregular outlines stemmed from terrain-limited spontaneous expansion in early periods, whereas unified post-earthquake planning smoothed settlement contours (Lin et al., 2023). Together with shrinking L/W, these metrics evidence a shift from terrain-driven banded sprawl toward compact agglomeration. Xiuxi Village evolved from nature-led outward expansion to human-guided internal consolidation with more regular and balanced spatial organization.

3.3 Analysis of fractal characteristics of village morphology

Based on boundary dimension, public-space box-counting dimension, road radius dimension and building correlation dimension, this paper measures Xiuxi Village's multi-stage spatial morphology. Results reveal a long-term evolutionary trend from natural adaptation to structural optimization and post-disaster readjustment, with divergent evolutionary traits among different spatial components. Slope constraints restrict horizontal expansion and force buildings to distribute along contours, generating typical three-dimensional mountain-settlement features. Though fractal measurements rely on 2-D planar data, field investigations indicate vertical elevation differences strongly shape building layouts and sight-line relations. Future research should adopt 3-D spatial analysis for further quantitative validation (Sun et al., 2018).

3.3.1 Evolution characteristics of boundary morphology

Boundary dimension reflects the contour complexity and expansion characteristics of village boundaries. Xiuxi Village's boundary dimension presents an obvious "rise - fall" trend, increasing from 1.1623 in the Ming and Qing Dynasties to 1.2056 in the early and mid-20th century, and declining to 1.1468 during 2008 - 2025 (Table 6). In the Ming and Qing periods, the small-scale village was simply structured, with buildings scattered along valleys and gentle slopes. Population growth and expanding construction activities later diversified the boundary morphology and raised its fractal complexity. After the mid-20th century, the village boundary gradually stabilized and became more regular. In particular, post-earthquake reconstruction promoted integrated and orderly building layouts, further reducing the boundary dimension and indicating enhanced peripheral spatial integration

(Wang et al., 2018). Overall, the village boundary evolved from locally complex and fragmented expansion toward standardized and regularized morphology, with weakened outward extensional growth.

3.3.2 Evolution characteristics of public space

The public-space box-counting dimension characterizes the structural complexity and organization of village public areas. For Xiuxi Village, this index rose from 1.279 (Ming-Qing period) to 1.338 (2008-2025) (Table 8). Early public spaces consisted mainly of road nodes, courtyard plazas and scattered open sites with simple spatial hierarchies. As the village expanded, more transitional spaces and activity venues emerged between buildings, increasing public-space quantity and connectivity (Xun et al., 2024). Post-earthquake reconstruction further optimized public facilities and open grounds, enriching its hierarchical system. The rising box-counting dimension demonstrates that public spaces evolved from discrete point-like distribution toward an interconnected composite system with growing organizational complexity.

3.3.3 Street network evolution characteristics

The road radius dimension characterizes street-network spatial distribution from the village core to its periphery. For Xiuxi Village, this value dropped from 0.9138 (Ming-Qing dynasties) to 0.6871 (mid-20th century-2008), before rising to 1.0862 in the post-earthquake reconstruction phase (Table 10). Early streets clustered around the settlement core with a concentrated road-network structure. As the village expanded, peripheral new buildings outpaced road construction, producing a centre-to-periphery decline in road-network density and a lower radius dimension. After 2008, infrastructure upgrades optimized the lane system, gradually completing peripheral street facilities and yielding more balanced road-network distribution, hence a notable rise in the radius dimension. Overall, Xiuxi Village's street network evolved from core-oriented agglomeration toward balanced distribution (Wang et al., 2021), with enhanced spatial equilibrium and peripheral road coverage.

3.3.4 The evolution characteristics of architectural layout

The building correlation dimension, which characterizes the spatial correlation and distribution of buildings, increased steadily from 0.587 (Ming-Qing period) to 1.651 (2008 – 2025) (Table 10). In the Ming-Qing era, buildings clustered densely within limited construction land with strong local aggregation. With settlement expansion, new constructions extended outward, broadening the spatial connection scope of buildings. After the mid-to-late 20th century, the architectural layout transcended original boundaries and formed multiple spatial clusters. Post-earthquake reconstruction integrated new and original buildings to establish a balanced, discrete building distribution (Sun et al., 2024). The rising dimension indicates Xiuxi Village's building layout evolved from single-center concentrated aggregation to multi-level, balanced spatial diffusion.

3.3.5 Summary of the evolution characteristics of village spatial form

Four fractal indicators collectively reveal the phased spatial evolution of Xiuxi Village. The declining boundary dimension indicates gradual contour regularization, shifting from tortuous terrain-adaptive boundaries to orderly outlines (Pan et al., 2026). Despite ongoing area growth, the village has transitioned from valley-oriented linear expansion to internal infilling, as supported by the slight post-2008 LSI rebound. Rising box-counting and correlation dimensions reflect diversified public space systems and increasingly uniform building distribution. The post-earthquake growth in road radius dimension further demonstrates planning's role in balancing road networks (Li et al., 2022). Overall, the village has evolved from terrain-driven linear sprawl to internally optimized, spatially

balanced development, providing robust quantitative evidence for its evolutionary mechanisms (Table 12).

Table 12 | The comprehensive evolution characteristics of the fractal characteristics of the spatial form of Xiuxi Village

index types	ming-qing dynasty	Early 20th century-mid 20th century	Mid-20th century-2008	2008 – 2025	evolution trend
aspect ratio (L/W)	4.46	2.98	2.04	1.98	From obvious banded to agglomerated development
landscape shape index (LSI)	2.3844	1.9714	1.5734	1.6241	From obvious banded to agglomerated development
boundary dimension	1.1623	1.2056	1.1815	1.1468	First rise and then fall, the boundary tends to be regular The transition from central
radius dimension	0.9138	0.6925	0.6871	1.0862	agglomeration to balanced distribution The complexity of public space continues to increase.
box-countin g dimension	1.279	1.247	1.295	1.338	The building layout is gradually balanced
correlation dimension	0.587	1.146	1.482	1.651	Evolution from linear expansion to group integration
spatial morphologic al characteris tics	On the mountain, banded aggregation	Extending along the valley, the boundary is complicated	The internal filling increases and the structure stabilizes.	Post-earthquak e restructuring and group development	The organizational structure tends to be more complex The complexity continues to increase
spatial organizatio n characters	Single center aggregation	The central expansion is obvious	Multi-node formation	Spatial structure equilibrium	
public space characteris tics	Few nodes, simple hierarchy	quantities uplifted	The system gradually improved	Rich levels, enhanced contact	
Architectur al layout characteris tics	Concentrated settlement	Diffusion along the road	Multi-group formation	equilibrium distribution	From aggregation to dispersion development

Although both LSI and boundary dimension involve boundary morphology, the spatial characteristics of the two measures are different. LSI reflects the degree of deviation of the overall shape of the village patch from the circle (sensitive to the macroscopic aspect ratio and contour flatness), and its monotonous decline indicates that the overall shape of the village gradually tends to be compact. The boundary dimension reflects the tortuous complexity of the boundary contour on multiple scales (sensitive to local concave-convex and detail changes of the boundary). Its “first rise and then fall” indicates that the boundary complexity increases in the middle period due to the expansion of the building along the terrain edge, and decreases in the later period due to planning integration. The two indicators reveal the evolution characteristics of the village boundary form from different scales. The difference in the trend of change is not contradictory, but reflects the independent evolution logic of the village boundary at the two levels of macro-morphological regularization and local detail complexity(Zhou et al, 2024).

4 Evolution mechanism and driving factor analysis

4.1 Congenital constraints of the natural environment

Xiuxi Village is located in the alpine valley of western Sichuan. The complex landform composed of steep slopes and deep valleys forms a natural constraint on the location, expansion direction and architectural pattern of the village. It also makes the initial layout of the village on the mountain and the buildings are arranged along the

contour line, thus avoiding large-scale terrain transformation. Slope conditions limit the extension of the village in the horizontal direction, so that the village extends in the vertical direction, forming a unique three-dimensional spatial structure ; the terrain not only shapes the tortuous boundary of the village, but also dominates the formation of the transitional virtual boundary between the village and the nature. The terrain elevation difference of Xiuxi Village is obvious, and its virtual boundary is mostly formed spontaneously along the natural terrain line, rather than delineated by manual planning. The natural terrain constitutes the base of the spatial pattern of Xiuxi Village, profoundly shapes its spatial form, and continues to affect the evolution of the village at various stages of development.

4.2 Acquired adjustment of social culture

From the early-to-mid-20th century, Xiuxi Village' s spatial morphology was mainly governed by residents' practical needs and local folk culture. Under an acquaintance-based social order, villagers carried out self-organized construction to expand village space. Dwelling sites were chosen near kin-related homesteads to sustain neighborhood kinship, while feng-shui beliefs guided building orientation and layout. The 2008 post-earthquake reconstruction shattered this self-development balance via external planning and administrative intervention. It introduced outside resources and technologies and accelerated modernization. Road renovation raised the radius dimension from 0.6871 to 1.0862, improving peripheral accessibility and network balance (Table 9). Nevertheless, newly built regular-width roads departed from terrain-following narrow curved traditional lanes. Though road connectivity and coverage were enhanced, road-terrain adaptation, interface continuity and spatial texture shifted from spontaneous traditional patterns to modern planned modes. Such transformation brought infrastructure benefits yet weakened traditional street features, rearranged public venues and disturbed original social networks. It demonstrates that human factors exert profound control over traditional-village spatial evolution.

4.3 Effect of mutation factors

The 2008 Wenchuan earthquake acted as a decisive external driver that restructured Xiuxi Village' s spatial evolution. Seismic damage destroyed buildings and altered land-use patterns, while subsequent post-disaster reconstruction further promoted staged spatial transformation. Artificial planning disrupted the original traditional street system, shifting the compact, centralized settlement structure toward a looser, decentralized layout. Government-led in-situ reconstruction standardized residential arrangements, reshaping the village' s morphological features and social spatial patterns.

Fractal results quantitatively confirm these post-disaster changes. The boundary dimension decreased from 1.1815 to 1.1468, indicating more regular village boundaries. The road radius dimension increased substantially from 0.6871 to 1.0862, reflecting balanced road distribution and improved peripheral accessibility. The public space box-counting dimension rose from 1.295 to 1.338, signifying enhanced public spatial complexity. Meanwhile, the building correlation dimension grew from 1.482 to 1.651, demonstrating more uniform and discrete building layouts. Overall, sudden disaster shocks and reconstruction intervention constitute key triggers for the comprehensive spatial restructuring of mountain traditional settlements.

4.4 The driving factors and mechanism interpretation framework of spatial form evolution

Based on fractal-characteristic measurements and historical-evolution analysis of Xiuxi Village, this paper

establishes an evolutionary-mechanism model of “natural-environment constraint-socio-cultural shaping-mutation-factor reconstruction” (Figure 5). Herein, rising fractal dimensions denote improved spatial organization. For mountain traditional villages, an increasing correlation dimension reflects building distribution shifting from early-stage highly-concentrated patterns confined to limited suitable land $D=0.587$ toward balanced, wide-ranging spatial layout $D=1.651$. Driven by population growth and land demand, the settlement breaks original site-selection constraints and develops multi-cluster, multi-node structures, embodying functional differentiation and upgraded spatial capacity. Likewise, the box-counting dimension increase ($1.279 \rightarrow 1.338$) marks public-space transition from single nodes to multi-level systems, representing enriched public-life functions. Accordingly, higher fractal dimensions in this study quantify enhanced structural complexity and functional adaptability rather than spatial disorder (Pei et al., 2023). Xiuxi Village’ s spatial morphology arises not from single drivers but from dynamic, multi-stage evolution jointly shaped by natural conditions, social-cultural forces and sudden events.

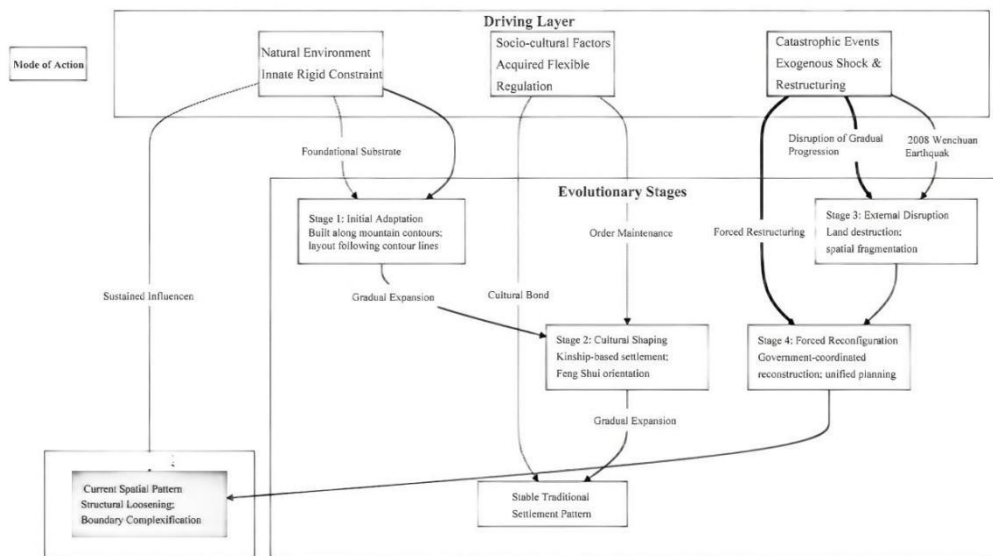


Fig.5 | The driving mechanism and stage response relationship model of spatial form evolution in Xiuxi Village

Xiuxi Village’ s spatial evolution is jointly driven by natural constraints, socio-cultural inheritance and exogenous disaster interference. Alpine canyon landforms shape its basic topographic framework, limiting early site selection and expansion and forming a path-dependent terrain-adapted spatial pattern. On this basis, traditional Qiang customs, including clan rules, feng shui concepts and local construction traditions, gradually established its unique spatial order. This cultural stage generated unbalanced structural changes: building correlation dimension (1.146-1.482) and public-space box-counting dimension (1.247-1.295) increased, reflecting dispersed buildings and enriched public spaces, while road radius dimension slightly declined (0.6925-0.6871), indicating lagging infrastructure development. This structural mismatch laid the foundation for post-disaster spatial renewal (Li et al., 2026). Different from slow endogenous evolution, the 2008 Wenchuan earthquake served as an abrupt external shock. Post-disaster planning reconstruction transformed the village from self-organized organic growth to externally regulated spatial reorganization, thoroughly restructuring its morphological system.

Overall, Xiuxi Village experienced four-phase evolution: “initial adaptation, cultural shaping, external disturbance, and forced reorganization” (Figure 5). The natural environment sets fundamental spatial boundaries, local culture shapes spatial organization, and post-disaster reconstruction acts as a key structural-adjustment turning point (Shi, 2019). Together they form a coupled mechanism of “rigid constraint-flexible adjustment-external reconstruction”, producing its hybrid spatial pattern combining traditional and reconstructed traits.

This study confirms prominent human-land coupling in Qiang traditional-village spatial evolution under natural constraints, cultural adaptation and external intervention. The proposed mechanism interprets mountain-Qiang settlement evolution and offers theoretical references for conservation, renewal and post-disaster regeneration of ethnic traditional villages in northwest Sichuan.

Xiuxi Village’s spatial evolution exhibits prominent staged characteristics with period-specific dominant drivers. Its Ming-Qing spatial pattern was naturally adapted to mountain and valley terrain. Since the 20th century, population growth and traditional cultural factors have driven the optimization of internal public spaces and street systems. The 2008 Wenchuan earthquake and post-disaster reconstruction marked a critical turning point, restructuring village space through planning and policy intervention (Table 13). Overall, the village’s morphology results from the coupling of natural constraints, cultural shaping and external reconstruction, rather than simple spatial expansion. Stage-differentiated factors reshape local architectural, road and public space layouts. This process reflects the unique human – land coupling of Qiang villages and demonstrates the evolutionary transition of ethnic mountain settlements from natural adaptation to planning-guided development (Han et al., 2021).

Table 13 | The corresponding relationship between the evolution stage of spatial form and the driving mechanism of Xiuxi Village

evolutionary phase	time range	spatial morphological characteristics	Main fractal response	Dominant driving factors	action mechanism
Natural adaptation stage	ming-qing dynasty	The settlement is small in scale, with a strip layout along the river valley, and the buildings are concentrated on the gentle slope zone	$L/W = 4.46$; boundary dimension 1.1623; correlation dimension 0.587	Natural topography, water system conditions	The settlement site selection conforms to the mountainous environment, and the spatial expansion is constrained by the landform, forming a linear growth pattern
Progressive expansion stage	Early 20th century-mid 20th century	The village expands to the surrounding gentle slope, the boundary complexity increases, and the number of buildings increases	The boundary dimension increases to 1.2056; the correlation dimension increases to 1.146	Population growth, production demand, clan settlement	The building expands around the original settlement area, forming a more obvious central agglomeration structure
Structural optimization stage	Mid-20th century-2008	The building density is increased, the public space system is gradually improved, and the multi-node space is formed	The box-counting dimension increased to 1.295; the correlation dimension increases to 1.482	Local culture, social development, infrastructure construction	The public space and street network continue to develop, and the internal structure of the settlement tends to be stable
Post-disaster reconstruction stage	2008-2025	The characteristics of group development are enhanced, the road network tends to be balanced, and the building layout is reorganized	The radius dimension increases to 1.0862; the box-counting dimension increased to 1.338; the correlation dimension increases to 1.651	Wenchuan earthquake, post-disaster reconstruction, planning intervention	Planning and construction reshape the spatial structure and promote the transformation of settlements from self-organized development to planning guidance

Comprehensive evolution results	whole process	The transition from zonal expansion to cluster agglomeration, and the evolution from single-center structure to composite space system	The boundary tends to be regular, the complexity of public space continues to increase, and the distribution of roads and buildings tends to be balanced	Natural environment, local culture and external intervention work together	Form a spatial evolution mechanism of “environmental constraints-cultural shaping-post-disaster reconstruction ”
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5 Results and discussion

5.1 Results

This study employs fractal theory and landscape-ecological approaches to examine multi-stage morphological evolution of Xiuxi Village, a representative Qiang settlement in northwest Sichuan. Results demonstrate its transition from terrain-driven linear expansion toward compact clustered agglomeration. The L/W ratio dropped from 4.46 to 1.98 and LSI fell from 2.3844 to 1.6241, showing a shift from strip-shaped sprawl to balanced clustered distribution. Post-disaster reconstruction induced slight boundary adjustments and modest LSI rebound yet preserved the clustering tendency, shifting growth mode from outward extension to internal infill and comprehensive optimization.

Xiuxi Village’ s inner spatial structure grew more complex and balanced over time. The public-space box-counting dimension increased from 1.279 to 1.338, implying improved spatial hierarchy and connectivity. The building correlation dimension rose sharply from 0.587 to 1.651, indicating a layout shift from heavy agglomeration toward uniform dispersion. After 2008, the road radius dimension jumped to 1.0862, proving enhanced street accessibility and even spatial coverage. Generally, the settlement transformed from spontaneous self-organization to deliberately organized spatial configuration.

Obvious staged differentiation exists in its spatial evolution. Pre-2008 development was mainly restricted by mountain topography and gradually optimized under socio-cultural influences. The 2008 Wenchuan earthquake and subsequent reconstruction formed a critical disruptive node. It terminated the long-term spontaneous evolution trajectory and reshaped the inherited spatial framework via top-down planning-led intervention.

Xiuxi Village’ s morphology is controlled by the triple coupled mechanism: natural constraint, cultural shaping and external reconstruction. Mountain landforms set its spatial boundary, indigenous Qiang customs modulated spatial textures, and post-disaster planning brought structural reorganization and functional promotion. This paper builds a multi-dimensional fractal-evolution framework for ethnic mountain settlements and supplies quantitative support for post-disaster renewal. Future work will enlarge case quantity and conduct comparative analysis to generalize evolutionary rules of Qiang traditional villages.

5.2 Discussion

5.2.1 Stage characteristics of spatial evolution of mountain ethnic settlements

Existing studies generally attribute settlement evolution to the interaction between natural environments and human activities. Unlike plain settlements driven primarily by population and land expansion, Qiang villages in northwest Sichuan are highly constrained by mountain terrain with strong environmental dependence. This study reveals that Xiuxi Village presents distinct phased evolution, shifting from natural adaptation and cultural shaping to externally driven reconstruction under emergent events and planning intervention (Bi et al., 2025). This staged transition reflects both the self-organizing growth of traditional settlements and the transformative impacts of external intervention on mountain ethnic villages. Different from the conventional “natural adaptation-population

expansion” model, Xiuxi Village exhibits prominent spatial restructuring after the earthquake, demonstrating that major external disturbances can serve as critical turning points in the long-term evolution of traditional village spatial systems.

5.2.2 The applicability of fractal method in the study of traditional village space

Fractal theory well explains scale properties and organizational rules of complex spatial systems, while its application to mountain-ethnic traditional villages is still inadequate. This study employs four fractal indices (boundary, radius, box-counting, and correlation dimensions) for multi-dimensional quantitative analysis of village morphology, uncovering evolutionary features of settlement boundaries, road networks, public spaces and building distributions. Such integrated multi-fractal framework overcomes drawbacks of conventional qualitative analysis and offers a fresh research perspective. Nevertheless, fractal outputs only capture statistical spatial trends and cannot fully unpack socio-cultural connotations behind spatial formation. Hence, future research ought to combine fractal quantification with social surveys and cultural-landscape analysis to better clarify evolutionary mechanisms of traditional settlements.

5.2.3 Research deficiencies and prospects

This study has several limitations. Limited by historical data accessibility, spatial information for the Ming-Qing and early-20th-century phases was partly reconstructed from documentary records and oral narratives. Multi-source cross-validation mitigated errors, yet early-stage spatial extraction remains less accurate than modern-period data; corresponding fractal outcomes are valid merely for trend interpretation. Local archives, genealogies and land deeds can be adopted to enhance historical-spatial restoration accuracy in follow-up research (Ma et al., 2024). Furthermore, this single-case study cannot fully validate result universality amid diverse terrain, resources and reconstruction patterns among Qiang villages. Future work shall build multi-temporal spatial databases, adopt multi-case comparison and machine-learning techniques to quantify and predict evolutionary drivers, delivering more robust theoretical references for ethnic-village conservation and planning.

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Competing interests

The authors declare no competing interests.

Data availability

The datasets generated and analysed during the current study are available from the corresponding author on reasonable request.

ETHICAL APPROVAL EXEMPTION / WAIVED

Formal ethical approval was waived by Hebei Academy of Fine Arts. All research procedures were performed in strict accordance with the ethical guidelines for humanities and social science field research. This study only involves historical document collation, remote sensing interpretation, and non-invasive field investigation of village public spatial morphology. No human participants, biological samples, private data, interviews or behavioral interventions were included. All field surveys were conducted in publicly accessible areas without privacy interference. This exemption complies with the General Ethical Requirements for Humanities and Social Science Research Projects issued by the Ministry of Science and Technology of China, which exempts non-interventional observational landscape and spatial morphology research from institutional ethical review.²

Informed consent

Please provide a statement within the ethics statement confirming that “informed consent was obtained from all participants and/or their legal guardians”.

Informed consent

Informed consent is not applicable because this study did not involve human participants.

ACCORDANCE

All research was performed in accordance with relevant named guidelines and regulations. The Declaration of Helsinki is not applicable to this work, given the absence of human subjects.

Acknowledgements

This research was funded by the Key Project of the National Social Science Fund, titled “Research on the

² General Ethical Requirements for Humanities and Social Science Research Projects. Available at: <https://www.most.gov.cn>

Uncovering of Historical Materials and Patterns of Historical Evolution Regarding Ethnic Interaction, Exchange, and Integration in Traditional Settlements along the Han-Tibetan-Qiang-Yi Corridor” (Project No.: 24AZD032). Meanwhile, we would like to thank our peers for their valuable assistance in refining this article and express our gratitude to the editors and anonymous reviewers for their insightful feedback and constructive suggestions.

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